

Reading with Filtered Fixations:  
Adult Age Differences in the Effectiveness of Low-level Properties of Text Within Central  
Vision

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### ABSTRACT

When reading, low-level visual properties of text are acquired from central vision during brief fixational pauses but the effectiveness of these properties may differ in older age. To investigate, a filtering technique displayed the low, medium, or high spatial-frequencies of text falling within central vision as young (18-28 years) and older (65+ years) adults read. Reading times for normal text did not differ across age groups but striking differences in the effectiveness of spatial frequencies were observed. Consequently, even when young and older adults read equally well, the effectiveness of spatial frequencies in central vision differs markedly in older age.

Key Words: Reading, eye movements

The ability to read is crucial for functioning effectively in everyday life. However, numerous studies indicate that many aspects of reading performance differ between young adults (aged 30 years and under) and older adults (aged 65 years and over; e.g., Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Castelhana, & Yang, 2009; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; see also Laubrock, Kliegl, & Engbert, 2006) and these differences are widely attributed to normal sensory and cognitive decline. But the precise nature of the differences in reading performance that occur as adults reach older age has yet to be fully determined.

Of particular importance is that the eyes move when reading and make a series of brief fixational pauses, with the effect that different areas of text can be viewed within central vision (an area approximately  $2^\circ$  wide around the point of fixation; for a review, see Rayner, 2009). Crucially, during these pauses, the visual system acquires only low-level visual properties from text and these visual properties then provide the bases for the subsequent linguistic analyses that ultimately allow readers to make sense of what they are seeing (e.g., Allen, Smith, Lien, Kaut, & Canfield, 2009; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Patching & Jordan, 2005a, 2005b). Indeed, the low-level properties of text falling within central vision provide a range of different scales of visual analysis (spatial frequencies) that are associated with different aspects of the text being read. So, for example, lower spatial frequencies allow readers to see a word's coarse overall shape but not its fine detail, whereas higher spatial frequencies allow readers to see a word's fine detail, such as the precise form of individual letter features (e.g., Allen et al., 2009; Jordan, 1990, 1995; Kwon & Legge, 2012; Legge, Pelli, Rubin, & Schleske, 1985; Patching & Jordan, 2005a,b). Thus, although spatial frequency analyses in central vision are unlikely to be apparent to the reader, reading relies fundamentally on these low-level visual properties of text.

Fresh insight into the role of spatial frequencies in central vision for reading has recently

been obtained for young adults, using an eye-movement paradigm that presented only subsets of the spatial frequency content of text falling within central vision during each fixational pause (Jordan, McGowan, & Paterson, 2012). The findings showed that, as young adults read, higher spatial frequencies in central vision were more effective than low for reading and, indeed, normal reading was particularly disrupted when only low spatial frequencies were presented. Moreover, higher spatial frequencies produced near-normal reading performance, indicating that young adults may use just subsets of the spatial-frequency content of text within central vision when reading.

But it is unclear whether the effectiveness of spatial frequencies within central vision shown by young adults remains unaltered in older age. Of particular significance is that normal aging produces a characteristic decline in sensitivity to various scales of spatial frequency, especially to higher spatial frequencies within central vision, due to a combination of optical changes and changes in neural transmission (for discussions, see Derefelt, Lennerstrand, & Lundh, 1979; Elliott, 1987; Higgins, Jaffe, Caruso, & deMonasterio, 1988; Laubrock et al., 2006; Owsley, 2011). As a result, older adults may be less able than young adults to process the visual detail of text falling within central vision during fluent reading, and this change may affect reading performance. Indeed, it is widely assumed that reading relies greatly on visual detail from within central vision (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Rayner, & Pollatsek, 2003; see also Rayner, 2009) and so reduced access to this detail for older adults may disrupt reading performance severely in this age group. In contrast, the visual detail of text within central vision may be particularly beneficial for reading by young adults, for whom access to higher spatial frequencies is not impaired by aging, and this is consistent with the study of young adults by Jordan et al. (2012). Consequently, it seems from the evidence available so far that the effectiveness of the spatial frequency content of text falling within central vision may differ substantially between young and older adults, and this

difference is likely to impair reading greatly in older age.

Differences between young and older adult readers in the effectiveness of the spatial frequencies of text falling within central vision remain to be determined but adult age differences in the effectiveness of spatial frequencies more generally in text have been observed (Paterson, McGowan, & Jordan, 2013a, 2013b). For example, Paterson et al. (2013a) used sentence displays in which entire sentences were filtered to contain only the very low, low, medium, high, or very high spatial frequency content of text. For young adults, normal performance was impaired only when low or very low spatial frequencies were presented, whereas normal performance for older adults was impaired by all the spatial frequencies that were used. Paterson et al. (2013b) developed this study further by using a gaze-contingent moving window paradigm in which text was shown as normal within a region centered at the point of fixation while all text outside this region was filtered to contain only a subset of normal spatial frequency content. The findings showed that higher spatial frequencies were more effective for reading by young adults but that lower spatial frequencies were more effective for reading by older adults.

Both of these studies provide important indications of age related differences in the effectiveness of spatial frequencies for reading but neither study was concerned with the specific role of spatial frequencies within central vision. Indeed, Paterson et al. (2013a) deliberately did not restrict the areas of text in which subsets of spatial frequencies were presented, and Paterson et al. (2013b) addressed only the role of spatial frequencies in text away from fixation. However, central vision is anatomically and functionally distinct from other areas of the visual field (e.g., Jordan & Paterson, 2009) and is especially important for reading because it provides information that is usually essential for word identification (e.g., Rayner, 2009). Consequently, the possibility that age related changes in the effectiveness of spatial frequencies for reading exist within central vision requires specific investigation.

Accordingly, the purpose of the present research was to determine the effectiveness of the spatial frequency content of text within central vision for reading by young and older adults. This was achieved by using the recently-developed foveal-filtering paradigm (Jordan et al., 2012) in which readers read lines of text that were presented normally except for a virtual filter 2° wide centered at the location of each fixational pause and which filled the width of central vision. The paradigm was adapted from the well-established “moving mask” technique (e.g., Rayner & Bertera, 1979; see also McConkie & Rayner, 1975) so that the location of the filter was yoked to the reader’s eye movements. In this way, when the reader’s eyes moved to fixate a new location along a line of text, the filter moved in synchrony with these eye movements in real time and was present at each fixation location. Throughout each fixational pause, text lying outside each filtered area was displayed as normal but text within each filtered area showed only its low, medium, or high spatial frequencies (see Figure 1). These bands of spatial frequencies are known to be influential in word recognition (e.g., Patching & Jordan, 2005a,b) and are well-suited to revealing differences in the use of spatial frequencies for reading. The phenomenological experience of all these displays for participants was that each filtered area moved in perfect synchrony with the eyes during reading.

If the effectiveness of the spatial frequency content of text in central vision differs between young and older adults, these changes should be revealed when this content is modulated for each age group. Of particular importance is that if the effectiveness of the high spatial frequency content decreases for older adults, presenting only this frequency content should be more disruptive for older adults than for young. Indeed, if older adults rely more than young adults on the lower spatial-frequency content of text in central vision (as age-related changes in vision suggest), presenting only lower spatial frequencies may actually produce better reading performance than high spatial frequencies for older adults. If this pattern of effects were observed, this would indicate important differences in the functional

relevance of the spatial frequency content of text falling within central vision as adults reach older age.

### Method

*Participants.* Participants were 16 young adults (mean age=21 years, range=18-28 years) and 16 older adults (mean age=69 years, range=65-77 years). All were native speakers of English. To help ensure representative visual abilities of young and older participants and to avoid problems associated with clinical impairments (for discussions, see Jordan, McGowan, & Paterson, 2011; McGowan, Paterson, & Jordan, 2013), all participants were screened for normal or corrected to normal vision, as determined by MNREAD (Mansfield, Ahn, Legge, & Luebker, 1993), Bailey-Lovie (Bailey & Lovie, 1980), ETDRS (Ferris & Bailey, 1996), and Pelli-Robson (Pelli, Robson, & Wilkins, 1988) assessments. Following this procedure, older adults showed lower visual acuity than young adults (older adults,  $M = 20/21$ , young adults,  $M = 20/17$ , where acuity is reported in Snellen values) and lower log contrast sensitivity (older adults,  $M = 1.80$ , young adults,  $M = 1.90$ ). In addition, both age groups had similar educational backgrounds (older adults,  $M = 15.8$  years, young adults,  $M = 15.9$  years) and reported similar reading experience (older adults,  $M = 18.1$  hours/week, young adults,  $M = 16.8$  hours/week).

*Design and Materials.* 160 sentences were displayed either entirely as normal or using a moving filter  $2^\circ$  wide, centered at each point of fixation. Text outside each filtered area was normal and text within each filtered area was altered using MATLAB to leave one of 3 different, 1-octave wide bands of spatial frequencies with center (peak) 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 frequencies respectively (see Patching & Jordan, 2005a,b). These alterations were achieved using Butterworth filters to provide mathematically tractable manipulations which avoid problems associated with other

filters. 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 condition but saw each sentence only once. This enabled all sentences to be shown equally often in each condition across participants but avoided repetition of any sentence for any participant. The primary focus of the research was reading time but the duration and number of fixational pauses made when reading were also recorded.

*Apparatus and Procedure.* The experiment was conducted using an Eyelink 2K eye-tracker with a spatial resolution of  $.01^\circ$ . Sentences were displayed in Courier typeface on a 19-inch monitor at 120 Hz and eye position was sampled at 1000 Hz using corneal reflection and pupil tracking. In each sentence, 4 letters subtended approximately  $1^\circ$  so as to approximate normal reading conditions (Rayner & Pollatsek, 1989). Custom software ensured that the filter moved in close synchrony with eye movements, and display changes were made within 10-12ms. At the beginning of the experiment, participants were instructed to always 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. When a participant was fixating this location accurately, a sentence was presented, with the first letter of the sentence replacing the square. Participants pressed a response key as soon as they finished reading each sentence. The sentence was then replaced by a comprehension question, to which participants responded (e.g., the sentence *Clive hates studying algebra because he finds it very hard* was followed by the question *Does Clive like the subject?*). Calibration was checked between trials and the eye-tracker was recalibrated as necessary.

## Results

Young and older adults showed similar, high levels of comprehension (response accuracy was 98% for each age group) with no differences between any display types (all  $F_s < 1.4$ ). For each sentence, measures of reading performance were provided by overall reading time, mean

fixation durations (the average length of fixational pauses during reading), and total number of fixations (the number of these fixational pauses). Reading times are shown in Figure 2, and fixation durations and number of fixations are reported in Table 1. For each of these measures, an Analysis of Variance with factors age and display type (normal, and low, medium, and high spatial frequencies) was conducted. Following standard procedures, fixations shorter than 80 ms or longer than 1200 ms were removed from these analyses (affecting 3.2 % of fixations). Post-hoc comparisons were performed using Bonferroni-corrected t-tests.

Reading times revealed main effects of age,  $F(1,29)=16.93$ ,  $p<.001$ ,  $\eta_p^2=.37$ , and display type,  $F(3,87)=26.01$ ,  $p<.001$ ,  $\eta_p^2=.47$ , and the interaction,  $F(3,87)=17.22$ ,  $p<.001$ ,  $\eta_p^2=.37$ . Across age groups, reading times did not differ for normal displays ( $p>.75$ ) but older adults showed longer reading times than young for each of the three spatial frequencies ( $ps<.01$ ). For young adults, reading times for high and medium spatial frequencies were no different from those for normal displays ( $ps>.50$ ) but the longest reading times of all occurred for low spatial frequencies ( $ps<.01$ ). For older adults, reading times for normal displays were shortest of all the four display types ( $ps<.01$ ) and, within the filtered displays, reading times were shortest for medium spatial frequencies, longer for low, and longest of all for high (all  $ps<.01$ ).

Similar patterns were observed for fixation behavior. Fixation durations revealed main effects of age,  $F(1,29)=44.56$ ,  $p<.001$ ,  $\eta_p^2=.61$ , and display type,  $F(3,87)=129.74$ ,  $p<.001$ ,  $\eta_p^2=.82$ , and the interaction,  $F(3,87)=43.69$ ,  $p<.001$ ,  $\eta_p^2=.60$ . Across age groups, older adults made longer fixations than young for all four display types ( $ps<.01$ ). For young adults, fixation durations were shortest for normal displays ( $ps<.01$ ), equally longer for high and medium spatial frequencies, and longest of all for low ( $ps<.01$ ). For older adults, fixation durations were also shortest for normal displays ( $ps<.01$ ) but, within filtered displays, were shortest for medium spatial frequencies, longer for low, and longest of all for high ( $ps<.01$ ).

Fixation numbers revealed a marginal main effect of age,  $F(1,29)=3.14$ ,  $p<.09$ ,  $\eta_p^2=.10$ , a

main effect of display type,  $F(3,87)=13.50$ ,  $p<.001$ ,  $\eta_p^2=.32$ , and the interaction,  $F(3,87)=10.32$ ,  $p<.001$ ,  $\eta_p^2=.26$ . Across age groups, number of fixations did not differ for normal, low, or medium spatial frequencies but, for high spatial frequencies, older adults made more fixations than young ( $ps<.01$ ). Young adults showed no differences across normal, high, and medium spatial frequencies, but made the most fixations for low spatial frequency displays ( $ps<.01$ ). For older adults, fixations were fewest for normal displays ( $ps<.01$ ) and, within filtered displays, were fewest for medium spatial frequencies, more for low, and most of all for high (all  $ps<.01$ ).

### Discussion

The findings of this study demonstrate that young and older adults rely very differently on the low-level visual properties of text encountered within central vision during the brief fixational pauses made when reading. To reveal this difference, a recently developed, real-time filtering technique was used in which only selected subsets of the normal spatial frequency content of text falling within central vision were presented during each fixational pause. For young adults, reading times, fixation durations, and fixation numbers all indicated that high and medium spatial frequencies were more effective for reading than low. Indeed, young adults maintained normal reading times even when only high and medium spatial frequencies were present across central vision and both these spatial frequencies produced patterns of fixation duration and number closest to those observed for normal text. This suggests that reading by young adults benefits particularly from relatively detailed analyses of text within central vision (e.g., allowing perception of distinct letter fragments and the precise shape of individual letters) that cannot be provided by low spatial frequencies, and that while low spatial frequencies are available in central vision for young adults, young adults place much less emphasis on these visual properties for reading (see also Jordan et al., 2012). But in comparison, for older adults, the reading times, fixation durations, and fixation counts

observed in the present study indicate that the lower spatial frequency content of text within central vision was much more effective for reading than high. Indeed, displaying only the high spatial frequency content of text disrupted older adults' reading performance substantially and most of all the spatial frequencies presented. As a result, reading by older adults appears to benefit more from the overall form of words and letters in central vision and much less from perception of visual detail.

The finding that young adults' reading times with normal text were unaffected when only high or medium spatial frequencies were presented is consistent with indications from previous research (with young adults) suggesting that single bands of spatial frequencies can be sufficient for reading in this age group (e.g., Jordan et al., 2012; Legge et al., 1985; Patching & Jordan, 2005a,b). But in contrast, for older adults, normal reading times were lengthened by each band of spatial frequencies, even by low and medium spatial frequencies which provided the best reading performance for this age group. Indeed, for older adults, medium spatial frequencies were the most effective for reading, suggesting that this frequency band may reflect the best single option for supporting linguistic analyses in this age group (e.g., by providing usable information about individual letters, letter groups, and whole words) although, alone, this band of spatial frequencies was still insufficient for normal reading. Thus, compared to young adults, older adults rely on a broader range of spatial frequencies from text within central vision for reading, and this may help compensate for the wide-spread decline in sensitivity across spatial frequencies that is often reported for this age group (e.g., Owsley, 2011). In sum, therefore, the patterns of performance observed with both age groups support the view that reading involves a wide range of spatial frequencies from text within central vision that may independently (and collaboratively, especially for older adults) activate processes of word perception during reading (e.g., Allen et al., 2009; Boden & Giaschi, 2009; Jordan, 1990, 1995; Leat & Munger, 1994; Legge et al., 1985; Patching & Jordan, 2005a,

2005b).

However, despite striking differences in the effectiveness of spatial frequencies for reading, both age groups produced near identical reading times when text was displayed normally. Consequently, changes in sensitivity to various spatial frequencies caused by normal aging need not produce a decline in reading performance. Instead, as adult readers get older, it appears that a shift can develop in the use of the spatial frequency content of text falling within central vision so that the low-level visual properties of text that are more visible in this area become more relevant for reading. Indeed, the differential effectiveness of spatial frequencies for reading by young and older adults was closely reflected in the duration and number of fixational pauses, suggesting that the influence of spatial frequencies on reading in each age-group is linked to fixation behavior. Consequently, it seems that readers within each age group can generate changes in fixation behavior that help ameliorate the effectiveness of the spatial frequency content that is visually available to them, and this may be a crucial component of maintaining reading performance when sensitivity to spatial frequencies changes with aging.<sup>1</sup>

Other factors are also likely to contribute to the effectiveness of spatial frequencies during reading by each age group. In particular, interactions between visual processing and cognitive processes associated with the syntactic, linguistic, and semantic content of language are normal components of reading (e.g., Jordan & Thomas, 2002; Rayner, 2009) and are likely to involve the influence of spatial frequencies in central vision. Indeed, although 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; Federmeier & Kutas, 2005; Federmeier, Kutas, & Schul, 2010), loss of sensitivity to spatial frequencies in older age may be offset by a greater use of contextual information, and this is consistent with the view that older readers compensate for processing difficulties by a greater reliance on discourse context (e.g., Stine-Morrow et al., 2008). Moreover, for both young and older adults, when fixations

are made during reading, information is also acquired from locations extending outside central vision in the direction of reading, and this parafoveal information is used to pre-process the identity of words before the next saccade is made in their direction (see Rayner 1998, 2009). Consequently, when reading from left to right, processing parafoveal words to the right of fixation is likely to be underway before the next rightward fixation takes place, and this pre-processing may facilitate the recognition of words within central vision using only a subset of their total spatial frequency content when a fixation brings into central vision text seen previously in parafoveal locations.

The notion that spatial-frequency processing occurs in several locations (e.g., foveal, parafoveal, peripheral) as the eyes move along each line of text is supported by previous research which suggests that these low-level visual properties are also influential in text outside central vision (Paterson et al., 2013a,b). Indeed, the findings of Paterson et al. (2013b) show that, outside central vision, young adult readers rely more on high spatial frequencies than low whereas older adult readers rely more on low spatial frequencies than high, and this resembles the pattern observed in the present study for text specifically within central vision. Accordingly, although maintaining a linguistic record of words can help integrate information acquired at each new fixation with that acquired previously along the same line (for discussions, see Mitchell, Shen, Green, & Hodgson, 2008), the low-level, spatial-frequency content of text may provide further, non-linguistic cues to help each age group maintain a cohesive matching of information acquired within central vision with that seen previously in other locations.

Finally, our study highlights the importance of determining the nature and influence of spatial frequencies for reading when developing accurate theoretical accounts of reading across the lifespan. However the low-level visual properties of text within central vision that contribute to reading by young and older adults have yet to become a focus for models of

reading. In particular, current accounts generally assume that visual influences on the rate at which lexical processing of words in central vision is completed are modulated only by the ability to perceive visual detail (e.g., Laubrock et al., 2006; Rayner, 2009; Reichle et al., 2003). In contrast, our study demonstrates that a range of spatial frequencies in central vision can provide effective visual input during normal reading by young and older adults. Moreover, while aging changes the effectiveness of different spatial frequencies, these changes are clearly not catastrophic for reading, and their influences appear to be refined by subtle changes in fixation behaviour. Indeed, as our study has now shown, although older age leads to differences in reading behavior, age-related responses to the low-level visual properties of text encountered within central vision during each brief fixational pause can help adults maintain efficient and effective reading well into later life.

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### Footnote

1. Some researchers (Risse & Kliegl, 2011) have speculated that differences in reading performance between young and older adults do not reflect an age related difference in the size of the perceptual span but instead reflect an age related difference in modulating fixation behavior in response to processing demands. From the findings of Paterson et al. (2013b), the region in which readers are sensitive to the spatial frequency content of text is substantially wider (about double) for older readers than for young. Moreover, in the present study, both age groups modulated their fixation behavior considerably in response to the visual information available in central vision. However, this modulation reflected age-related differences in the effectiveness of low, medium, and high spatial frequencies, and so this aspect of performance provides some support for the notion that young and older adults produce different patterns of fixation modulation in response to the processing demands of reading. It seems likely, therefore, that a full understanding of the role of fixation modulation in reading requires a full understanding of the role of the low-level visual properties of text.

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## Figure Legends

Figure 1. A sentence displayed entirely as normal or with text falling within central vision filtered to contain only low, medium, or high spatial frequencies. In this example, the actual location of the fixation was the letter *e* in *really*. Note that the visual appearance of the filtered text in the figure will be affected by the age of the reader and is approximate due to restrictions in resolution and print medium.

Figure 2. Mean reading times (ms) for young and older adults for normal text and for low, medium, and high spatial frequency displays.

Figure 1

Normal

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

Low Spatial Frequency

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

Medium Spatial Frequency

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

High Spatial Frequency

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

Figure 2

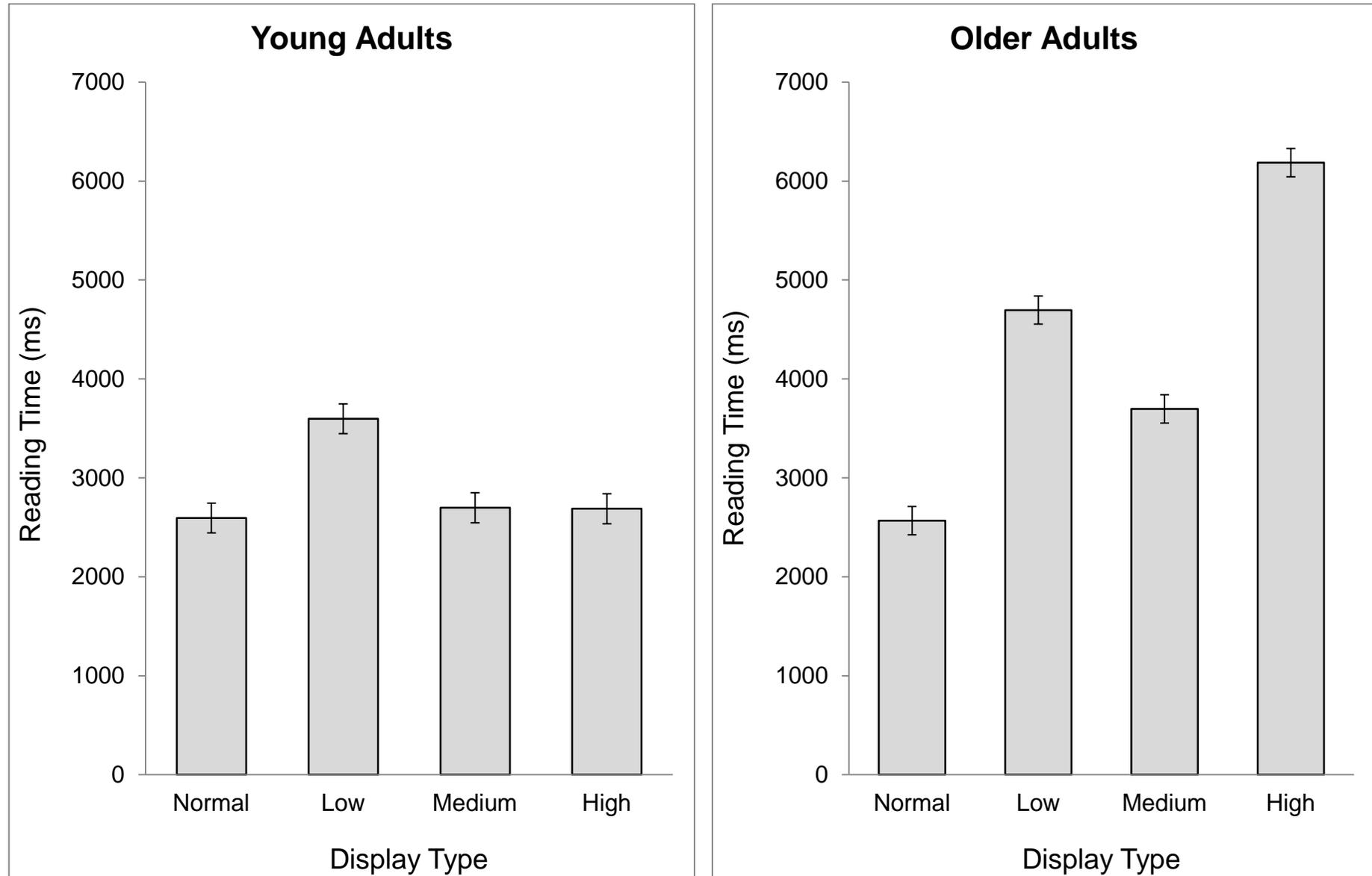


Table 1. Fixation Durations and Number of Fixations for Each Display Type

	Display Type			
	Normal	Low	Medium	High
Fixation durations				
Young	213	260	229	234
	(5)	(7)	(7)	(7)
Older	232	304	289	331
	(5)	(7)	(7)	(7)
Number of fixations				
Young	10.55	12.03	10.24	10.33
	(0.54)	(0.86)	(0.61)	(0.61)
Older	9.32	13.16	11.20	15.90
	(0.52)	(0.83)	(0.59)	(1.09)

Durations are in milliseconds and Standard Errors are in parentheses.