Aging Effects on the Visual Span for Alphabetic Stimuli

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Abstract

Background: The visual span (i.e., an estimate of the number of letters that can be recognized reliably on a single glance) is widely considered to impose an important sensory limitation on reading speed. With the present research, we investigated adult age differences in the visual span for alphabetic stimuli (i.e., Latin alphabetic letters), as aging effects on span size may make an important contribution to slower reading speeds in older adulthood.

Method: A trigram task, in which sets of three letters were displayed randomly at specified locations to the right and left of a central fixation point, was used to estimate the size of the visual span for young (18-30 years) and older (65+ years) adults while an eye tracker was used to ensure accurate central fixation during stimulus presentation. Participants also completed tests of visual acuity and visual crowding.

Results: There were clear age differences in the size of the visual span. The older adults produced visual spans which were on average 1.2 letters smaller than the spans of young adults. However, both young and older adults produced spans smaller than those previously reported. In addition, span size correlated with measures of both visual acuity and measures of visual crowding.

Conclusion: The findings show that the size of the visual span is smaller for older compared to young adults. The age-related reduction in span size is relatively small but may make a significant contribution to reduced parafoveal processing during natural reading so may play a role in the greater difficulty experienced by older adult readers. Moreover, these results highlight the importance of carefully controlling fixation location in visual span experiments.

Key Words: Visual Span, Aging, Letter Recognition, Visual Acuity, Visual Crowding

Introduction

Readers move their gaze through text by making rapid eye movements (saccades), separated by brief fixational pauses during which they acquire linguistic information. This pattern of eye movement behavior is a consequence of limitations in retinal acuity, which is greatest at the center of gaze and declines sharply with increasing distance from this point (Hilz & Cavonius, 1974). As a result, only a few letters can be recognized accurately on each eye fixation during normal reading (and for a review of the consequences for reading, see Rayner, 1998, 2009). Considerable evidence additionally shows that eye movement behavior during reading differs across the adult lifespan, such that older adults (65+ years) read more slowly than young adults (18-30 years) by making more and longer fixations on words, despite achieving similar levels of comprehension (e.g., Kliegl, Grabner, Rolfs, & Engbert, 2004; McGowan, White, Jordan & Paterson, 2014; McGowan, White & Paterson, 2015; Paterson, McGowan, & Jordan, 2013a,b,c; Rayner, Castelhano, & Yang, 2009; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Rayner, Yang, Schuett & Slattery, 2014; Stine-Morrow, Shake, Miles, Lee, Gao, & McConkie, 2010; Warrington, McGowan, Paterson & White, 2018, in press; Warrington, White & Paterson, 2018; Whitford & Titone, 2016, 2017). An important unresolved issue concerns whether this age-related slowdown in reading is due to older adults acquiring less information on each fixation compared to young adults (Rayner et al., 2009, Rayner et al.,2014; Risse & Kliegl, 2011; Whitford & Titone, 2016).

Older age is associated with subtle reductions in visual abilities, especially outside of central vision (Elliott, Yang, & Whitaker, 1995; Owsley, Sekuler, Siemsen, 1983; see Owsley, 2011). These include declines in visual acuity (e.g., Owsley et al., 1983), as well as increased effects of visual crowding, which is the reduced ability to recognize a visual object, such as a letter, when it is closely surrounded by similar objects (Bouma, 1970; Levi, 2011; Scialfa, Cordazzo, Bubric, & Lyon, 2013; Whitney & Levi, 2011; see also Grainger, Dufau, & Ziegler, 2016). Both factors are likely to play a role in limiting the amount of information that can be processed on each fixation and may limit the ability of older adults to recognize information presented outside of foveal vision. Therefore, it is important to establish whether these changes in visual abilities in later adulthood affect the amount of linguistic information that older adults can process on a single glance, which may contribute to slower reading.

Several methods have been developed to estimate the number of letters that can be recognised on a single glance, each with different conceptual definitions (for a review, see Frey & Bosse, 2018). Key concepts are the visual span (O'Regan, 1990, 1991) and the perceptual span (McConkie & Rayner, 1975). The visual span, as noted above, refers to the number of letters that can be identified on a single glance, whereas the perceptual span describes the area of text from which linguistic information can be acquired during natural reading. Investigations of these concepts employ different paradigms, but crucially both allow the estimation of the number of letters processed on a single glance (Legge, Ahn, Klitz, & Luebker, 1997). These methods are discussed in more detail in the following sections. Further, a similar, but distinct concept, the visual attention span, has also been developed. In contrast to the visual span and perceptual span, the visual attention span refers to the amount of distinct visual elements which can be processed in parallel in a multi-element array and assesses visual short-term memory (e.g., Luck & Vogel, 1997), or visual attention capacity (parameter K in Bundesen's Theory of Visual Attention model; Bundesen, 1990). As this does not test the key variable of interest (the horizontal eccentricity across which letters can be identified accurately on a single glance), it is not discussed further.

The perceptual span is typically studied using gaze-contingent moving window paradigms in which text is presented normally within a region (window) around fixation and text outside this region is obscured (e.g., by replacing each letter in words with an 'x'; McConkie & Rayner, 1975). Different window sizes are used across the experiment, following the logic that window sizes that produce normal reading rates must encompass the linguistic information that readers require on each fixational pause for reading to be normal. Previous research employing this method suggests older adults have a smaller and more symmetrical perceptual span compared to young adults (Rayner et al., 2009; but see Whitford & Titone, 2016). Therefore, it is important to examine this further, as a smaller perceptual span could be a key factor in older adults' slower reading speeds. It also is important to note, however, that the perceptual span is defined in terms of the functional demands of reading, and so performance may be influenced by various factors including allocation of attention (Henderson & Ferreira, 1990; Kennison & Clifton, 1995), use of context (e.g., Rayner et al., 2006) and word knowledge (e.g., Braze, Tabor, Shankweiler, & Mencl, 2007).

These considerations may be particularly important when examining adult age differences in the perceptual span as these influences are likely to differ across age groups. In particular, older adults typically experience greater difficulty processing the identity of fixated words compared to young adults, and this may limit their allocation of attention to upcoming words. Older adults also have greater difficulty ignoring distracting visual information (Kemper & McDowd, 2006; Mund, Bell, & Buchner, 2010) and so the 'x' mask typically employed in such studies may interfere with normal reading. Additionally, other research suggests that older readers attempt to compensate for their greater reading difficulty by adopting a more "risky" reading strategy in which they are more likely, compared to young adults, to infer the identities of upcoming words based on contextual knowledge and only partial word information (e.g., Rayner et al., 2006). Older adults also typically have larger vocabularies than young adults (Ben-David, Erel, Goy, & Schneider, 2015; Keuleers, Stevens, Mandera & Brysbaert, 2015) which may also play a role in driving their behavior. Accordingly, the extent to which adult age differences in the perceptual span during natural reading are a consequence of age-related perceptual limitations as opposed to differences in attention allocation or language processing during reading remains unclear.

The visual span, which focuses on sensory bottom-up constraints on reading, may provide a clearer indication of specifically perceptual limitations on the acquisition of linguistic information. In this paradigm, a non-reading task (the trigram task) is used to estimate the number of letters that can be recognized reliably on each glance without moving the eyes (see Frey & Bosse, 2018; He & Legge, 2017; Legge et al., 1997; Legge, Cheung, Yu, Chung, Lee, & Owens, 2007; Legge, Mansfield, & Chung, 2001; O'Regan, 1990; Yu, Cheung, Legge, & Chung, 2007).

The visual span is typically calculated by asking participants to recognize unrelated letters in trigrams (random strings of three letters) flashed briefly at varying eccentricities to the left or right of a fixation point (for an example, see Figure 1, e.g., Wang, He, & Legge, 2014; Cheong, Legge, Lawrence, Cheung, & Ruff, 2008; Legge et al., 2001, 2007). Immediately after presentation of each trigram, the participant is asked to report the identity of the presented letters, in left to right order. The number of letter positions at which letters can be recognized accurately (typically >80%) is considered to be the size of the visual span. Generally, accuracy is very high for letters presented close to central fixation and decreases with increasing distance from this point. Note that in these experiments, the number of letters presented on each trial does not vary, but rather the location of these letters relative to a central fixation point is varied. The paradigm does not, therefore, provide a test of sensory memory capacity, but assesses the eccentricity across which linguistic information (i.e., letters) can be identified. Experiments using this method typically report a span size of ~10 characters for normally sighted young adults (see Legge et al., 2001). Crucially, the visual span is correlated with reading speed for individuals with both normal and low vision (Cheong et al., 2008; Legge et al., 2001, 2007, Liu, Patel, & Kwon, 2017) and while influenced by visual acuity, appears to be even more strongly influenced by visual crowding

(Legge et al., 2007). The visual span may therefore provide an effective measure of sensory limitations on the amount of linguistic information that can be acquired on each glance that has implications for reading performance.

While numerous studies have investigated the visual span in skilled adult readers, and some have investigated span size in low vision (for a review, see Frey & Bosse, 2018) only one study to date has been published that compares the visual span of young and older adult readers. This recent study provided an initial indication that the size of the visual span for older adults may be smaller than for young adults, by around 1.3 letters (Liu et al., 2017). With the current experiment, we sought to replicate these findings and, additionally, to explore the contribution of crowding and visual acuity to the size of the visual span for both age groups. Further, Liu et al (2017) characterized the span in terms of bits of information, with number of letters not explicitly reported. While such calculations are useful as they remove the need for a set criterion (e.g. 80%) threshold for accurate performance, the values this method produces are less readily interpretable. Accordingly, with the present experiment, we assessed visual span size both in terms of number of letters and bits of information.

It was of further concern for the present research that many previous studies did not use an objective means of ensuring both that participants accurately fixated the central fixation point and did not move their eyes during stimulus presentations. Most studies instead rely on instructions to fixate accurately, the experimenter observing each participant's eyes for eye movements (e.g. Wang et al.,2014; Yu, Legge, Wagoner & Chung, 2014; Legge et al., 2001; Kwon, Legge & Dubbels, 2007), the experimenter asking each participant to report eye movements (e.g. Wang et al.,2014), and/or the use of a webcam to monitor eye movements (e.g. Cheong et al., 2007; He, Scholz, Gage, Kallie, Liu, & Legge, 2015; He & Legge, 2017; Wang et al., 2014). However, other research has already shown that mere instructions are ineffective at ensuring the participants fixate designated fixation locations accurately in experiments and that fixation inaccuracy can adversely affect performance in studies assessing the recognition of lateralized presentations of linguistic stimuli (Jordan, Patching, & Milner, 1998, 2000; see also, Jordan & Paterson, 2009; Jordan, Paterson, Kurtev, & Xu, 2009). The lack of use of objective methods to monitor fixation location during stimulus presentation is therefore of concern as it may affect performance in the trigram task, potentially biasing estimates of visual span size due to either variation in fixation control or willingness or ability to follow instructions. Whether these effects also differ across adult age groups is also a matter of concern, although investigations suggest only small age differences in fixation control (Kosnik, Kline, Fikre, & Sekuler, 1987). To address this concern, the present research used an eye-tracker and fixation-contingent stimulus presentations to ensure that both age groups of participants in the present experiment accurately fixated the central point before a stimulus was presented. This approach also eliminated the possibility of participants making anticipatory eye movements prior to a stimulus presentation and allowed us to ensure central fixation throughout stimulus presentation.

Accordingly, the current experiment examined the size of the visual span in young and older readers of English under conditions in which fixation accuracy was ensured. It was anticipated that visual span size would be smaller for older compared to younger adults, due primarily to poorer processing of linguistic information outside of foveal vision. Moreover, we expected that performance on the trigram task would correlate with acuity and performance on an assessment of visual crowding and that visual crowding, in particular may be an important contributory factor determining the size of the visual span. Such findings would provide evidence that subtle sensory deficits associated with normal aging might limit the amount of linguistic information that older adults can acquire on each glance, which may be an important component of the age-related reading difficulty they experience.

Method

This study received ethical approval from the University of Leicester Psychology Ethics committee and was conducted in accordance with the principles of the Declaration of Helsinki. All participants gave written informed consent.

Participants. Twenty-six young adults aged 19-29 years (M = 22 years) and 26 older adults aged 65-80 years (M = 72 years) were recruited from the University of Leicester and the surrounding community. All were native English speakers, matched for years of formal education (young adults, M = 16 years, range = 12-18 years; older adults, M = 15 years, range = 11-20 years, p >.05), and all reported reading for at least several hours per week. No participants reported a visual or reading impairment. Visual acuity was assessed using an Early Treatment Diabetic Retinopathy Study (ETDRS) chart (Ferris & Bailey, 1996) at the viewing distance in the experiment (80cm) and visual crowding was assessed using the Keeler logMAR crowded letter acuity test. Compared to the young adults, the older adults had lower acuity (in Snellen values: young adults, M = 20/18, range = 20/14-20/28; older adults, M = 20/28, range = 20/18-20/40; $t(50) = 6.83$, p <. 001, d = 1.895) and experienced greater visual crowding (in logMAR values: young adults, M = 0.04; older adults, M = 0.07, $t(50) = 2.28$, p = .027, d = 0.631, values refer to the mean difference in acuity scores for crowded versus uncrowded conditions). The older adults were screened for unimpaired cognitive abilities using the Montreal Cognitive Assessment, applying the standard exclusion criterion of scores <26/30 (Nasreddine et al., 2005).

Stimuli & Design. Stimuli were trigrams of letters drawn from the 26 lowercase letters of the Latin alphabet. These were selected randomly, although a letter never appeared more than once within each trigram and none of the trigrams formed real English words. All letters were displayed in lowercase Courier New font, which is a monospaced font. We used a fixed-width font, rather than proportionally spaced font, because it has a constant center to center spacing between letters, which simplifies the measurement of visual-span profiles. At an 80cm viewing distance, each letter subtended approximately 1° of visual angle and letters were of comparable size to stimuli in previous visual span experiments (Legge et al., 2014). Each trigram was displayed with its first letter appearing at either a central point (position 0) or one of 9 positions with increasing eccentricity to the right and left of this point (see Figure 1). Characters at adjacent display positions were 1° apart (from the center of one character to the center of the next). Fewer characters were displayed at positions ±8 and ±9 than other positions (only the first character in trigrams at -9 and first and middle characters at -8; and, conversely, only the last character in trigrams at +9 and middle and last characters at +8) and so letter recognition accuracy was assessed only for positions -7 to +7, including position 0. The presentation position was selected randomly on each trial and trigrams were presented at each position at equal number of times for each participant. There were 255 trials in total, split across 5 blocks. A mixed experimental design was used with the between-participants factor age group (young adult, older adult) and display location (positions -7 to +7, including position 0).

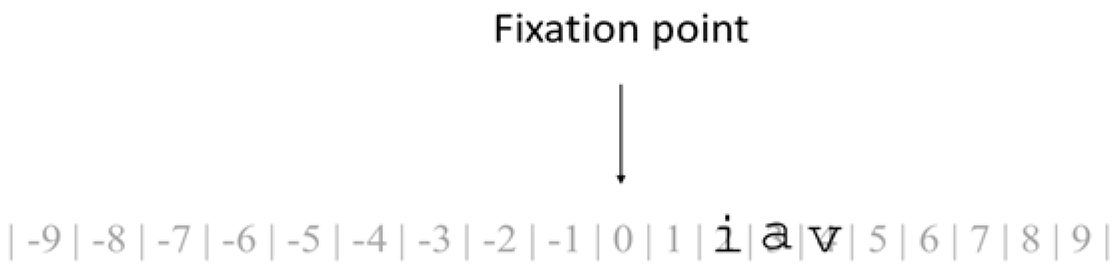


Figure 1. An example of a trigram presented in a horizontal line at positions 3, 4 and 5.

Apparatus and Procedure. An EyeLink 1000 eye-tracker interfaced with a 24-inch high-definition BenQ display screen (1920 x 1080 resolution, 120 Hz refresh rate) monitored the location of right eye fixations (during binocular viewing) and controlled the presentation of stimuli. Custom software ensured participants accurately fixated within 0.5° of the central fixation point before a stimulus was displayed. At the beginning of the experiment, a 3-point horizontal calibration and validation procedure ensured spatial accuracy was < 0.35°. Recalibrations were always conducted between each block, and as necessary to maintain high spatial accuracy throughout the experiment.

Participants took part individually. At the beginning of the session, the participant had the procedure explained to them. They were instructed that, on each trial, three letters would be displayed briefly at a central point or one of 8 locations to its right or left, and that their task was to report the three letters in left to right order. Participants were further instructed that they should guess if unsure. Each participant was then sat at the eye-tracker and their eye movements calibrated. The experiment began with a practice block to familiarize participants with the task and ensure that they could fixate the central point accurately. Participants then completed 5 blocks of trials. On each trial, a fixation point (a black dot) appeared at the center of the screen. Once the participant fixated this location for 100 ms, the fixation point disappeared, and a trigram was displayed briefly (200 ms). The participant reported the letters they had seen in left to right order and an experimenter recorded their response. For each participant, the experiment lasted approximately 30 minutes.

Results

Reporting accuracy for each display position (from -7 to +7) was plotted to create a visual-span profile for each age group (positions ±8 were not included because the absence of trigram stimuli at ± 9 meant few stimuli were tested at ±8). The visual span was calculated by fitting Gaussian curves to these data using MATLAB (version R2017b). A single Gaussian and the sum of two Gaussians were fitted individually to the data of each participant with the parameters, mean, amplitude and standard deviation (resulting in six parameters for the sum of two Gaussians) and the best fit was selected on a case by case basis based on visual inspection and the r^2 values (*M* = .97) associated with the fit. In the majority of cases (48 of 52) the best fit was provided by the sum of two Gaussians. However, in a minority of cases (4 of 52), the sum of two Gaussians resulted in over-fitting and so a single Gaussian was selected. The visual span size was calculated as the width of the fitted profile curve (number of letter positions) at an 80% correct criterion, and the visual span size reported as number of letters at which this accuracy level was achieved. However, for completeness, and for comparability with previously reported findings (i.e., Liu et al., 2017), we also computed span size as bits of information, using an entropy calculation where information transmitted at a given letter position was computed from the percentage of letters reported accurately. This ranged from 0 bits (for chance accuracy of 3.8% correct) to 4.7 bits (for 100% accuracy; for an explanation of information theory, see Han & Kobayashi, 2002, and for its application to the visual span, see Legge et al., 2001). This provides a measure of recognition accuracy without reference to a criterion value.

Figure 2 plots the mean visual span profiles and the mean size of the visual span in bits for the young and older adults. Recognition accuracy was above 80% correct at position 0 for all participants (central fixation) and declined with increasing distance from this location. Recognition accuracy at the central point was very high for both age groups (older adults, *M* = 99%; young adults, *M* = 99%). Two-tailed independent samples t-test were conducted to compare span size across the two age groups. These showed older adults had a smaller span than the young adults. Moreover, this was the case when span size was calculated either as number of letters or bits of information (number of letters: older adults, *M* = 6.4, SE = 0.2; young adults, *M* = 7.6, SE = 0.2), $t(50) = 4.28$, $p < .001$, $d = 1.188$; bits of information: older adults, M = 57.0, SE = 0.8; young adults, M = 62.3, SE = 0.4), $t(50) = 6.08$, $p < .001$, d = 1.685). The older adults, on average, recognized 1.2 letters (or 5.3 bits) fewer than the young adults. This finding accords with previous estimation of aging effects on the visual span for alphabetic letters (Liu et al., 2017). It is nevertheless noteworthy that the span size for young adults (7.6 letters) is smaller than that reported in previous research (i.e., ~10 letters; see Legge et al., 2001). Possible reasons for this are considered in the discussion.

Individual acuity and crowding scores were entered into a correlation analysis with visual span size (See Figure 3). In the current experiment where degrees of freedom = 50, a correlation value must exceed r = .273 to be significant at the $p = .05$ value. There was a significant correlation between crowding and the visual span (r = -.330, $p = .017$) and acuity and the visual span r = -.359, $p = .009$, suggesting that both factors are important in determining the size of the visual span.

(a)

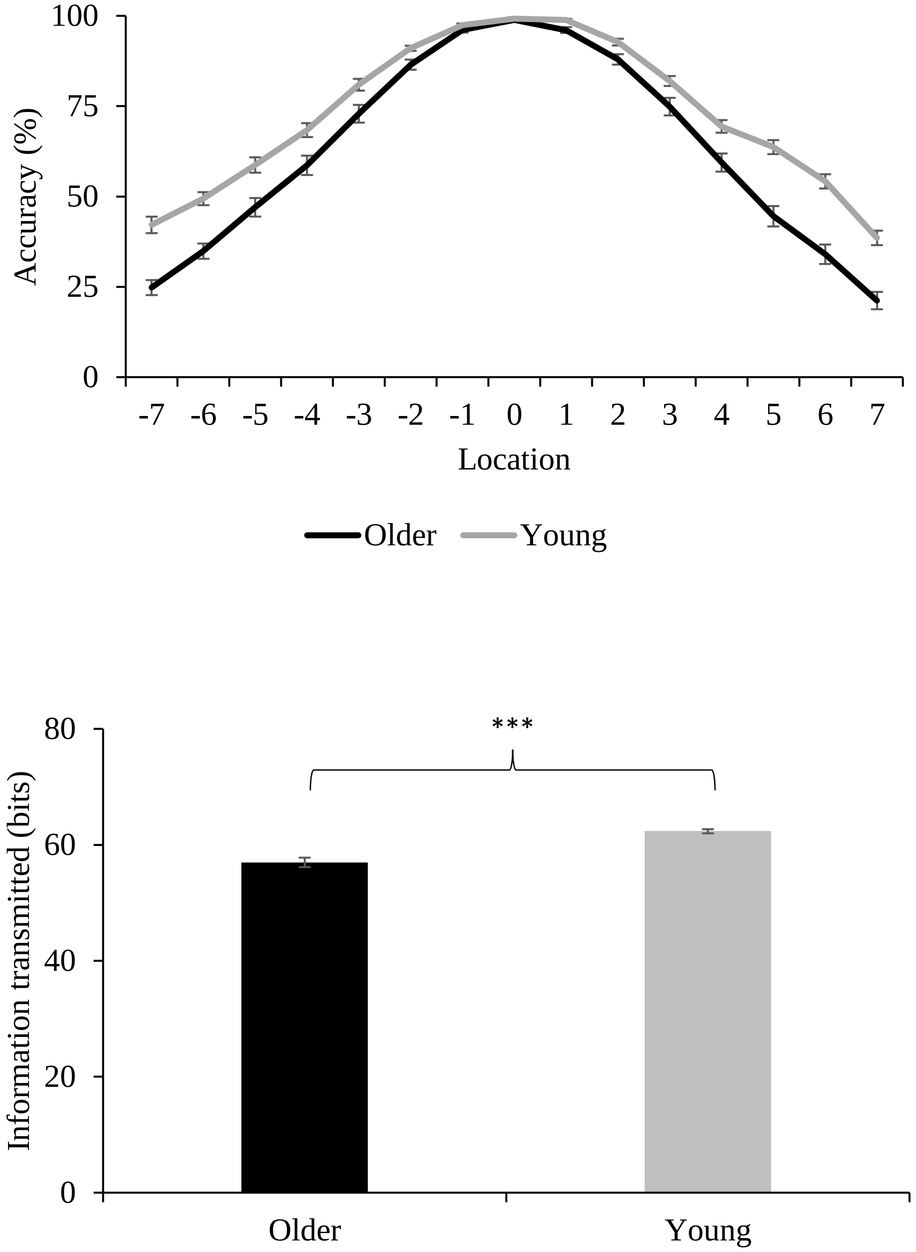
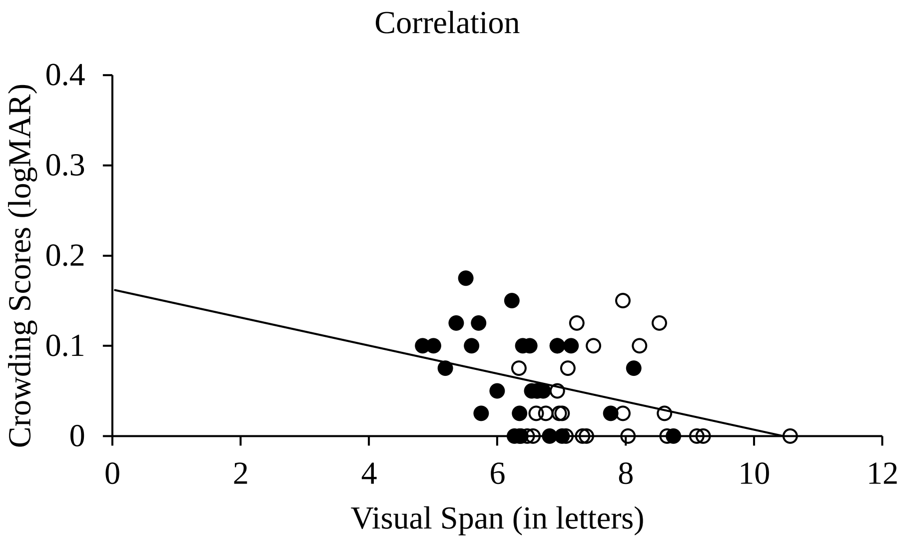
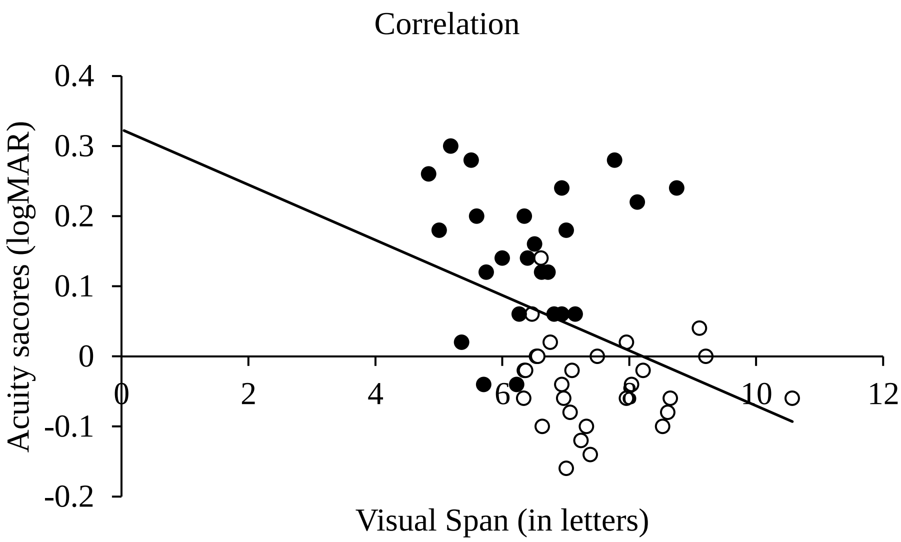


Figure 2. Panel a shows the mean visual span profile plot for young and older adults, Panel b shows mean span size in bits for young and older adults.

(a)



(b)



Note: For ease of analysis, Snellen acuity scores were converted to logMAR for these calculations.

Figure 3. Correlation of vision ability with visual span size, (a) vision crowding, (b) vision acuity.

Discussion

The present experiment examined the size of the visual span for young and older adult readers of English using a trigram task. This experiment produced several important findings. Crucially, the results provide further evidence of a smaller visual span for older, compared to young, adults. We observed that, on average, the older adults had a visual span which is 1.2 letters smaller than the visual span of young adults. This finding is comparable with previous estimations of aging effects on the visual span (Liu et al., 2017). Crucially, however, the present study demonstrates that this difference is observed under conditions in which fixation accuracy is ensured and so not affected by age differences in fixation control or the ability to follow instructions to fixate a specified location accurately (e.g., Jordan et al., 1998, 2000, 2009). Accordingly, as the visual span is assumed to provide a direct test of bottom-up sensory limitations on processing (see, e.g., Legge et al., 2007), the results indicate that sensory declines in older age may limit the amount of linguistic information processed on each glance, with implications for their reading performance. One possibility is that these sensory limitations also limit how much information is acquired on each fixation during natural reading, resulting in a smaller perceptual span for older compared to younger adult readers (e.g., Rayner et al., 2006; but see Whitford & Titone, 2016, for counter evidence). However, the size of the perceptual span in natural reading is also influenced by other factors, including allocation of attention and use of context (Braze et al., 2007; Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Rayner et al., 2006). Consequently, older readers may attempt compensate for reductions in sensory processing likely to produce slower reading by adjusting their reading strategy and making greater use of context to predict upcoming words (see, e.g., Rayner et al., 2006). Accordingly, while is important for future to research to investigate the effects of age-related declines in sensory processing on older adults' reading performance, it also will be important to assess their use of compensatory strategies.

In addition to demonstrating a reduced visual span for older adults, the present research showed that visual acuity and visual crowding both correlate with the visual span size. This is consistent with the view that the visual span reflects a primarily sensory limit on language processing that is affected by acuity but may largely derive from crowding effects outside of central vision (see, e.g., Legge et al., 2007; Wang et al., 2014). Our finding that the visual span is smaller for older adults is also consistent with other evidence that older readers experience greater effects of visual crowding in peripheral vision, as a consequence of age-related change in visual abilities (e.g., Liu et al, 2017; Scialfa et al., 2012).

Finally, although the reduction in span size we observed for older adults was comparable to that reported in previous research (Liu et al., 2017), it was noteworthy that the span sizes we obtained for young adults were also smaller than generally reported in previous studies (7.6 letters compared to ~10 letters, see Legge et al., 2001). While we took care to use the same experimental methods as used in previous research, a crucial difference was that the present experiment also used an eye-tracker to ensure that participants accurately fixated a designated central fixation point during each trial (Jordan & Paterson, 2009; Jordan et al., 1998, 2000, 2009). This generally was not the case in previous visual span studies, which more often relied solely on overt instructions to ensure that participants fixated accurately. Unfortunately, considerable evidence indicates that such instructions cannot be relied upon to ensure that participants fixate accurately in studies involving lateralized presentations of stimuli (Jordan et al., 1998, 2000, 2009). Moreover, this previous research also indicates that participants can make saccadic eye movements with the 200 ms display time typically used in these experiments. The use of an eye-tracker in the present experiment ensured both the participants accurately fixated the central point before a stimulus was displayed and did not make an eye movement towards the trigram during stimulus presentation. One possibility is that studies that have not used objective methods to monitor fixation location may have overestimated the size of the visual span due to participants either failing to fixate the central point before a stimulus presentation or making an eye movement following stimulus presentation, both of which may have helped participants to identify stimuli presented at eccentric locations. This possibility could be tested directly, by comparing fixation behaviour under instructions alone compared to when fixation accuracy is ensured (but see Jordan et al., 1998, 2000, 2009, for existing evidence that mere instructions are inadequate). A straightforward recommendation, however, would be to use an eye-tracker either to monitor fixation location or ensure fixation accuracy in such tasks (for discussion, see Jordan & Paterson, 2009).

In sum, the present findings contribute to our understanding of effects of age-related sensory declines by confirming that span size is smaller, by on average 1.2 characters, for older compared to younger adults. Moreover, we present evidence that this reduction in span size may be related to changes in key visual abilities in older age. Our findings therefore reveal that subtle declines in visual abilities in older age place a small, but potentially important, limit on the amount of linguistic information that can be processed on each glance or fixation, which may be an important component of the age-related reading difficulty typically observed in those aged 65+. The study also highlights the importance of using objective methods to monitor or ensure fixation accuracy in tasks involving the presentation of lateralized stimuli and where accurate fixation of a central point is paramount.

Declaration of interest statement: The authors report no conflict of interest.

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