Revealing Similarities in the Perceptual Span of Young and Older Chinese Readers

Fang Xie[1]

Victoria A. McGowan[2]

Min Chang[1]

Lin Li[1]

Sarah J. White[2]

Kevin B. Paterson[2]

Jingxin Wang[1]

Kayleigh L. Warrington[2]

Author Note:

Fang Xie, Academy of Psychology and Behavior, Tianjin Normal University; Victoria A. McGowan, Department of Neuroscience, Psychology and Behaviour, University of Leicester; Min Chang, Academy of Psychology and Behavior, Tianjin Normal University; Lin Li, Academy of Psychology and Behavior, Tianjin Normal University; Sarah J. White, Department of Neuroscience, Psychology and Behaviour, University of Leicester; Kevin B. Paterson, Department of Neuroscience, Psychology and Behaviour, University of Leicester; Jingxin Wang, Academy of Psychology and Behavior, Tianjin Normal University; Kayleigh Warrington, Department of Neuroscience, Psychology and Behaviour, University of Leicester.

Victoria A. McGowan, Kevin B, Paterson, Jingxin Wang, Kayleigh L. Warrington, Sarah J. White, and Fang Xie contributed to the experimental design. Min Chang, Lin Li, Victoria A. McGowan, Kayleigh L. Warrington, and Fang Xie collected the data. Kayleigh L.

Warrington and Fang Xie analyzed the data, and Kayleigh L. Warrington, Kevin B. Paterson, and Fang Xie prepared the manuscript. All authors approved the final manuscript.

Correspondence can be addressed to Jingxin Wang, Academy of Psychology and Behavior, Tianjin Normal University, Hexi District, Tianjin, China, 300374, Email: wjxpsy@126.com or Kayleigh Warrington, Department of Neuroscience, Psychology and Behaviour, University of Leicester, University Road, Leicester, UK, LE1 9HN. Email: klw53@leicester.ac.uk

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Abstract

Older readers (aged 65+ years) of both alphabetic languages and character-based languages like Chinese read more slowly than their younger counterparts (aged 18-30 years). A possible explanation for this slowdown is that, due to age-related visual and cognitive declines, older readers have a smaller perceptual span and so acquire less information on each fixational pause. However, while aging effects on the perceptual span have been investigated for alphabetic languages, no such studies have been reported to date for character-based languages like Chinese. Accordingly, we investigated this issue in three experiments that used different gaze-contingent moving window paradigms to assess the perceptual span of young and older Chinese readers. In these experiments, text was shown either entirely as normal or normal only within a narrow region (window) comprising either the fixated word, the fixated word and one word to its left, or the fixated word and either one or two words to its right. Characters outside these windows were replaced using a pattern mask (Experiment 1) or a visually-similar character (Experiment 2), or blurred to render them unidentifiable (Experiment 3). Sentence reading times were overall longer for the older compared to the younger adults and differed systematically across display conditions. Crucially, however, the effects of display condition were essentially the same across the two age groups, indicating that the perceptual span for Chinese does not differ substantially for the older and young adults. We discuss these findings in relation to other evidence suggesting the perceptual span is preserved in older adulthood.

Key Words: Aging; Eye Movements during Reading, Perceptual Span, Chinese

During reading, the eyes make a sequence of rapid eye movements (saccades) separated by brief fixational pauses. This behavior is a consequence of limitations in retinal acuity, which is greatest in central (i.e., foveal) vision and declines sharply with increasing distance from this point into parafoveal vision and beyond (e.g., Hilz & Cavonius, 1974). Due to these limitations, readers must move their eyes so that successive portions of text can be sampled in high-acuity vision (e.g., Rayner, 2009). Researchers therefore have investigated how much linguistic information can be acquired on each fixational pause. This is referred to as the *perceptual span* and is studied using gaze-contingent moving window paradigms. In these, text is presented normally within a narrow region (window) around each fixation and text outside this region is masked (e.g., by replacing the letters in words with an 'X'; e.g., McConkie & Rayner, 1975, 1976; Rayner, 1975; for a review, see Rayner, 2014). This window moves in synchrony with the reader's eye movements, so that when the reader moves their eyes to fixate a new location, text at this location is shown normally and text at the previous location is masked. The size of the span can be estimated by systematically varying the size of the moving window across an experiment, following the logic that windows which produce normal reading rates must contain all the linguistic information required for reading to be normal.

Research using this paradigm shows that skilled young adult readers of alphabetic scripts like English obtain useful information from a region extending about 3-4 letters to the left of fixation and up to 14-15 letters to the right (McConkie & Rayner, 1975, 1976; Rayner, Well, & Pollatsek, 1980). This asymmetry is a function of reading direction (e.g., Jordan et al., 2014; Paterson et al., 2014; Pollatsek, Bolozky, Well, & Rayner, 1981), due to greater allocation of attention in the direction of reading to facilitate parafoveal processing of the next word (or words) and to guide decisions about where next to move the eyes (e.g., Balota, Pollatsek, & Rayner, 1985; Briihl & Inhoff, 1995; Drieghe, Rayner, & Pollatsek, 2005;

McConkie & Rayner, 1975; Rayner, 1975; Rayner, Well, Pollatsek, & Bertera, 1982; White, Johnson, Liversedge, & Rayner, 2008; for a review, see Schotter, Angele, & Rayner, 2012). The physical size of the perceptual span also varies cross-linguistically and is smaller for scripts with more compact orthographies (see Rayner, 2014). For instance, in Chinese it is asymmetric to the right (as Chinese is read horizontally from left-to-right) but physically smaller compared to English, extending only about one character to the left and up to four characters to the right, most likely because Chinese characters convey complex linguistic information (see Inhoff & Liu, 1998; Liu, Angele, Luo, & Li, 2018; M. Yan, Zhou, Shu, & Kleigl, 2015). However, if span size is measured in words rather than graphemes, the rightward span for Chinese is about two words and so the same for both scripts (Inhoff & Liu, 1998; Rayner, 1986; Rayner et al., 1982).

Other research shows that span size varies a function of text difficulty and reading ability. For instance, developing readers have smaller perceptual spans than skilled adult readers (e.g., Häikiö, Bertram, Hyönä, & Niemi, 2009; Rayner, 1986; Sperlich, Meixner, & Laubrock, 2016), and less-skilled adult readers have smaller spans than highly-skilled adult readers (Chace, Rayner, & Well, 2005; Rayner, Slattery, & Bélanger, 2010; Veldre & Andrews, 2014). In both cases, this is attributed to reduced parafoveal processing of upcoming text by less-skilled readers, possibly because word recognition difficulty causes greater allocation of attentional resources to fixated words at the expense of parafoveal processing (e.g., Henderson & Ferreira, 1990; Kennison & Clifton, 1995). Older adults (aged 65+ years) also experience greater reading difficulty compared to skilled young adults (aged 18-30 years) when reading alphabetic scripts (Kliegl, Grabner, Rolfs, & Engbert, 2004; McGowan, White, Jordan & Paterson, 2014; Paterson, McGowan, & Jordan, 2013a,b; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Rayner, Castelhano, & Yang, 2009, 2010; Rayner, Yang, Schuett, & Slattery, 2014; Stine-Morrow et al., 2010; Warrington, McGowan, Paterson & White, 2018, 2019; Whitford & Titone, 2016, 2017) or Chinese (S. Li, Li, J. Wang, McGowan & Paterson, 2018; L. Li et al., 2019; J. Wang, Li, Li, Chang et al., 2018; J. Wang, Li, Li, Liversedge et al., 2018; Zang et al., 2016; Zhao et al., 2019). This has led researchers to speculate that visual and cognitive declines in later adulthood, including reduced sensitivity to parafoveal information (Ball, Beard, Ronker, Miller & Griggs, 1998; Crassini, Brown, & Bowman, 1988; Sekuler, Bennett, & Mamelak, 2000), lead older adults to have a smaller perceptual span. In support of this view, Rayner et al. (2009) presented evidence from two experiments suggesting that, compared to young adults, older adults have a smaller and more symmetric perceptual span. Other studies also suggest less efficient parafoveal processing by older readers (Rayner, Castelhano, & Yang, 2010; Rayner et al., 2014). However, contrary to these findings, several studies show little or no age differences in perceptual span effects (Risse & Kliegl, 2011; Whitford & Titone, 2016).

Studies to date have not investigated adult age differences in perceptual span effects for character-based languages like Chinese, however, although the visual and linguistic characteristics of this writing system might also be expected to lead older readers to process less information parafoveally. Chinese script is composed of box-like pictograms called characters, which contain differing numbers of strokes (lines, dashes) and so vary in complexity (Hoosain, 1991, 1992). For instance, simple characters may contain a single stroke (e.g., 一 [“yi”], meaning “one’) while more complex characters contain upwards of 20 strokes (e.g., 罐 [“guan”], meaning “pot”). Moreover, while a single character will sometimes correspond to a word, most words comprise two (and sometimes more) adjacent characters, although word boundaries are not demarcated using spaces or other visual cues so that readers must segment the unspaced text into words (see X. Li, Zang, Liversedge, & Pollatsek, 2015; Zang, Liversedge, Bai, & Yan, 2011). Evidence suggests these characteristics of the Chinese script are a particular source of difficulty for older readers (S. Li et al., 2018; L. Li et al., 2019; Zang et al., 2016; Zhang, Zhang, Xue, & Yu, 2007), limiting the number of characters they can recognize on one glance without moving the eyes (Xie et al., 2019). The perceptual span for Chinese therefore may be smaller for older than younger readers. Accordingly, as this has not been tested empirically, we used the moving window paradigm to investigate this issue.

A further concern for the present research was to establish if these effects might be influenced by the type of mask used. In particular, there is ongoing controversy about whether masking procedures used in many eye movement tasks provide a neutral, baseline condition that reflects the absence of linguistic information (for recent discussion, see Hutzler, Schuster, Marx and Hawelka, 2019). At least some evidence from studies with young adult participants suggests this is an important consideration. For instance, the 14-15 letter rightward span reported for English was obtained using masking letters that were visually similar to the letters they replaced (e.g., replacing ‘b’ with ‘k’, or ‘q’ with ‘j’), span size has been estimated to be smaller (only about ten letters wide) in some studies where letters were masked using an ‘X’ (McConkie & Rayner, 1975, 1976; Rayner et al., 1980; but see Bélanger, Slattery, Mayberry, & Rayner, 2012; Veldre & Andrews, 2014). Similarly, the rightward span for Chinese was estimated as about three characters using masks composed of unfamiliar complex characters (Inhoff & Liu, 1998), but at least four characters when the mask comprised familiar characters visually similar to the ones they replaced (M. Yan et al., 2015). Consistent with this finding, other research also shows span size is larger when letters are replaced by real characters rather than a pattern mask (G. Yan, Zhang, Zhang, & Bai, 2013). Such differences may be because orthographic processing is facilitated when the mask contains visually similar information (M. Yan et al., 2015), or because orthographically unfamiliar information or distracting patterns in the parafovea disrupt processing (see, e.g., Hutzler et al., 2019; Jordan, Thomas, & Patching, 2003). But while such effects have been shown for young adult readers, it is unclear whether they differ for older readers. This may be an important consideration, however, in light of evidence that older adults are more susceptible to distracting visual information (e.g., Kemper & McDowd, 2006; Mund, Bell, & Buchner, 2010; Meijer, de Groot, Van Boxtel, Van Gerven, & Jolles, 2006). Moreover, while we consider this issue in relation to Chinese reading, it is also likely to be important to investigations of perceptual span effects with alphabetic scripts.

Accordingly, we conducted three eye movement experiments using different masks to assess age differences in perceptual span effects for Chinese. Our approach was inspired by the Rayner et al. (2009) study reporting age differences in the perceptual span for English. We therefore employed the same word-based windows as this study, rather than windows based on numbers of letters or characters, to ensure comparability with their findings. This meant assessing reading performance for sentences shown normally or displayed using a moving window paradigm in which only the fixated word (W), the fixated word and one word to its left (W + L1), or the fixated word and either one or two words to its right (W + R1 and W + R2) were shown normally, and text outside these windows was masked.

As most Chinese words contain two characters (Lexicon of Common Words in Contemporary Chinese, 2008), W + R2 windows were broadly equivalent to the maximum rightward span reported previously for young adult Chinese readers (Inhoff & Liu, 1998; Yan et al., 2015). These were also equivalent to the W + R2 windows that produced normal reading times for young adults in the Rayner et al. (2009) study. We therefore expected the young adults in the present research to produce normal reading times for W + R2 windows, and to have longer compared to normal reading times for the smaller W + R1 windows. We expected, in addition, to replicate previous findings showing that normative patterns of age-related reading difficulty cause older adults to read Chinese more slowly than young adults (e.g., S. Li et al., 2018; Wang, Li, Li, Chang et al., 2018; Wang, Li, Li, Liversedge et al., 2018; Zang et al., 2016 Zhao et al., 2019).

The key question, however, was whether we would observe age differences in perceptual span effects. Rayner et al. reported that the rightward span for older adults in their study corresponded to about one word and so was smaller than for young adults. Consequently, if the rightward span is similarly reduced in the present research, older adults may produce reading times close to normal for W + R1 windows and show no further benefit for W + R2 windows (as the additional rightward information in these windows would be redundant). Therefore, in the current experiments the comparison of W +R1 and W + R2 windows will provide a key test of age differences in the perceptual span. Rayner et al. also found that older readers made greater use of information from the left of fixation, resulting in a larger reduction, compared to young adults, in the reading time cost for one-word windows when the word to the left of the fixated word also is available. Therefore, if a similar effect is observed in the present research, older adults should produce a larger decrease in reading times than young adults for W + L1 compared to W windows.

We tested these hypotheses in three experiments, each using a different masking procedure (see Figure 1 for examples). Experiment 1 used a non-character symbol (i.e., ※) widely employed in Chinese research (e.g., G. Yan et al., 2013). This removes orthographic cues to character identities while preserving information about spatial location. However, the mask also produces a regular pattern outside each window, disrupting the normal visual appearance of text. This may be distracting, especially for the older readers (e.g., Kemper & McDowd, 2006; Mund et al., 2010; Meijer et al., 2006) and so has the potential to produce age differences in reading performance. This masking procedure is also broadly similar to that used by Rayner et al. (2009), where letters in words outside each moving window were replaced with an ‘X’, and so it seemed important to include this masking procedure in the present research to ensure comparability with their findings.

Experiment 2, by comparison, followed the same procedure as M. Yan et al. (2015) by using masks composed of familiar characters that were visually similar to the characters they replaced (e.g., 使 replaced 但, and 璃 replaced 糖). These masks hid the identities of characters while preserving character location and providing visually similar orthographic information. This approach may produce larger estimations of the perceptual span than a pattern mask by providing orthographically congruent information beyond an area within which characters can be accurately identified (see, e.g., Rayner, 1975). However, these masks also have the capacity to disrupt normal reading by providing incorrect orthographic information that subsequently has to be corrected in moving window conditions in which the mask encroaches on the perceptual span. Such effects may be especially likely in Chinese because it has a physically smaller perceptual span, increasing the likelihood that when the mask encroaches on the perceptual span, orthographic information will be perceived in relatively high acuity vision and disrupt processing. Moreover, it is unclear whether such effects will differ for older compared to younger adults due to age differences in parafoveal retinal acuity (e.g., Crassini et al., 1988). Accordingly, to avoid such problems, Experiment 3 used a novel parafoveal masking procedure in which characters outside each window were blurred so they were unidentifiable while preserving information about the location and shape of characters. A similar approach was used successfully in studies investigating perceptual span effects in languages (e.g., Arabic, Urdu) where the use of pattern masks or letter replacements is unsuitable (Jordan et al., 2014; Paterson et al., 2014). It therefore may be effective for assessing age differences in perceptual span effects in Chinese that avoids the use of potentially disruptive pattern masks or character replacement procedures.

General Method

Ethics Statement. The research was approved by the research ethics committee in the Academy of Psychology and Behavior at Tianjin Normal University and conducted in accordance with the principles of the Declaration of Helsinki.

Participants. Participants were 105

[1] young adults from Tianjin Normal University and 105 older adults from a residential home in Tianjin. Of these, 35 young and 35 older adults participated in Experiment 1, a different 35 young and 35 older adults participated in Experiment 2, and another 35 young and 35 older adults participated in Experiment 3. All participants were native Mandarin Chinese readers, assessed for educational background, interest in reading and visual and cognitive abilities, as described below. A summary of the participant characteristics is shown in Table 1.

--Table 1--

For each experiment, the young and older adults were matched as closely as possible for years of formal education, and all participants reported reading for at least several hours per week. All participants were screened for normal high-contrast visual acuity (i.e., greater than 20/40 vision in Snellen values) using a Tumbling E eye-chart (Taylor, 1978). Acuity was nevertheless higher for the young adults compared to the older adults, as is typical for these age groups (Elliott, Yang, & Whitaker, 1995). Older participants were screened for non-impaired cognition using the Beijing version of the Montreal Cognitive Assessment (applying the standard exclusion criterion of scores equal or greater than 26/30; Nasreddine et al., 2005). Vocabulary and short-term memory capabilities were assessed for both age groups using the Vocabulary Knowledge Test from the Chinese version of the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, Chen, & Chen, 2002) and the WAIS-III Digit Span subtest (Wechsler, 1997) respectively. Age-adjusted vocabulary scores were broadly similar for the young and older adults. However, as is typical for these age-groups (Ryan, Sattler, & Lopez, 2000), age-adjusted digit spans were lower for the older adults.

The sample size required for each experiment was estimated by conducting simulations of statistical power using the simR package in R (Green & MacLeod, 2016) and means and standard deviations for the interaction between age group and window size in the study by Rayner et al. (2009). First, a simulated data set was constructed. An LMM model was then applied to the simulated data set. The resulting β estimates were then used to conduct the power simulations. We focused on the ability to detect a difference between normal displays and windows containing the fixated word and two words to the right, as this was the key window size over which we might observe an age difference in the rightward span. It was also the comparison with the smallest effect and so likely to require the most participants to detect. The analysis indicated that a sample size of 20 participants would be required to detect an effect with power = 80%. This suggested that the present experiments were sufficiently well-powered to detect an age difference in this key effect.

Materials and Design. In total, 300 sentences were constructed, with 100 sentences in each experiment. These were between 8 and 15 words long. The locations of word boundaries (as retrieved from the Modern Chinese corpus: http://www.cncorpus.org/) were confirmed by 10 young and 10 older adults (none of whom participated in the experiments) for the sentences in Experiment 1, and confirmed by another 10 young and 10 older adults for the sentences in Experiments 2 and 3. Word boundaries given by these participants corresponded to those in the corpus more than 97% of the time. According to the Lexicon of Common Words in Contemporary Chinese (2008), about 6% of Chinese words are one-character words, 72% two-character words, 12% three-character words, and the remainder mostly three or four characters long. Based on the consensus of word boundary judgements we obtained, the sentence stimuli used in each experiment contained broadly similar compositions of words. In Experiment 1, 7.7% were one-character words, 87.3% were two-character words, and the remainder contained three or four characters. In Experiment 2, 7.7% were one-character words, 87.5% were two-character words and the remainder three -or four-character words. Finally, in Experiment 3, 12.8% were one-character words, 77.6% two-character words, and the others three- or four-character words.

In each experiment, the sentences were presented either entirely as normal or using a gaze-contingent moving window paradigm (see Rayner, 2014). In this paradigm, contingent on current gaze position, a predefined region of text (the window) was made visible to the readers while other characters were masked. The three experiments used the same word-based windows in which either only characters corresponding to the fixated word (W), the fixated word and the word to its left (W + L1), the fixated word and the next word to its right (W + R1), or the fixated word and the next two words to its right (W + R2) were shown normally on each fixation.

A different masking procedure was used in each experiment (see Figure 1). In Experiment 1, characters outside each window were replaced using a pattern mask. In Experiment 2, they were replaced with a visually similar character, following the same procedure as used by M. Yan et al. (2015). The original characters were replaced by masking characters of similar shape and construction (e.g., 使 replaced by 但, and 璃 replaced by 糖). These were matched for number of strokes ($M = 8.3$ for the mask, $M = 8.3$ for the original character, $t(801) = .51$, $p = .61$) and for character frequency using the Modern Chinese corpus ($M = 1832$ for the mask, $M = 1697$ for the original character; $t(801) = 1.24$, $p = .22$). None of the masking characters provided a meaningful continuation of the text. The mask stimuli did not share the phonetic and semantic radicals with the original characters. In Experiment 3, characters outside the moving window were blurred using MATLAB with a Gaussian blur with 4 pixels radius to render the characters unidentifiable while retaining character location information. Ten young adults asked to read versions of the stimuli in which all of the characters were blurred were unable to do so.

--Figure 1--

In each experiment, participants read each sentence only once, in one of the display conditions, and read 20 sentences in each display condition. The sentences were presented an equal number of times in each display condition for each age group in each experiment. Each participant also read ten practice sentences at the start of the experiment. The experiments used a 2 x 5 mixed design with the between-participants factor age group (young or older adult) and within-participants factor display condition (normal sentence displays and W, W + L1, W + R1 and W + R2 windows).

Apparatus and Procedure. Sentences were displayed as black text on a white background in Song font on a high-resolution monitor using a fast refresh rate (120 Hz). At an 80 cm viewing distance, each character subtended approximately 0.7° and so was of normal size for reading. Eye movements were recorded from the right eye during binocular reading using an EyeLink 1000 eye-tracker (SR Research inc., Toronto, Canada), which has high spatial and temporal resolution (spatial resolution = .001° RMS; temporal resolution = 1000 Hz). A chin and forehead rest were used to minimize head movements.

Participants took part individually. At the start of the experiment, each participant was informed of the procedure, including the use of the moving window paradigm, and instructed to read normally and for comprehension. The eye-tracker was then calibrated to the participant's eye movements using a 3-point horizontal calibration, ensuring spatial accuracy better than 0.40° for each participant. At the start of each trial, a fixation cross (equal in size to one character space) was presented on the left side of the screen. Once the participant fixated this location, a sentence was presented with the first character replacing the cross. The participant pressed a response key once they finished reading each sentence. On one third of trials, the sentence was then replaced by a yes / no comprehension question, to which the participant responded by pressing one of two response keys. Calibration was checked prior to each trial and the eye-tracker recalibrated as necessary to maintain accuracy better than 0.40°. The experiment lasted approximately 45 minutes for each participant.

Results

Accuracy answering comprehension questions that followed sentences was high (greater than 80% correct) for all participants in all three experiments, and did not differ significantly across age groups (Experiment 1, young adults = 97.2%, older adults = 96.2%, *t*(38) = 1.26, *p* = .21; Experiment 2, young adults = 93.2%, older adults = 92.3%, *t*(38) = .68, *p* = .50; Experiment 3, young adults = 95.4%, older adults = 90.5%, *t*(48) = 1.70, *p* = .09). This indicated that the young and older adults comprehended the sentences well.

Following standard procedures, fixations shorter than 80 ms or longer than 1200 ms were removed (affecting less than 5% of fixations for each experiment, and with a similar proportion for the young and older adults). Trials also were removed if they were terminated prematurely or track loss occurred (affecting less than 0.7% of trials for each experiment).

Sentence reading time provides the most comprehensive measure of reading performance in moving window experiments (McConkie & Rayner, 1975), and has been the key measure in previous experiments examining age differences in the perceptual span. Therefore, this was the focus of our analyses. Word per minute (WPM) and character per minute (CPM) reading rates are also reported to allow comparison with previous experiments reporting reading rates for young adults. The following additional eye movement measures are included in the Supplementary File: average fixation duration (the mean duration of all fixations); number of fixations (the number of fixational pauses); number of regressions (backwards movements in the text); progressive saccade length (the amplitude (in characters) of forward-moving saccades). Data were analyzed by Linear Mixed-Effects Models (LMMs, Baayen, Davidson, & Bates, 2008) using R (R Development Core Team, 2016) and the lme4 package (Bates, Mächler, Bolker, & Walker, 2014). Participants and stimuli were specified as crossed-random effects. A maximal random effects structure was used where possible (see Barr, Levy, Scheepers, & Tily, 2013). The model structure used for each measure is detailed individually in the analysis script. As the data were observed to be skewed, log transformation was applied, however, for completeness, untransformed analyses are also reported in the tables. The MASS package (Venables & Ripley, 2002) was used to define main effects of age group, and a contrast matrix was used to assess display condition effects. These compared one-word window conditions against window conditions including the word to the left (W vs. W + L1), one-word windows against windows including the word to the right (W vs. W + R1), and windows including the word to the right against those including two words to the right (W + R1 vs. W + R2). Finally, we compared normal sentence displays against window conditions including two words to the right (N vs. W + R2). Age differences in effects of display condition were assessed by examining the interaction between these contrasts and age group. Following convention, $t > 1.96$ was considered statistically significant, as when degrees of freedom are high, *p*-values are less than 0.05 when *t/z*-values are greater than 1.96. For ease of interpretation, all reported means are calculated using raw data. Means and standard errors for sentence reading times and reading rates are shown for each experiment in Table 2 and the corresponding statistical effects summarized in Table 3, 4 and 5.

--Tables 2-5--

Experiment 1: Pattern-Masking. A main effect of age group was due to older adults reading sentences more slowly than the young adults, and a similar age group effect was observed when comparing age differences in reading times, WPM and CPM reading rates for normal sentence displays (reading times: $b = 0.61$, $SE = 0.08$, $t = 7.83$; WPM: $b = 0.61$, $SE = 0.08$, $t = 7.79$; CPM: $b = 0.61$, $SE = 0.08$, $t = 7.83$). These findings are consistent with previous research showing older adults read more slowly than young adults (S. Li et al., 2018; L. Li et al., 2019; Wang, Li, Li, Chang et al., 2018; Wang, Li, Li, Liversedge et al., 2018; Zang et al., 2016; Zhao et al., 2019).

For all measures, W + L1 windows and W + R1 windows both produced shorter reading times and faster reading rates than one-word windows, suggesting that readers benefitted from the availability of text to the left and to the right of fixation. In addition, W + R2 windows produced quicker reading times and faster reading rates than W + R1 windows. Windows that extended two words to the right produced reading times and reading rates similar to normal sentence displays, suggesting that the fixated word and two words to the right was sufficient for normal reading.

Interactions between age group and display condition were observed for comparisons of Age Group x W + L1 vs. W and Age Group x W vs. W +R1. Follow-up contrasts revealed significant effect of display condition (W + L1 vs. W) for young, but not older adults, with young adults producing longer reading times (young adults, b = 0.09, SE= 0.02, t= 4.49; older adults, b = 0.03, SE= 0.02, t= 1.48), slower reading rates (CPM reading rate: young adults, b = 0.09, SE= 0.02, t= 4.52, older adults, b = 0.03, SE= 0.02, t= 1.48; WPM reading rate: young adults, b = 0.09, SE= 0.02, t= 4.47, older adults, b = 0.03, SE= 0.02, t= 1.47) for one-word windows compared with W + L1 windows. However, follow-up contrasts for W vs. W + R1 revealed a similar pattern of effects for both age groups in reading times (young adults, b = 0.47, SE= 0.03, t= 17.84, older adults, b = 0.31, SE= 0.03, t= 12.03), and reading rates (CPM reading rate: young adults, b = 0.47, SE= 0.03, t= 17.95, older adults, b = 0.31, SE= 0.03, t= 12.10; WPM reading rate: young adults, b = 0.47, SE= 0.03, t= 17.80, older adults, b = 0.31, SE= 0.03, t= 12.00). Crucially, no interactions between display condition and age group were observed in Age Group x W + R1 vs. W + R2 or Age Group x W + R2 vs. N, suggesting a similar rightward extent of the perceptual span for both age groups.

In addition to the LMM analysis, Bayes factors (Kass & Raftery, 1995) were calculated to confirm the null two-way interaction between age group and display condition for different comparisons (W+L1 vs. W, W vs. W+R1, W+R1 vs. W+R2, and W+R2 vs. N). These were computed using the lmBF function within the BayesFactor package (Morey & Rouder, 2015) in R (R Core Team, 2015), with the scaling factor for g-priors set to 0.5 and using 100,000 Monte Carlo iterations. Participants and items were specified as random factors. Following Vandekerckhove, Matzke, and Wagenmakers (2015; derived from Jeffreys, 1961), Bayes factors (BFs) > 3 were taken to provide weak to moderate support for a model, and BFs > 10 to provide strong support, while BFs < 1 were taken to provide evidence against a model and in favor of the base model. The denominator model (the base model to which other models were compared) included main effects of age group and display condition (W+L1 vs. W, W vs. W+R1, W+R1 vs. W+R2, and W+R2 vs. N). A model containing main effects of age group and display condition plus interactions between them was compared against the denominator model. The results of these analyses are displayed in Table 6. The analyses provided support (a high BF value) for a model with an interaction between age group and display condition over a model with only main effects for the contrast of W+L1 condition versus W condition and the WR1 condition versus the W condition. However, for all other comparisons a main effects model was preferred. In addition, a sensitivity analysis with different priors (i.e., 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8) provided consistent results. To sum, the Bayes Factor analysis confirmed the LMM analysis findings and provided evidence for the absence of age difference in the rightward span.

Experiment 2: Similar Character Replacements. A main effect of age group was due to longer reading times and slower reading rates for older than younger adults, and a similar age difference was observed in reading times, WPM and CPM reading rates for normal sentence displays (reading times: $b = 0.74$, $SE = 0.10$, $t = 7.49$; WPM: $b = 0.74$, $SE = 0.10$, $t = 7.42$; CPM: $b = 0.74$, $SE = 0.10$, $t = 7.45$).

As in Experiment 1, W + L1 windows and W + R1 windows both produced shorter reading times and faster reading rates than one word windows. W + R2 windows produced shorter reading times and faster reading rates than W + R1 windows. In contrast with Experiment 1, W + R2 windows produced longer reading times and slower reading rates compared with normal sentence displays, suggesting that readers were sensitive to linguistic information outside even the largest rightward window.

In contrast to Experiment 1 interactions with age group were found for the comparison of W+R2 windows and normal text displays. Follow-up contrasts revealed a similar pattern of effects for both age groups, with longer reading times (young adults, $b = 0.34$, $SE = 0.03$, $t = 10.10$; older adults, $b = 0.16$, $SE = 0.03$, $t = 4.79$) and slower reading rates (CPM: young adults, $b = 0.34$, $SE = 0.03$, $t = 9.99$; older adults, $b = 0.16$, $SE = 0.03$, $t = 4.74$; WPM: young adults, $b = 0.34$, $SE = 0.03$, $t = 10.10$; older adults, $b = 0.16$, $SE = 0.03$, $t = 4.79$) for W + R2 windows condition than normal displays. However, this effect was larger for the young adults. Therefore, when text outside moving windows was masked by visually similar characters, younger adults may have experienced greater disruption. We consider this effect further in the General Discussion. No other interactions were observed, indicating that both young and older adults made use of at least two words to the right and one word to the left of fixation.

As in Experiment 1, Bayes factors (Kass & Raftery, 1995) were calculated to confirm the null two-way interaction between age group and display condition for different comparisons (W+L1 vs. W, W vs. W+R1, W+R1 vs. W+R2, and W+R2 vs. N). These analyses provided support for a model with an interaction between age group and display condition over a model with only main effects for the contrast of normal condition versus W + R2 windows. However, a main effects model was preferred for all other comparisons, including the crucial comparisons between W+R1 and W+R2 windows, indicating no age difference in the benefits of increasing the rightward span. In addition, a sensitivity analysis with different priors (i.e., 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8) provided consistent results. To sum, the Bayes Factor analysis confirmed the LMM analysis findings and provided further evidence for the absence of age difference in the rightward span.

Experiment 3: Parafoveal Blurring. As in Experiments 1 and 2, a main effect of age group was due to longer reading times and slower reading speeds for older than younger adults, and a similar effect was observed in reading times and reading speeds for normal sentence displays (reading times: $b = 0.83$, $SE = 0.10$, $t = 8.61$; WPM: $b = 0.83$, $SE = 0.10$, $t = 8.58$; CPM: $b = 0.83$, $SE = 0.10$, $t = 8.64$). Contrasts to examine effects of display condition showed that, as in Experiment 1 and 2, W + R1 windows produced shorter reading times and faster reading rates than one-word windows. In contrast to Experiment 1 and 2, there was no significant difference in reading times and reading rates between one-word windows and W + L1 windows. W + R2 windows produced shorter reading times and faster reading rates than W + R1 windows. In line with Experiment 1, but in contrast to Experiment 2, windows that extended two words to the right produced reading times and reading rates similar to normal sentence displays, suggesting that the fixated word and two words to the right was sufficient for normal reading. Crucially, there was no indication that these effects differed across age groups. Indeed, the only indication of an interaction effect was observed for one-word compared to W + R1 windows, due to longer reading times (young adults, $b = 0.19$, $SE = 0.02$, $t = 10.26$; older adults, $b = 0.11$, $SE = 0.02$, $t = 6.28$) and slower reading rates (CPM: young adults, $b = 0.19$, $SE = 0.02$, $t = 10.51$, older adults, $b = 0.11$, $SE = 0.02$, $t = 6.42$; WPM: young adults, $b = 0.19$, $SE = 0.02$, $t = 10.31$, older adults, $b = 0.11$, $SE = 0.02$, $t = 6.31$) when only the fixated word was visible. While this pattern was observed for both age groups, the disruption was larger for young compared with older adults.

As before, Bayes factors (Kass & Raftery, 1995) were calculated to confirm the null two-way interaction between age group and display condition for different comparisons (W+L1 vs. W, W vs. W+R1, W+R1 vs. W+R2, and W+R2 vs. N). The Bayes factor analyses provided support for a model with an interaction between age group and display condition over a model with only main effects for the contrast W + R1 vs. W only. All other comparisons found no support for an interaction model over a main effects model. Again, sensitivity analysis with a range of priors also produced similar results. To sum, the Bayes Factor analysis confirmed the LMM analysis findings and provided evidence for the absence of age difference in the rightward span for both age groups.

General Discussion

The present study used a moving window paradigm and window sizes shown previously to produce age differences in perceptual span effects for English (Rayner et al., 2009) to establish if similar effects are observed in Chinese reading. However, whereas Rayner et al. masked text outside each window by replacing letters in words with an 'X', we used different masking procedures across three experiments, motivated by observations that the type of mask might affect performance in this paradigm when reading Chinese. As in previous perceptual span research, we focused on effects on sentence reading times and reading rates as these provide the most comprehensive measure of reading performance in moving window experiments (McConkie & Rayner, 1975).

The findings were very clear. First, they showed that older adults had longer reading times and slower reading rates compared to young adults in all three experiments, including when comparing effects in conditions in which sentences were presented entirely as normal. This was consistent with previous research showing that older adults read Chinese more slowly than young adults (S. Li et al., 2018; L. Li et al., 2019; Wang, Li, Li, Chang et al., 2018; Wang, Li, Li, Liversedge et al., 2018; Zang et al., 2016; Zhao et al., 2019). This demonstrates that the older adults in the present research exhibited typical age-related reading difficulty.

The findings also showed that restricting the availability of linguistic information to the right of the fixated word increased sentence reading times. This effect was largest when only each fixated word was visible, showing the importance of the availability of parafoveal information in natural reading (see Schotter et al., 2012; and for similar evidence from Chinese, see, e.g., Pollatsek, Tan, & Rayner, 2000; Liu, Inhoff, Ye, & Wu, 2002). Moreover, this effect was observed for both young and older adults. Restricting the availability of information to the left of fixation also increased reading times in Experiment 1 and 2, though in Experiment 1 this effect was larger for young adults. Overall, it seems clear that both age groups of readers are sensitive to parafoveal information to both the left and right of fixation. We also found that increasing the rightward span by up to two words reduced reading times for both age groups so that these either returned to normal (Experiments 1 & 3) or were close to normal (Experiment 2). Therefore, in line with previous findings in Chinese and alphabetic scripts, participants could read effectively when only the fixated word and about two words to the right were visible (e.g., Häikiö, et al., 2009; Inhoff & Liu, 1998; Rayner, 1986; Rayner et al., 1982; M. Yan et al., 2015). Our findings are therefore consistent with the view that roughly this amount of rightward information can support normal reading.

We nevertheless observed variation in rightward span effects across the experiments, most likely as a consequence of the different masking procedures used (e.g., G. Yan et al., 2013; M. Yan et al., 2015). Though, it is important to note that the stimuli also differed across experiment and so cross experiment comparisons must be interpreted with some caution. The rightward span was largest in Experiment 2 when masks provided similar but incorrect orthographic information The present findings therefore confirmed that masking techniques which retain orthographic information increase estimations of the perceptual span compared to when this information is masked (M. Yan et al., 2015; see also G. Yan et al., 2013). We also found that the rightward span was larger, extending beyond the two-word windows, when masks provided incorrect but similar orthographic information (in

Experiment 2) compared to when orthographic information was degraded (in Experiment 3). It is unclear, however, if this is a consequence of disruption by incorrect orthographic information outside windows, or because degradation of this information impaired orthographic processing. There is, however, considerable evidence that, during parafoveal processing, Chinese readers not only acquire orthographic information but also semantic information (Tsai, Kliegl, & Yan, 2012; M. Yan, Richter, Shu, & Kliegl, 2009; Yan, Risse, Zhou, & Kliegl, 2012; M. Yan, Zhou, Shu, & Kliegl, 2012; Yang, Wang, Tong, & Rayner, 2012). Consequently, masks that provide incorrect orthographic information may be particularly disruptive to Chinese reading as they may not only interfere with orthographic processing but also elicit incorrect semantic information that can disrupt reading.

We also observed variation in the leftward span across the experiments. This was examined by comparing W and W + L1 windows. These showed no difference, and so no benefit of increasing the leftward span, when masks provided degraded orthographic information (Experiment 3). However, reading times were shorter for W + L1 compared with W windows when using a pattern mask (Experiment 1) or masks provided incorrect orthographic information (Experiment 2). This may be because the pattern mask (Experiment 1) encouraged less left-of-fixation processing so that readers did not benefit from an increase in the leftward span. In Experiment 2, participants may have experienced disruption to processing when characters outside one-word windows provided incorrect orthographic information, and this disruption may have been reduced when windows included the word to the left. The findings nevertheless are important in showing that different masking techniques may elicit subtly different pattern of perceptual span effects in Chinese reading, underscoring the importance of the careful selection of masks in such studies. Little age difference was observed in this effect of the leftward span, with only Experiment 1 showing an interaction between age group and the contrast between one-word windows and W+L1 windows.

Moreover, this interaction was due to a larger benefit of leftward information for young compared to older adults. The studies therefore provide no evidence that older Chinese readers have a larger leftward span and so more symmetrical perceptual span compared to young adults, as Rayner et al. (2009) argued for older readers of alphabetic languages.

We also observed little age difference in rightward perceptual span effects in any experiment. No meaningful age differences in span size were observed in Experiments 1 or 3. Similarly, Experiment 2 showed no age differences in the benefit of windows extending two words rather than only one word to the right of the fixated word, and so no age differences in this crucial measure of span size. We did, however, observe a larger reading time cost for young adults, compared to older adults, for W + R2 windows compared to normal displays. This may be because younger readers had greater sensitivity to visual information outside the moving window when characters were replaced by visually similar characters but that this did not affect the perceptual span (see, e.g., Jordan, Kurtev, McGowan, & Paterson, 2016). In sum, there was no indication from these findings that older Chinese readers have a smaller perceptual span. This finding is surprising given the considerable evidence that older adults have much greater difficulty reading Chinese (Wang, Li, Li, Chang et al., 2018; Wang, Li, Li, Liversedge et al., 2018; Zhao et al., 2019) and appear to have particular difficulty identifying characters (L. Li et al., 2019; Zang et al., 2016) and segmenting words in unspaced text (S. Li et al., 2018).

One indication that older adults might process fewer characters on each fixation was provided in a recent study by Xie et al. (2019). This showed in a non-reading task that the visual span for Chinese characters (i.e., the number of characters arranged horizontally that can be recognized on a single glance without moving the eyes) is smaller for older than younger adults, especially when characters are more complex. However, the relationship between the visual span and the perceptual span currently is not clear. First, the two tasks assess different aspects of reading (for a review, see Frey & Bosse, 2018). In particular, the visual span is argued to reflect limits on perceptual processing distinct from oculomotor, attentional or linguistic influences associated with natural reading (e.g., Legge, Ahn, Klitz, & Luebker, 1997; Liu, Patel, & Kwon, 2017; Wang, He, & Legge, 2014). It usually is assessed using the trigram task, in which sequences of three letters or characters that do not form a word are displayed briefly (typically for about 200 ms) at a central fixation point and locations to the left and right of this point, with span size calculated as the range of locations across which stimuli can be reported with at least 80% accuracy. These measures have been shown to correlate with reading speed (Legge et al., 2007; Liu et al., 2018; Xie et al., 2019) but are not predictive of parafoveal processing during sentence reading (Risse, 2014). Consequently, while the findings reported by Xie et al. shed light on age differences in perceptual limitations on character recognition, they may not be directly informative about perceptual span effects during natural reading, as these are likely to be influenced by attentional and linguistic factors as well as perceptual factors.

The present findings are also contrary to previously-reported age differences in the perceptual span in English (Rayner et al., 2009). One possibility is that this reflects cross-linguistic differences in aging effects. In particular, as Chinese has a more compact script than English, the perceptual span for Chinese is physically smaller and extends less far into parafoveal vision. Consequently, age-related changes in parafoveal visual sensitivity (e.g., Crassini et al., 1988) may impair parafoveal processing to a lesser extent in Chinese than English. Alternatively, Chinese readers may develop greater parafoveal processing efficiency because of the need to segment unspaced text into words (see, .e.g., Zhou, Kliegl, Yan, 2013), and this enhanced capability may be maintained into older age. Another possibility, however, is that evidence for an adult age difference in the perceptual span for alphabetic languages is not as robust as has been assumed. Rayner et al. (2009) showed that the young adults in their experiment read sentences normally when windows extended two words rightwards. By comparison, the older adults had similar reading times when windows extended either one or two words rightwards. Rayner et al. took this as evidence that older adults acquire information from only about one word to the right of the fixated word and so have a smaller rightward span. However, the older adults also had longer reading times for both rightward windows compared to normal sentence displays, and so not even windows including two words to the right were capable of supporting normal reading. One possibility, which Rayner et al. considered, is that the older adults also require information from the left of fixation to read normally. However, another possibility is that the use of 'X' masks created a regular pattern in parafoveal vision that was more distracting for the older adults and disrupted their reading performance. Consequently, the experiment may not provide such clear evidence that older readers have a smaller perceptual span as widely reported. Similar concerns apply to other studies that have used 'X'-masks to investigate age differences in parafoveal processing (e.g., Rayner et al., 2014). Moreover, recent research failed to replicate these findings of an age difference in perceptual span effects using a moving window paradigm (Whitford & Titone, 2016). However, this study also used a pattern mask, composed of dashes, to replace letters and fill the spaces between words outside each window. Consequently, it will be important to establish if age differences in perceptual span effects for alphabetic scripts are observed in moving window paradigms that preserve orthographic and spatial information without disrupting the normal visual appearance of text.

In sum, the present study reports three experiments providing novel evidence for similarity in the perceptual spans of young and older Chinese readers. These findings challenge the prevailing view that visual and cognitive declines limit the capacity for older adults to acquire useful parafoveal information on each fixational pause, and that this is a major source of reading difficulty. Instead, the present findings point to preservation of these capabilities in older adults, although it will be important to establish if similar findings can be obtained with alphabetic scripts while taking care to use masking paradigms that address this issue appropriately.

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[1] Additional participants were recruited following the initial round of reviews, therefore data were analysed twice.

Figure Legend

Figure 1. Example Stimuli for Experiments 1-3. Panel A shows an example sentence displayed normally and in each mask condition with a W + 2R window. Panel B shows an example sentence displayed normally and in each display condition using the pattern mask. These condition were the same for each experiment, with only the mask changing. In both panels, a dashed line is used to indicate fixation location. N = normal sentence displays; W one-word window; W + L1= window containing the fixated word and one word to the left; W + R1= window containing the fixated word and one word to the right; W + R2 = window containing the fixated word and two words to the right.

Figure 2. Bar charts showing (a) sentence reading times, (b) character-per-minute reading rates, and (c) word-per-minute reading rates for young and older adults in Experiments 1-3. Error bars show the Standard Error of the Mean.

Figure 1

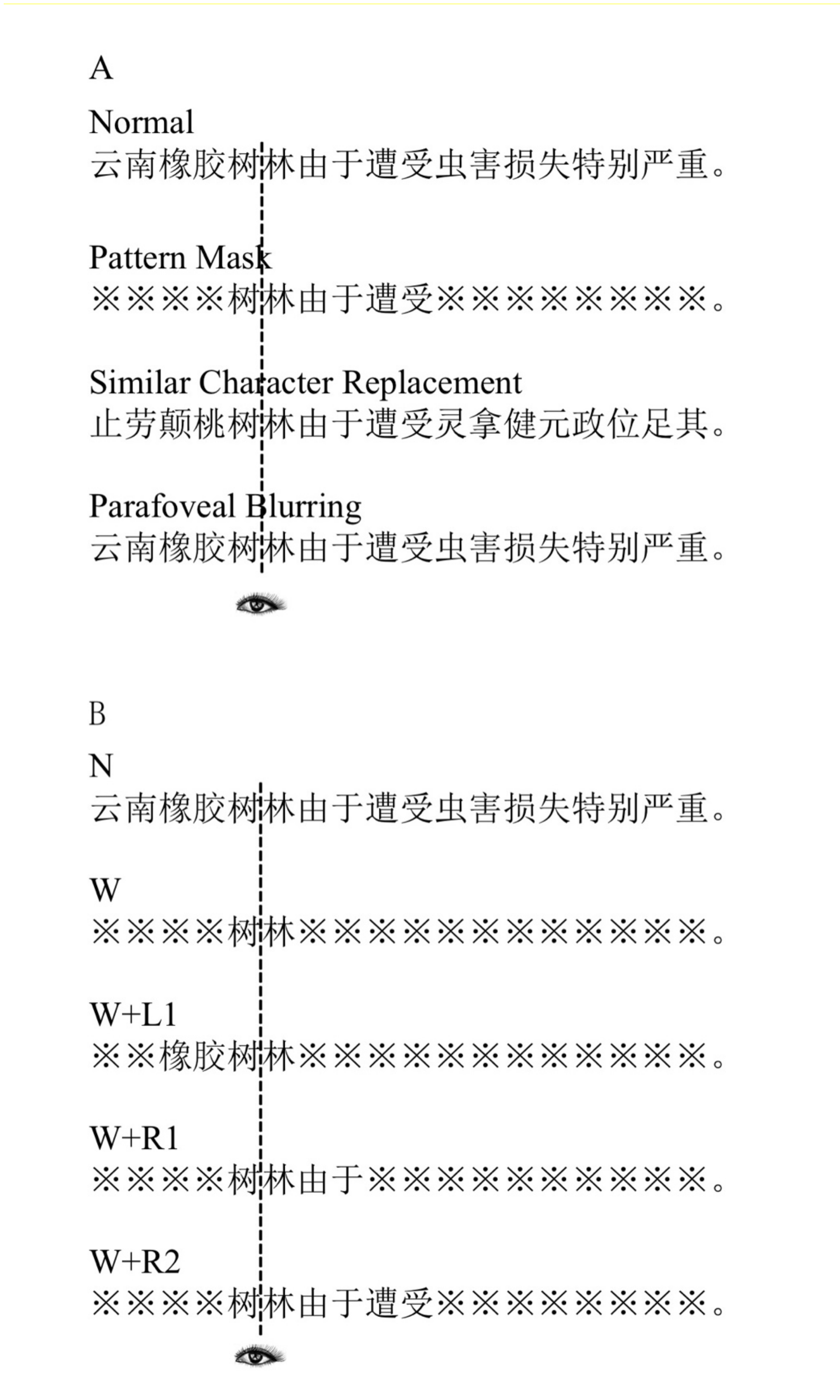
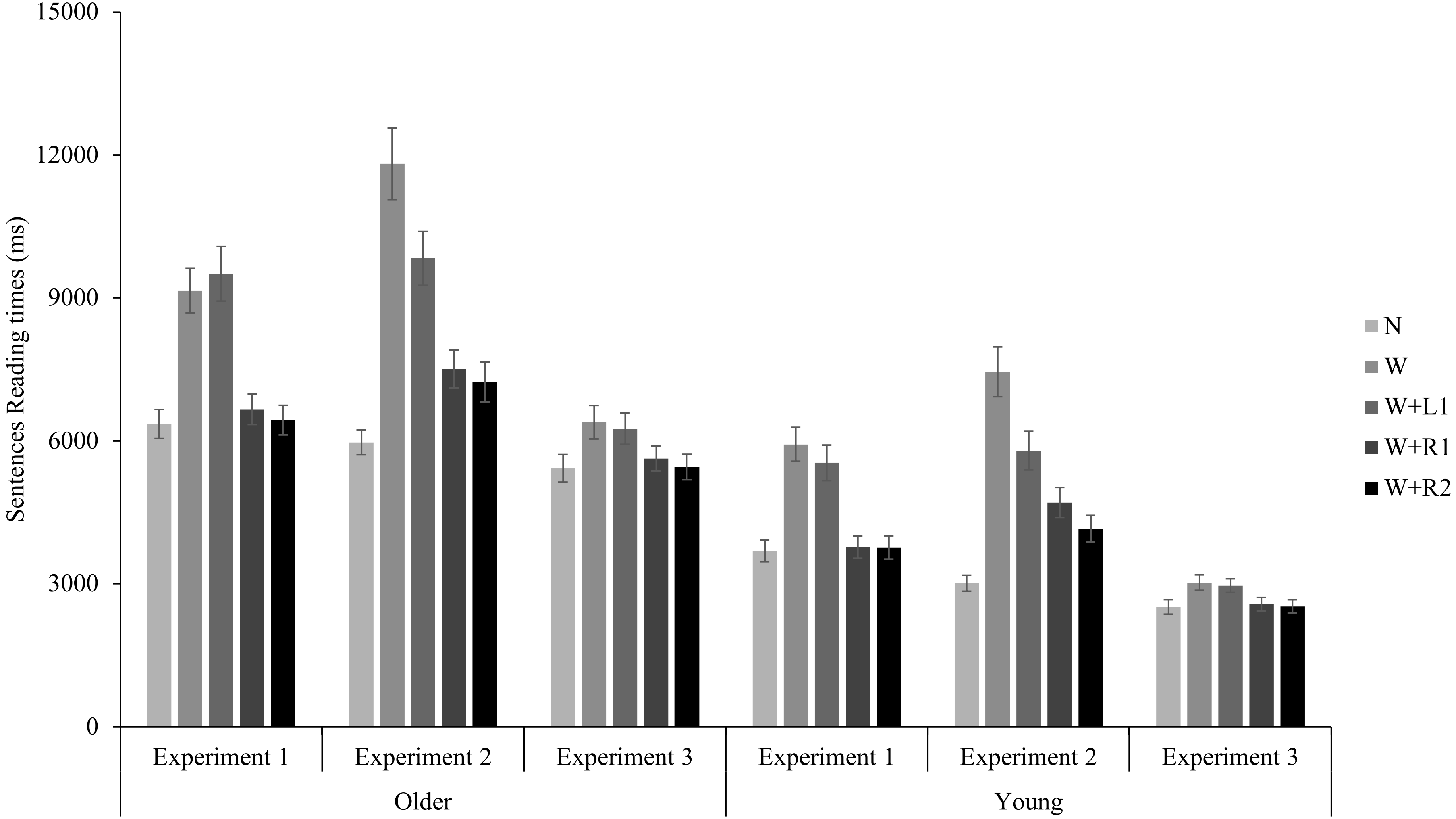
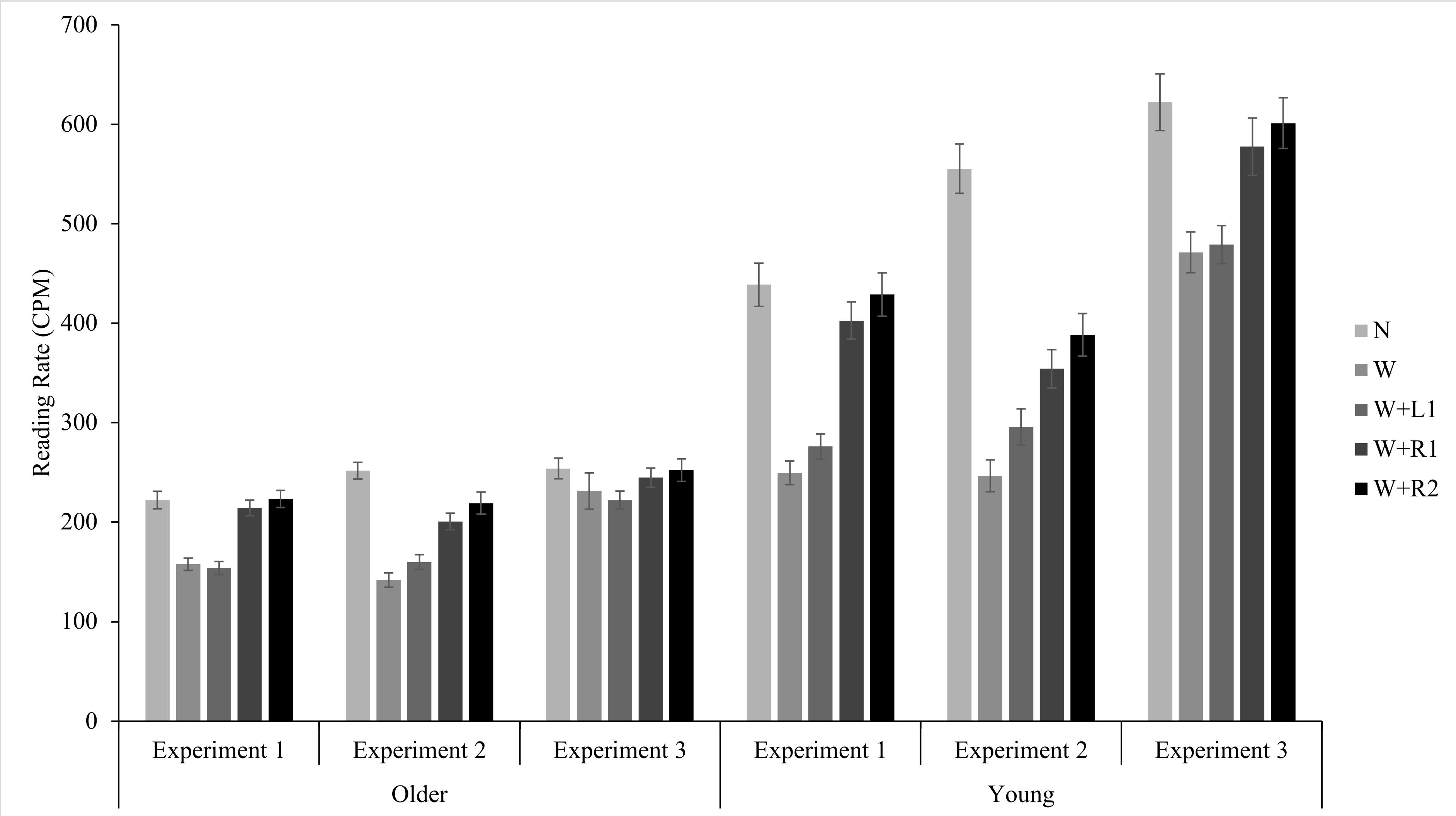

A
Normal
云南橡胶树林由于遭受虫害损失特别严重。
Pattern Mask
※※※※树林由于遭受※※※※※※※※。
Similar Character Replacement
止劳颠桃树林由于遭受灵拿健元政位足其。
Parafoveal Blurring
云南橡胶树林由于遭受虫害损失特别严重。
B
N
云南橡胶树林由于遭受虫害损失特别严重。
W
※※※※树林※※※※※※※※※※※※。
W+L1
※※橡胶树林※※※※※※※※※※※※。
W+R1
※※※※树林由于※※※※※※※※※※。
W+R2
※※※※树林由于遭受※※※※※※※※。

Figure 2

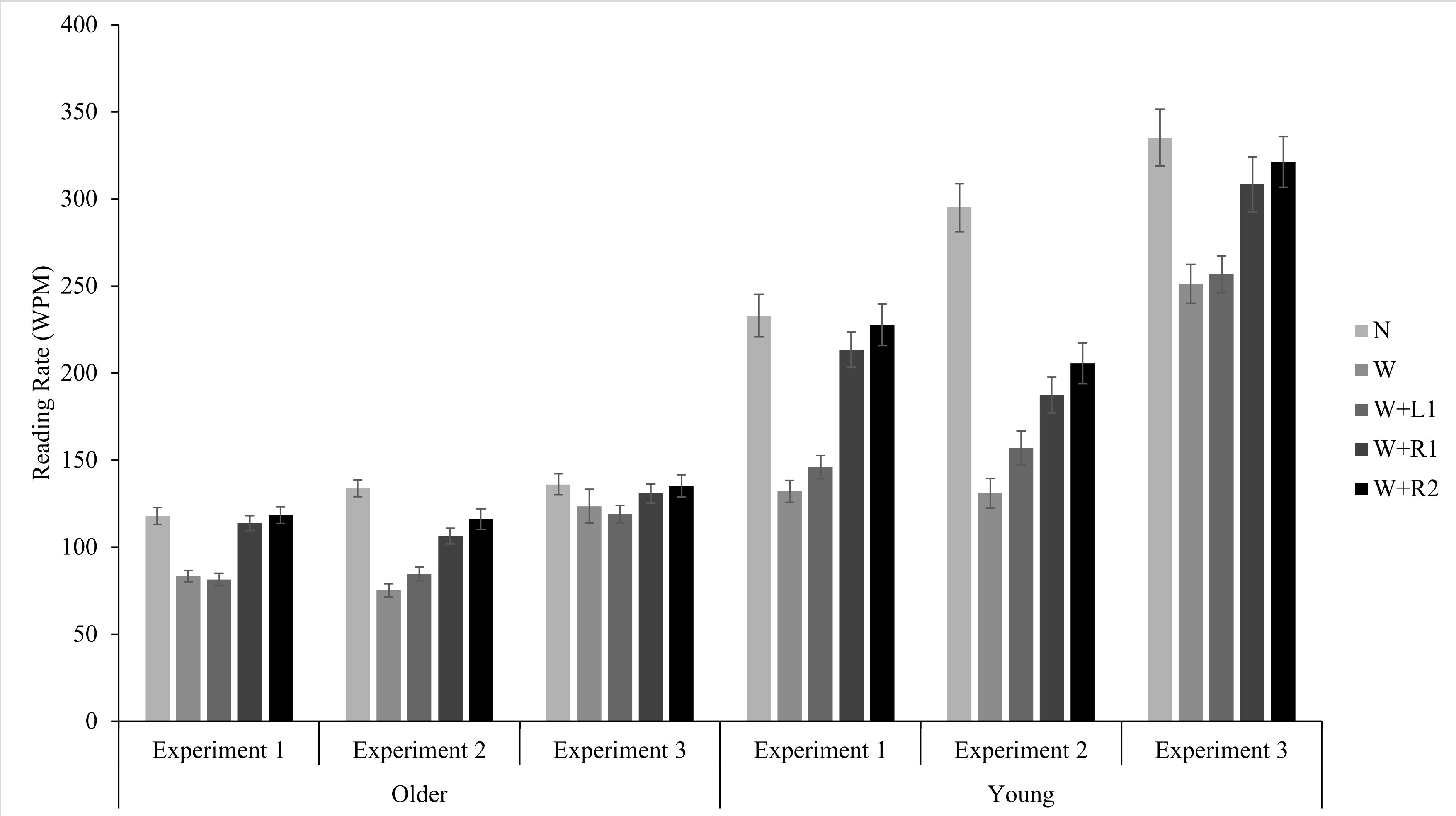
a.


15000
12000
9000
6000
3000
0
Sentences Reading times (ms)
Experiment 1
Experiment 2
Experiment 3
Experiment 1
Experiment 2
Experiment 3
Older
Young
N
W
W+L1
W+R1
W+R2

b.


Reading Rate (CPM)
700
600
500
400
300
200
100
0
N
W
W+L1
W+R1
W+R2
Experiment 1
Experiment 2
Experiment 3
Experiment 1
Experiment 2
Experiment 3
Older
Young

c.



400
350
300
250
200
150
100
50
0
Reading Rate (WPM)
Experiment 1
Experiment 2
Experiment 3
Experiment 1
Experiment 2
Experiment 3
Older
Young
N
W
W+L1
W+R1
W+R2

Table 1. Participant Characteristics.

	Age Group	Age (Years)	Visual Acuity (Snellen Values)	Formal Education (Years)	Vocabulary (Scaled Scores)	Digit Span (Scaled Scores)
Experiment 1	Young	21 (2.1)	20/22	14.4 (1.5)	14.8 (1.7)	13.9 (2.3)
		Range=19-26	Range=20/16-20/32	Range=13-18	Range=11-18	Range=9-19
	Older	68 (4.5)	20/29	13.7 (3.4)	14.1(1.7)	11.6 (1.9)
		Range=60-80	Range=20/19-20/40	Range=9-24	Range=10-17	Range=8-15
				t(38)=1.14, *p*=.26	*t*(38)=1.64, *p*=.11	*t*(38)=4.38, *p*=.00
Experiment 2	Young	21 (1.8)	20/20	12.9 (.8)	14.7 (1.8)	14.3 (2.4)
		Range=18-25	Range=20/16-20/28	Range=12-15	Range=12-18	Range=10-19
	Older	71 (5.8)	20/29	12.2 (2.2)	15.2 (.8)	12.0 (1.7)
		Range=65-83	Range=20/17-20/40	Range=9-18	Range=12-18	Range=9-16
				t(38)=1.65 *p*=.10	*t*(38)=1.48, *p*=.15	*t*(38)=4.59, *p*=.00
Experiment 3	Young	20 (1.5)	20/20	13.2 (.8)	14.6 (1.1)	14.0 (2.4)
		Range=18-24	Range=20/16-20/28	Range=12-15	Range=12-18	Range=9-19
	Older	70 (4.0)	20/27	12.5 (2.5)	15.1 (.8)	12.7 (2.1)
		Range=65-80	Range=20/17-20/40	Range=9-18	Range=14-17	Range=9-19
				t(48)=1.49, *p*=.14	*t*(48)=1.09, *p*=.28	*t*(48)=2.45, *p*=.02

Note. The Standard Deviation of the Mean is shown in parentheses.

Table 2 Means and SE (in Parentheses) for Eye Movements Measures (log transformation) in each Experiment

	Age Group	Display condition				
		Normal	W	W + L1	W + R1	W + R2
Experiment 1						
SRT	Young Adult	3694 (228)	5930 (358)	5539 (375)	3773 (232)	3769 (247)
	Older Adult	6359 (305)	9169 (468)	9536 (576)	6664 (319)	6437 (312)
Reading rate (CPM)	Young Adult	438 (22)	250 (12)	276 (13)	403 (19)	429 (22)
	Older Adult	222 (9)	158 (6)	154 (7)	214 (8)	223 (9)
Reading rate (WPM)	Young Adult	233 (12)	132 (6)	146 (7)	213 (10)	228 (12)
	Older Adult	118 (5)	83 (3)	81 (4)	114 (4)	118 (5)
Experiment 2						
SRT	Young Adult	3013 (166)	7452 (522)	5793 (406)	4707 (317)	4158 (281)
	Older Adult	5978 (259)	11821 (752)	9841 (564)	7500 (400)	7246 (421)
Reading rate (CPM)	Young Adult	555 (25)	247 (16)	296 (18)	354 (19)	388 (21)
	Older Adult	252 (8)	142 (7)	160 (7)	201 (8)	219 (11)
Reading rate (WPM)	Young Adult	295 (14)	131 (9)	157 (10)	187 (10)	206 (12)
	Older Adult	134 (5)	75 (4)	85 (4)	107 (4)	116 (6)
Experiment 3						
SRT	Young Adult	2513 (150)	3026 (161)	2964 (143)	2576 (144)	2522 (139)
	Older Adult	5428 (293)	6387 (353)	6260 (329)	5627 (260)	5450 (267)
Reading rate (CPM)	Young Adult	623 (29)	472 (21)	479 (19)	577 (29)	602 (26)

	Older Adult	254 (10)	231 (18)	222 (9)	245 (10)	253 (11)
Reading rate (WPM)	Young Adult	336 (16)	251 (11)	257 (11)	308 (16)	322 (15)
	Older Adult	136 (6)	124 (10)	119 (5)	131 (6)	135 (6)

Note. SRT = sentences reading times, CPM = characters per minute, WPM = words per minute. Standard errors were calculated across participant variance.

Table 3 Linear Mixed Model Statistics for Eye Movements Measures in Experiment 1

Source of variance		Sentences reading times (ms)	Sentences reading times (log transformed)	Reading rate (CPM)	Reading rate (CPM) (log transformed)	Reading rate (WPM)	Reading rate (WPM) (log transformed)
Intercept	*b*	6086.90	8.57	276.69	5.47	146.64	4.84
	SE	208.55	0.04	10.83	0.03	5.79	0.03
	t	29.19	243.10	25.54	159.44	25.33	138.79
Age Group	*b*	3093.19	0.56	164.79	0.56	87.39	0.56
	SE	390.49	0.07	21.13	0.07	11.16	0.07
	t	7.92*	8.52*	7.80*	8.52*	7.83*	8.52*
Display Condition							
W + L1 vs. W	*b*	8.52	0.03	11.12	0.03	5.91	0.03
	SE	151.54	0.01	3.35	0.01	1.81	0.01
	t	0.06	2.14*	3.32*	2.12*	3.27*	2.10*
W vs. W + R1	*b*	2329.40	0.39	104.91	0.39	55.89	0.39
	SE	163.03	0.02	6.69	0.02	3.39	0.02
	t	14.29*	20.69*	15.67*	20.70*	16.47*	20.60*
W + R1 vs. W + R2	*b*	117.05	0.03	17.42	0.03	9.40	0.03
	SE	98.14	0.02	5.29	0.02	2.70	0.02
	t	1.19	2.22*	3.30*	2.21*	3.48*	2.20*
W + R2 vs. N	*b*	75.76	0.01	4.41	0.01	2.49	0.01

	SE	100.89	0.02	8.12	0.02	4.24	0.02
	t	0.75	0.60	0.54	0.60	0.59	0.60
*Age Group * Display Condition*							
Age Group * W + L1 vs. W	*b*	765.64	0.12	30.35	0.12	15.86	0.12
	SE	271.46	0.03	6.68	0.03	3.62	0.03
	t	2.82*	4.27*	4.55*	4.27*	4.38*	4.24*
Age Group * W vs. W +R1	*b*	346.11	0.15	96.18	0.15	50.84	0.15
	SE	312.26	0.04	12.87	0.04	6.79	0.04
	t	1.11	4.21*	7.48*	4.21*	7.49*	4.20*
Age Group * W + R1 vs. W + R2	*b*	220.79	0.00	16.97	0.00	9.65	0.00
	SE	194.78	0.03	9.78	0.03	5.40	0.03
	t	1.13	0.15	1.74	0.15	1.79	0.14
Age Group * W + R2 vs. N	*b*	6.15	0.02	11.01	0.02	5.85	0.02
	SE	201.21	0.04	15.47	0.04	8.48	0.04
	t	0.03	0.45	0.71	0.45	0.69	0.45

Note. * denotes significant fixed-factor effects ($t > 1.96$)

Table 4 Linear Mixed Model Statistics for Eye Movements Measures in Experiment 2

Source of variance		Sentences reading times (ms)	Sentences reading times (log transformed)	Reading rate (CPM)	Reading rate (CPM) (log transformed)	Reading rate (WPM)	Reading rate (WPM) (log transformed)
Intercept	*b*	6750.70	8.61	281.46	5.43	149.19	4.79
	SE	310.30	0.05	14.81	0.05	8.03	0.05
	t	21.75	186.98	19.01	118.47	18.57	104.08
Age Group	*b*	3452.00	0.58	173.37	0.58	91.98	0.58
	SE	598.60	0.09	29.30	0.09	15.81	0.09
	t	5.77*	6.43*	5.92*	6.41*	5.82*	6.41*
Display Condition							
W + L1 vs. W	*b*	1818.60	0.18	33.64	0.18	17.82	0.18
	SE	233.00	0.02	4.99	0.02	2.73	0.02
	t	7.81*	8.81*	6.75*	8.45*	6.53*	8.89*
W vs. W + R1	*b*	3533.30	0.41	83.44	0.41	43.91	0.41
	SE	339.90	0.03	6.38	0.03	3.33	0.03
	t	10.40*	14.37*	13.07*	14.37*	13.17*	14.73*
W + R1 vs. W + R2	*b*	403.40	0.09	26.11	0.09	13.89	0.09
	SE	118.10	0.01	4.82	0.01	2.53	0.01
	t	3.42*	6.07*	5.42*	6.08*	5.49*	6.48*
W + R2 vs. N	*b*	1204.50	0.25	99.71	0.25	53.54	0.25

	SE	144.00	0.02	13.28	0.02	7.27	0.02
	t	8.37*	10.38*	7.51*	10.24*	7.37*	10.53*
*Age Group * Display Condition*							
Age Group * W + L1 vs. W	*b*	321.20	0.06	31.58	0.06	17.09	0.06
	SE	466.00	0.04	9.59	0.04	5.24	0.04
	t	0.69	1.49	3.29*	1.49	3.26*	1.50
Age Group * W vs. W +R1	*b*	1578.50	0.01	48.43	0.01	25.18	0.01
	SE	679.70	0.06	12.34	0.06	6.39	0.06
	t	2.32*	0.20	3.93*	0.19	3.94*	0.19
Age Group * W + R1 vs. W + R2	*b*	292.60	0.05	16.09	0.05	8.59	0.05
	SE	236.20	0.03	9.27	0.03	4.87	0.03
	t	1.24	1.79	1.74	1.80	1.76	1.79
Age Group * W + R2 vs. N	*b*	122.60	0.18	134.58	0.18	71.95	0.18
	SE	287.90	0.05	25.87	0.05	14.15	0.05
	t	0.43	3.83*	5.20*	3.78*	5.09*	3.75*

Table 5 Linear Mixed Model Statistics for Eye Movements Measures in Experiment 3

Source of variance		Sentences reading times (ms)	Sentences reading times (log transformed)	Reading rate (CPM)	Reading rate (CPM) (log transformed)	Reading rate (WPM)	Reading rate (WPM) (log transformed)
Intercept	*b*	4275.62	8.17	395.88	5.78	211.89	5.16
	SE	216.75	0.05	21.99	0.05	11.88	0.05
	t	19.73	173.93	18.00	123.66	17.83	108.57
Age Group	*b*	3110.67	0.79	309.77	0.79	165.92	0.79
	SE	416.55	0.09	43.18	0.09	23.11	0.09
	t	7.47*	8.80*	7.17*	8.80*	7.18*	8.80*
Display Condition							
W + L1 vs. W	*b*	96.80	0.01	0.78	0.01	0.44	0.01
	SE	75.57	0.01	9.50	0.01	4.86*	0.01
	t	1.28	1.47	0.08	1.29	0.09	1.30
W vs. W + R1	*b*	607.33	0.15	59.87	0.15	32.26	0.14
	SE	84.25	0.01	11.15	0.01	5.75	0.01
	t	7.21*	14.46*	5.37*	11.43*	5.61*	11.52*
W + R1 vs. W + R2	*b*	114.81	0.03	16.38	0.03	8.96	0.03
	SE	63.57	0.01	7.78	0.01	3.96	0.01
	t	1.81	2.79*	2.11*	2.58*	2.27*	2.58*
W + R2 vs. N	*b*	17.01	0.01	11.00	0.01	7.34	0.01

	SE	82.41	0.01	7.28	0.13	4.24	0.01
	t	0.21	1.12	1.51	0.94	1.73	0.94
*Age Group * Display Condition*							
Age Group * W + L1 vs. W	*b*	68.01	0.01	16.56	0.01	9.91	0.01
	SE	146.75	0.01	15.96	0.02	8.32	0.02
	t	0.46	0.28	1.04	0.25	1.19	0.25
Age Group * W vs. W +R1	*b*	312.27	0.07	92.13	0.07	49.48	0.07
	SE	166.10	0.02	19.25	0.02	10.00	0.02
	t	1.88	3.65*	4.79*	2.87*	4.95*	2.88*
Age Group * W + R1 vs. W + R2	*b*	120.40	0.01	17.19	0.01	9.26	0.01
	SE	125.84	0.02	15.54	0.02	7.85	0.02
	t	0.96	0.34	1.11	0.31	1.18	0.31
Age Group * W + R2 vs. N	*b*	17.42	0.01	19.56	0.01	13.13	0.01
	SE	154.00	0.02	14.54	0.02	8.49	0.02
	t	0.11	0.34	1.35	0.28	1.55	0.28

Table 6 Bayes Factors for each comparison.

	Bayes Factor	W vs. WL1	W vs. WR1	WR1 vs. WR2	N vs. WR2
Experiment 1					
Sentences reading times	BF	4.61×10^4	2.59×10^9	0.06	0.08
Reading rate (CPM)	BF	5.07×10^4	2.70×10^9	0.06	0.08
Reading rate (WPM)	BF	5.00×10^4	2.55×10^9	0.06	0.08
Experiment 2					
Sentences reading times	BF	0.81	0.06	0.43	8.55×10^{11}
Reading rate (CPM)	BF	0.81	0.06	0.44	8.99×10^{11}
Reading rate (WPM)	BF	0.83	0.06	0.42	8.25×10^{11}
Experiment 3	BF				
Sentences reading times	BF	0.06	27.75	0.06	0.07
Reading rate (CPM)	BF	0.06	29.13	0.06	0.06
Reading rate (WPM)	BF	0.06	28.23	0.06	0.06

Note. Bayes factors were calculated for log-transformed data.