1   Perceptual span is independent of font size for older and young readers: Evidence

2   from Chinese

3

4   Fang Xie

5   Tianjin Normal University

6   Jingxin Wang

7   Tianjin Normal University

8   Lisha Hao

9   Tianjin Normal University

10   Xue Zhang

11   Tianjin Normal University

12   Kayleigh L. Warrington

13   University of Leicester

14

1   The data sets supporting these analyses are available through Figshare:

2   https://figshare.com/s/0fb4f02aa48c3232bbd1

1   Abstract

2   Research suggests that visual acuity plays a more important role in parafoveal processing in

3   Chinese reading than in spaced alphabetic languages, such that in Chinese, as font size

4   increases, the size of the perceptual span decreases. The lack of spaces and the complexity of

5   written Chinese may make characters in eccentric positions particularly hard to process.

6   Older adults generally have poorer visual capabilities than young adults, particularly in

7   parafoveal vision and so may find large characters in the parafovea particularly hard to

8   process compared with smaller characters, due to their greater eccentricity. Therefore, the

9   effect of font size on the perceptual span may be larger for older readers. Crucially, this

10   possibility has not previously been investigated, however this may represent a unique source

11   of age-related reading difficulty in logographic languages. Accordingly, to explore the

12   relationship between font size and parafoveal processing for both older and young adult

13   readers we manipulated font size and the amount of parafoveal information available with

14   different masking stimuli in two silent reading experiments. The results show that decreasing

15   font size disrupted reading behavior more for older readers, such that reading times were

16   longer for smaller characters, but crucially, the influence of font size on the perceptual span

17   was absent for both age groups. These findings provide new insight into age-related reading

18   difficulty in Chinese by revealing that older adults can successfully process substantial

19   parafoveal information across a range of font sizes. This indicates that older adults'

20   parafoveal processing may be more robust than previously considered.

21

22   Key words: reading, perceptual span, visual acuity, font size

23

24   Main body word count, excluding abstract and references = 7820

25

26

1   Normal reading relies on a series of saccadic eye movements along each line of text,

2   separated by brief fixational pauses, during which visual information is acquired. The region

3   of text (e.g. the number of characters/letters or words) from which useful information can be

4   extracted on a single fixation is termed the "perceptual span". It has been studied using gaze-

5   contingent moving-window techniques (McConkie & Rayner, 1975) in which text is

6   presented normally within a specified region (window) around fixation and text beyond this

7   window is obscured (e.g., by replacing letters in words with an 'X'; McConkie & Rayner,

8   1975, 1976; for a review, see Rayner, 2014). This window moves in synchrony with the

9   reader's eye movements, so that when the eyes fixate a new location, text at this location is

10   shown normally (within the defined window) and text outside of the window, both to the left

11   and right of fixation, is masked. To examine the extent that readers use information in the

12   periphery, the assumption is that when the window is smaller than the perceptual span,

13   reading will be disrupted. The size of the window can be varied to determine the window size

14   required for reading to proceed at its normal speed; this window represents the perceptual

15   span.

16   The perceptual span plays an important role in fluent reading. Research shows that span

17   size varies as a function of text difficulty and reading ability such that when the fixated word

18   is more difficult to process, more resources are allocated to this word, resulting in a smaller

19   perceptual span (Henderson & Ferreira, 1990; Kennison & Clifton, 1995). It is therefore

20   noteworthy that substantial evidence indicates older adults (60+ years) typically experience

21   greater reading difficulty than young adults (18-30 years) during alphabetic (e.g., English) or

22   logographic (e.g., Chinese) reading and so have slower reading speeds and make more and

23   longer fixations, despite typically achieving similar levels of comprehension in eye

24   movement experiments (e.g., Kliegl, Grabner, Rolfs, & Engbert, 2004; McGowan, White,

25   Jordan & Paterson, 2014; Paterson, McGowan, & Jordan, 2013a,b,c; Rayner, Reichle, Stroud,

Williams, & Pollatsek, 2006; Rayner, Yang, Schuett & Slattery, 2014; Warrington,

McGowan, Paterson & White, 2018, 2019; Whitford & Titone, 2016, 2017; Li, Li, Wang,

McGowan & Paterson, 2018; Wang, Li, Li, Xie, Chang, Paterson, White, & McGowan,

2018a; Wang, Li, Li, Xie, Liversedge, & Paterson, 2018b; Zang, Zhang, Bai, Yan, Paterson,

& Liversedge, 2016; Xie, Li, Zhao, Wang, Paterson, White, & Warrington, 2019, though note

that in depth off-line assessments of comprehension often do report age differences, see

Wingfield & Stine-Morrow, 2000; Thornton & Light, 2006; DeDe & Flax, 2016; Stine-

Morrow & Radvansky, 2017).

This has led researchers to speculate that visual and cognitive declines in later

adulthood, including reduced sensitivity to parafoveal information (Crassini, Brown, &

Bowman, 1988; Sekuler, Bennett, & Mamelak, 2000) results in a smaller perceptual span and

produces slower reading. Indeed, Rayner et al. (2009) presented evidence that older adult

readers have a smaller and less asymmetric perceptual span compared with young adult

readers. Other studies also suggest less efficient parafoveal processing by older readers

(Rayner, Castelhano, & Yang, 2010; Rayner et al., 2014). However, more recent research has

failed to replicate this age difference (Whitford & Titone, 2015; see also Risse & Kliegl,

2011) or has suggested that age differences in parafoveal processing may depend on the

cognitive demands of the task (Payne and Stine-Morrow, 2012). Further, generally the

observed differences have been small and only marginally significant (Rayner et al., 2014).

Therefore, whether there are adult age differences in the use of parafoveal processing to

facilitate reading remains an open question.

Crucially, to date knowledge about the effects of visual and cognitive aging on the

reading process is based almost exclusively on findings from alphabet languages and it is not

known whether these effects generalize to other writing systems. As such, very little is

known about the nature of parafoveal processing in older age in Chinese. However, there is

1   reason to believe that parafoveal processing may be particularly challenging in logographic

2   languages. The perceptual span of skilled young adult readers of Chinese extends

3   approximately 1 character to the left of the fixated character and 3-4 characters to its right

4   (Inhoff & Liu, 1998; see also Yan, Zhou, Shu, & Kleigl, 2015) compared with 3-4 letters to

5   the left of fixation and 14-15 letters to the right (McConkie & Rayner, 1975, 1976; Rayner,

6   Well, & Pollatsek, 1980) in English. This smaller perceptual span is likely a consequence of

7   the increased visual complexity of written Chinese, relative to English. In particular, there are

8   no spaces to mark word boundaries, and so readers must depend on lexical knowledge to

9   segment characters into words (Li, Rayner, & Cave, 2009; Wei, Li, & Pollatsek, 2013).

10 Individual characters can also contain many individual strokes (e.g., 鸛 ["guan"], meaning

11 "stork"), making them visually dense. Further, characters typically carry more complex

12 linguistic information (Inhoff & Liu, 1998; Liu, Angele, Luo, & Li, 2018) such that a single

13 character can convey complex meaning which may require many letters in English. The

14 increased complexity of written Chinese relative to languages such as English may pose

15 unique difficulty to older readers. It therefore seems clear that exploring parafoveal

16 processing in a visually dense language such as Chinese may be crucial to understanding

17 cross-language variation (or similarity) in age-related reading difficulty. Particularly as

18 evidence already suggests these characteristics of the Chinese script are a source of difficulty

19 for older adults during normal reading (S. Li et al., 2018; L. Li et al., 2019; Zang et al.,

20 2016).

21   In addition to the Chinese perceptual span being smaller in size, the factors

22 determining the size of the span may also differ from alphabetic languages. Specifically,

23 there is interesting evidence that, across a range of typical font sizes (O'Regan, 1983) the

24 span for alphabetic languages is unrelated to letter size (and so, visual acuity) due to an

25 almost perfect trade-off between the increase of letter visibility with large font size and the

1   decrease of visual acuity with the large text becoming more eccentric (O'Regan, 1990). This

2   has been demonstrated using parafoveal magnification to offset acuity limitations (Miellet,

3   O'Donnell & Sereno, 2009), and more standard perceptual span paradigms (Yan, Zhou, Shu

4   & Kliegl, 2015, Experiment 2). In contrast, research suggests that the perceptual span in

5   Chinese is modulated by font size, such that the perceptual span is smaller when the text is

6   larger (Yan et al., 2015, Experiment 3, see also Shu, Zhou, Yan & Kliegl, 2011.)

7   In Yan et al's (2015) study, text was presented either entirely normally (unmasked) or

8   with one character to the left of fixation and three characters to the right presented normally

9   and the remaining characters masked with visually similar characters. The aim was to directly

10   examine the processing of parafoveal information for three font sizes: small, medium or large

11   (corresponding to 0.7°, 1.0°, and 1.3° of visual angle per-character). They found that the

12   disruption resulting from the parafoveal mask was greatest in the small font condition and

13   smallest in the large font condition, such that in the large font condition, reading speeds were

14   similar to in the unmasked condition. This reduction in disruption was taken to indicate more

15   limited parafoveal processing for large characters. Yan et al (2015) concluded that the

16   presence of spaces in alphabetic languages plays a key role in guiding the eyes across a range

17   of font sizes, even when acuity is low (e.g., McConkie, Kerr, Reddix, & Zola, 1988; Reichle,

18   Rayner, & Pollatsek, 1999; Shu, et al., 2011). The indication is that acuity plays a more

19   important role in parafoveal processing in Chinese than in spaced alphabetic languages as the

20   lack of spaces in written Chinese, coupled with the greater complexity of the characters,

21   makes characters in eccentric positions particularly hard to process.

22   It is this finding that is of central interest in the current experiments as if the size of

23   the perceptual span for Chinese is determined by visual acuity, we may expect these effects

24   to be enhanced for older adults. It is well documented that older adults have poorer visual

25   capabilities due to declines that occur naturally in later life and these declines are greater

1   outside of central vision (for a review, see Owsley, 2011). In addition, older adults

2   experience a loss of sensitivity to fine visual detail (Crassini et al., 1988; Elliott, Whitaker, &

3   MacVeigh, 1990), a loss of contrast sensitivity (e.g., Wright and Drasdo, 1985), and an

4   increase in sensitivity to visual crowding (Scialfa, Cordazzo, Bubric, & Lyon, 2013), all of

5   which may limit their ability to resolve the identity of individual characters. Research in

6   English suggests that older adults read more slowly when text is very small or very large

7   (.15° and 12° per character, respectively, Akutsu, Legge, Ross, Schuebel, 1991). Moreover,

8   such effects may be enhanced in Chinese due to visual complexity and the lack of spaces.

9   Therefore, older Chinese adults' overall reading speed may benefit from having text

10   presented in a larger font. However, as age-related declines in visual acuity are more

11   pronounced in the parafovea, older adults may have particular difficulty in recognizing large

12   font size characters parafoveally due to their eccentricity as fewer large characters can

13   occupy foveal vision and the uncrowded window (Pelli, & Tillman, 2008). Older readers

14   therefore may have a larger font size effect on the processing of parafoveal information

15   compared with young adults, and so may have a smaller perceptual span for large characters,

16   despite possibly having faster reading speeds due to the greater ease of identifying these

17   characters foveally. No studies to date have investigated this issue for older adults. However,

18   if older Chinese readers do show reduced parafoveal processing for large text, this may

19   represent an important cross-linguistic difference in the manifestation of age-related reading

20   difficulty. Therefore, in order to fully understand the relationship between acuity, attention

21   and the perceptual span across different writing systems, it is crucial to examine font size

22   effects on parafoveal processing for both older and young Chinese readers.

23   The key aim of the current experiments was to compare the effect of font size on

24   parafoveal processing for the two age groups, and not to provide a comprehensive

25   investigation of the size of the perceptual span. As such, the window size used in the masked

1   condition was selected to match that employed by Yan et al (2015) and to roughly match the

2   size of the perceptual span reported in previous experiments for young adults (one character

3   available to the left of fixation and three to the right). However, the current study may also

4   provide an important initial indication of whether the perceptual span changes in older age.

5   Accordingly, we manipulated font size (small, medium and large characters) in

6   different viewing conditions (masked and unmasked) in two Experiments. We anticipated, in

7   line with previous research, that older adults would read more slowly than their younger

8   counterparts. In line with findings for alphabetic languages (e.g., Akutsu et al., 1991) we also

9   anticipated that older adults may read particularly slowly when font size is small. With

10   respect to the masking manipulation, for young adults, we expected to replicate the findings

11   of Yan et al (2015), that is, the difference in reading times between unmasked and masked

12   conditions would be largest for small font size characters and decrease with increasing font

13   size, indicating a reduction in the perceptual span with increasing character size. Most

14   importantly, we aimed to examine whether the effect of font size on the parafoveal

15   processing differs in older age. A larger font size effect for older adults, such that the

16   reduction in disruption between the masked and unmasked condition for large characters is

17   greater for this age group, may indicate a greater decrease in the size of the perceptual span

18   with increasing character size.

19   Method

20   This research was approved by the research ethics committee of the Faculty of

21   Psychology at Tianjin Normal University and conducted in accordance with the principles of

22   the Declaration of Helsinki.

23   *Participants.* Participants were 48 young adults from Tianjin Normal University and

24   48 older adults from a residential home in Tianjin. All participants completed both

25   Experiment 1 and Experiment 2, and testing on Experiment 2 began around one month after

1   the completion of Experiment 1. All were native Mandarin Chinese readers, assessed for

2   educational background, interest in reading and visual and cognitive abilities, as described

3   below. A summary of the participant characteristics is shown in Table 1. The age groups

4   were closely matched on years of formal education and all participants reported reading for

5   several hours per-week. Participants were screened for high-contrast acuity (corrected acuity

6   of > 20/40 in Snellen values) using a Tumbling E eye-chart (Taylor, 1978), and as is typical

7   (Elliott, Yang, & Whitaker 1995), acuity was higher for young than older adults. Participants

8   were also screened for non-impaired cognition using the Beijing version of the Montreal

9   Cognitive Assessment (Nasreddine et al., 2005), applying an exclusion criterion of < 26/30.

10   Vocabulary and working memory capabilities were assessed using the Vocabulary

11   Knowledge Test from the WAIS-III Chinese version (Wechsler, Chen, & Chen, 2002) and

12   the WAIS-III forward and backward Digit Span subtest (Wechsler, 1997). Raw vocabulary

13   scores were slightly higher for older adults (though scaled scores did not differ). However,

14   raw scores for both forward and backward digit span were lower for the older adults, as is

15   typical for these age-groups (Ryan, Sattler, & Lopez, 2000).

16   Insert Table 1

17   Simulations of statistical power were conducted using the simR package in R (Green

18   & MacLeod, 2016). We selected the participant number to match Yan et al.'s study (2015)

19   and then conducted analyses to ensure that this design provided sufficient power. The power

20   to detect effects of viewing condition, and font, and the interaction of viewing condition and

21   font (L vs. M; M vs. S) were assessed based on means and standard deviations for fixation

22   duration from Yan et al. (2015). (Note that Yan et al.'s (2015) study only included young

23   adults). These analyses confirmed that this design was sufficiently powered (> 99%).

24   *Materials and Design*. One hundred and Ninety-two sentences were constructed as

25   reading material. These were between 15 and 24 characters and 8 and 14 words long. Of

1   these sentences, 96 were used in Experiment 1, another 96 were used in Experiment 2. In

2   each Experiment, participants read 16 sentences in each condition, and across participants

3   each sentence was shown in every experimental condition. The experimental sentences were

4   preceded by 10 practice items in each experiment.

5   The sentences were presented using a gaze-contingent moving-window paradigm in

6   which text outside the window region was masked. The study used a 2 (age-group: older

7   adults and young adults) × 2 (viewing condition: unmasked and masked) × 3 (font size: 32,

8   42, and 56 pixels; corresponding to 0.7°, 1.0°, and 1.3° of visual angle per-character,

9   respectively) mixed design. In order ensure comparability with previous research, viewing

10   condition and font size were chosen to match those used in Yan et al.'s (2015) study. The

11   masked viewing condition allowed readers to obtain correct character information from one

12   character to the left of the fixated character and its three successive characters to the right of

13   it.

14   In Experiment 1, characters outside the window of visible text were masked with

15   pseudo-characters (characters formed from components found in Chinese characters but not a

16   real character in Chinese). (See Figure 1). The average number of strokes contained in each

17   character was slightly higher for pseudo-characters compared to the original characters (i.e.

18   the characters presented in the normal condition, $M = 8.3$ for original, $M = 9.8$ for masking

19   pseudo-characters, $p < .01$). The pseudo-characters were created with the character editor on

20   a Window system laptop. A norming task with 10 young and 10 older adults (none of whom

21   participated in the main experiment), where participants were asked to indicate whether the

22   presented character was a real character or not, confirmed that participants were able to

23   successfully identify these characters as pseudo-characters ($M = 95\%$).

24   In Experiment 2, characters outside the window of visible text were masked with

25   visually-similar characters (See Figure 1). Visual similarity was achieved by matching shapes

1   and structures between original characters and their corresponding masking characters. As

2   shown in Figure 1, original characters were substituted by masking characters with the same

3   layouts (i.e., horizontal, vertical, or surround). Characters were matched in number of strokes

4   ($M = 8.3$ for original, $M = 8.3$ for masking similar characters) and character frequency ($M =$

5   665 per million for original, and $M = 664$ per million for masking). The frequency analysis is

6   based on the Modern Chinese corpus: http://www.cncorpus.org/. Visual complexity (i.e.

7   number of strokes) and frequency were controlled both within and outside the visible window

8   of text. None of the masking characters provided a meaningful continuation of the text

9   beyond the experimentally defined window.

10   *Apparatus and Procedure.* Sentences were displayed as black text on a white

11   background in Song font on a 24-inch high-definition BenQ monitor (1920 x 1080 resolution,

12   144Hz refresh rate). The time taken for the display change to complete was ~9ms. The

13   viewing distance used in the experiment was 75cm. Eye movements were recorded using an

14   EyeLink 1000 plus eye-tracker (SR Research), using the tower mount, with a spatial

15   resolution of .01° and the position of each participant's right eye sampled at 1000Hz. A chin

16   and forehead rest were used to minimize head movements. Although viewing was binocular,

17   only right eye movements were recorded.

18   At the start of the experiment, participants were instructed to read normally and for

19   comprehension. The eye-tracker was calibrated for each participant using a 3-point horizontal

20   calibration to ensure spatial accuracy $< .40°$. At the start of each trial, a fixation cross was

21   presented to the left of the screen. To avoid having to vary the level of fixation accuracy

22   required to trigger the sentence, the cross was the same size in all conditions (equal in size to

23   one medium font character). Once the participant fixated this location, a sentence was

24   presented, with the first character replacing the cross. Participants pressed a response key

25   once they finished reading each sentence. On one-third of trials, the sentence was then

1   replaced by a yes/no comprehension question, to which participants responded by pressing a

2   response key. Calibration was checked between trials and the eye-tracker was recalibrated as

3   necessary.

4   *Data analysis.* Comprehension accuracy was high for all participants (Experiment 1:

5   young adults, $M = 90.3\%$; older adults, $M = 92.8\%$; Experiment 2: young adults, $M = 95.2\%$;

6   older adults, $M = 96.5\%$, min: 81%) and did not differ across age groups ($ps > .05$),

7   indicating that both groups could comprehend the sentences well. Mean comprehension

8   accuracy was above 90% in all conditions and did not differ across font size or viewing

9   condition ($ps > .05$). Following standard procedures, fixations shorter than 80ms or longer

10   than 1200ms were removed (affecting 5.0% of fixations for Experiment 1 and 4.6% in

11   Experiment 2), and trials were removed if they were terminated prematurely, if track loss

12   occurred or if very few fixations were made (< 5 fixations, affecting $< 1\%$ trials in each

13   experiment).

14   Data were analyzed with Linear Mixed-Effects Models (LMMs, Baayen, Davidson, &

15   Bates, 2008) using R (R Development Core Team, 2016) and the lme4 package (Bates,

16   Maechler, & Bolker, 2014). Following current practice, a maximal random effects model was

17   used where possible (Barr, Levy, Scheepers, & Tily, 2013). If the maximal model did not

18   converge, the model was trimmed by first trimming the random structure for items, starting

19   with removal of the random effect correlations, then the random slopes. Participants and

20   items were specified as crossed random effects. Contrasts to examine effects of age-group

21   (young vs. older), viewing condition (unmasked vs. masked), and font size (large vs.

22   medium, and medium vs. small) were defined using sliding contrasts in the MASS package

23   (Venables & Ripley, 2002; sliding contrasts were employed both for main effects and to

24   examine interactions).

25   Further contrasts comparing the large font size versus the small font size were also

1   conducted; however, the pattern of results was very similar for the medium versus small

2   contrast, and so, for brevity, these are reported in the Supplemental files. Following reviewer

3   suggestion, additional models were also constructed with (centered) acuity and digit span

4   scores included as continuous variables and model comparison was used to determine

5   whether these variables should be included in the reported models. For both Experiments 1

6   and 2, including acuity did not improve model fit for any measure (in all cases $p > .18$). In

7   both experiments, a larger digit span was associated with shorter fixation durations

8   (Experiment 1: $b = -3.28$, $SE = 1.28$, $t = -2.57$, Experiment 2: $b = -3.54$, $SE = 1.35$, $t = -2.62$.

9   However, digit span did not interact with age, font or viewing condition. Where adding digit

10   span improved model fit, the pattern of effects was the same as for the base models in which

11   digit span was not included. For simplicity, these variables are not discussed further and the

12   remaining results report models without acuity or digit span.[i]

13   Sentences reading time is the main measure of interest[2]. In addition, to provide greater

14   insight into the time course of these effects, several additional sentence-level measures were

15   examined: average fixation duration (the mean duration of all fixations); progressive saccade

16   length (the amplitude (in characters) of forward-moving saccades); number of regressions

17   (number of backwards movements in the text); first-pass reading time (the sum of fixations

18   that occurred the first time a word was encountered) and re-reading time (the sum of fixations

19   on words after first-pass). As the pattern of results was consistent across measures, for

20   simplicity, sentences reading time, average fixation and progressive saccade length are

21   reported in the main text, while number of regressions, first-pass reading time and re-reading

22   time are reported in Supplemental files. Analyses for both untransformed and log-

23   transformed data produced the same patterns of results, and so only results for untransformed

24   data are reported. Following convention, $t > 1.96$ were considered significant.

25   Experiment 1

1   In the current experiment, we first aimed to verify the effect of font size of the

2   processing of parafoveal information found for young adults in Yan's study, and further

3   explore whether there are age differences in this effect.

4   *Results.* Means and standard errors for eye movement measures are shown in Table 2.

5   The results of LMM analyses are summarized in Table 3. Follow-up contrasts are

6   summarized in the text and statistical values are included in the Supplemental files. Plots

7   showing sentences reading time are shown in Figure 2. Compared with young adults, older

8   adults read more slowly and made longer fixation durations. These findings suggest that the

9   older adults experienced greater reading difficulty and resonate with previous findings on

10   adult age differences in eye movements when reading Chinese or alphabetic languages (e.g.,

11   Li et al., 2018; Wang et al., 2018a, b; Warrington et al., 2018, 2019; Xie et al., 2019). Also

12   consistent with previous findings for Chinese language reading, the older adults made shorter

13   progressive saccades compared with the young adults (e.g., Li et al, 2018; Wang et al, 2018a,

14   b; Xie et al, 2019), indicating that the older readers moved their eyes more cautiously.

15   Insert Table 2 and 3 and Figure 2

16   Further, the effect of viewing condition replicated previous findings (Yan et al.,

17   2015). When rightward vision was limited to three characters, readers exhibited longer

18   reading times, longer average fixation durations, and shorter progressive saccades. Thus,

19   reading was disrupted when text to the right of the fixated word was limited to three

20   characters and suggests that readers acquire parafoveal information at least four characters to

21   the right of fixation.

22   These effects of viewing condition further interacted with age. Follow-up contrasts

23   showed significant effects of viewing condition for both age groups, with longer reading

24   times and longer fixation durations for the masked condition compared with unmasked

25   condition, $ts > 1.96$. However, these effects of viewing condition were larger for the young

1   adults (sentences reading time: young adults = 558-ms effect, older adults = 387-ms effect;

2   average fixation duration: young adults = 17-ms effect, older adults = 11-ms effect)

3   compared with the older adults. In addition, there was a significant difference in progressive

4   saccade length between unmasked and masked viewing condition for younger, but not for

5   older adults. These results provide evidence to suggest that both young and older adults can

6   process parafoveal information at least four characters to the right of fixation when characters

7   are masked by pseudo-characters. However, as these effects are larger for young adults, there

8   may be age-group differences in the size of the perceptual span, or in the depth of parafoveal

9   processing undertaken across the span. Further research is needed to establish this.

10   Moreover, main effects of font size were also significant. Increasing character size

11   significantly decreased reading times, average fixation durations and the length of

12   progressive saccades. Font size effects were qualified by interactions with age-group in all

13   measures. Follow-up contrasts for average fixation duration showed significant effects of font

14   size for both age groups, with longer fixation durations for smaller font size compared with

15   larger, *ts* > 1.96. These effects were larger for older, compared to young adults (large vs.

16   medium: young adults = 11-ms effect, older adults = 18-ms effect; medium vs. small: young

17   adults = 10-ms effect, older adults = 23-ms effect). For the sentences reading time, further

18   contrasts revealed that reading times for smaller font characters were significantly longer

19   than for larger font characters for older, but not young adults (large vs. medium: young adults

20   = 24-ms effect, older adults = 126-ms effect; medium vs. small: young adults = 21-ms effect,

21   older adults = 199-ms effect). Similarly, for the progressive saccade length, there was

22   significant difference in large and medium font size for older, but not young adults. Overall,

23   young adults' reading behaviour was quite consistent across different font sizes. However,

24   for older adults, reading times decreased as font size increased. This indicates that older

25   adults may experience difficulty processing small characters. This likely reflects age-related

1   changes in vision and attentional mechanisms.

2   Surprisingly, there were no significant two-way interactions between font size and

3   viewing condition in any of the measures examined, suggesting that the effect of font size is

4   similar across different viewing conditions. Crucially, the absence of an interaction between

5   viewing condition and font size is in direct contrast to the findings of Yan et al. (2015) and

6   suggest that perhaps in Chinese, like in alphabetic languages, the perceptual span is

7   independent of character size. Further, a three-way interaction was only found in average

8   fixation duration. However, follow-up contrasts revealed a similar pattern of disruption for

9   each age group. Overall, the results of the LMM analyses suggests that character size does

10   not influence the acquirement of parafoveal information during the reading of Chinese for

11   either older adults, or young adults.

12   In addition to the LMM analysis, Bayes factors (Kass & Raftery, 1995) were

13   calculated for each measure to confirm the null two-way interaction between viewing

14   condition and font size and the three-way interaction between age, viewing condition, and

15   font size. These were computed using the lmBF function within the BayesFactor package

16   (Morey & Rouder, 2015) in R (R Core Team, 2015), with the scaling factor for g-priors set to

17   0.5, and using 100,000 Monte Carlo iterations. Participants and items were specified as

18   random factors. Following Vandekerckhove, Matzke, and Wagenmakers (2015), Bayes

19   factors (BFs) > 3 were taken to provide weak to moderate support for a model, and BFs > 10

20   to provide strong support, while BFs < 1 were taken to provide evidence against a model and

21   in favor of the base model. Based on the LMM analysis, we constructed a denominator model

22   (base model to which other models were compared) for each measure. The Bayes factor

23   analysis favored the denominator model over either a model containing a two-way interaction

24   between viewing condition and font size (sentences reading time, BF = 0.004, average

25   fixation duration, BF = 0.004, progressive saccade length, BF = 0.011) or a model containing

1   a three-way interaction (sentences reading time, BF = 0.005; progressive saccade length, BF

2   = 0.011), suggesting that the perceptual span is independent of the font size for both age

3   groups. In addition, in line with the LMM analysis, Bayesian analysis for average fixation

4   duration provided moderate support for a model including a three-way interaction (BF =

5   6.980). To sum, the Bayes Factor analysis confirmed the LMM analysis findings and

6   provided evidence for the absence of a font size effect on the acquirement of parafoveal

7   information.

8   *Discussion.* In the current study, we aimed to replicate the effect of font size on the

9   acquirement of parafoveal information in Chinese reading reported by Yan et al. (2015).

10   More importantly, we aimed to explore whether there are age differences in this effect.

11   However, in Experiment 1, we failed to obtain evidence for a notion that the perceptual span

12   depends on font size during Chinese reading for either age group, as most interactions

13   between age, viewing condition and font size were far from significance. Overall, the

14   findings in Experiment 1 give little evidence to show that character size has an effect on the

15   acquirement of parafoveal information during Chinese reading. Therefore, this would suggest

16   that older Chinese readers can successfully process parafoveal information across range of

17   font sizes and that older adults' parafoveal processing may be more robust than previously

18   assumed. If this is the case, age-related limitations in parafoveal acuity may not limit

19   parafoveal processing in older age.

20   However, it is worthy to note that we adopted different mask stimuli from the ones

21   used in Yan et al.'s (2015) study. In Experiment 1, each character outside the window of

22   legible text was masked by a pseudo-character. These characters were generally more

23   complex than the characters within the window, creating a difference in the average stroke-

24   complexity within and outside of the defined window. This transition in complexity could

25   have affected oculomotor activity even if it occurred to the right of the effective range of

1   vision (Inhoff & Liu, 1998). Moreover, previous moving-window studies demonstrate that

2   the size of the perceptual span of young adults is dynamically influenced by the type of

3   masking stimuli (Yan, Zhang, Zhang, & Bai, 2013, note that this study is published in the

4   Chinese language). This may be because visually-similar masks effectively provide useful

5   parafoveal orthographic information, which is known to facilitate the subsequent foveal

6   processing (Yan et al., 2015). The information provided by the pseudo-characters is not real

7   information. Moreover, as the pseudo-character was unrelated to the masking character, it

8   could not provide any useful orthographic information for pre-processing (e.g, see

9   parafoveal-on-foveal effect, Drieghe, 2011) which may increase processing difficulty, and

10   prove distracting. Considerable evidence suggests that older adults are typically more

11   susceptible to external distraction than young adults (e.g., Kemper & McDowd, 2006; Mund,

12   Bell, & Buchner, 2010; Meijer, de Groot, Van Boxtel, Van Gerven, & Jolles, 2006). Certain

13   types of text replacement, such as pseudo-characters, may interfere with normal reading and

14   the font size effects on the perceptual span, moreover, this interference may be more marked

15   for older than young adult readers. Therefore, in order to provide a direct replication of Yan

16   et al.'s (2015) study, and to further explore whether there is an effect of font size on the

17   perceptual span for both older and young adults, Experiment 2 employs a visually-similar

18   character-replacement.

19   Experiment 2

20   The results of Experiment 1 provided a suggestion that there is no effect of font size

21   on parafoveal processing for either older adults, or young adults. As these results are in

22   contrast to previous findings, we aimed to examine this issue further. Therefore, Experiment

23   2 examined whether the perceptual span depends on font size, and whether the nature and

24   size of these effects differs across age groups, when characters are replaced by visually-

1   similar characters. The design of this experiment is identical to that employed by Yan et al,

2   with the addition of the older adult group.

3   *Results.* Means and standard errors are shown in Table 2. The results of LMM

4   analyses are summarized in Table 4. Follow-up contrasts are summarized in the text and

5   statistical values are included in the supplemental files. Plots showing sentences reading time

6   are shown in Figure 3. In line with Experiment 1, main effects of age-group were obtained in

7   all measures. This again suggests that older adults experienced greater reading difficulty than

8   young adults. There were also significant main effects of viewing condition. In comparison to

9   the unmasked condition, the masked viewing condition produced longer reading times, longer

10   fixation durations and shorter progressive saccades.

11   Insert Table 4 and Figure 3

12   Main effects of viewing condition further interacted with age-group. Follow-up

13   contrasts revealed significant effects of viewing condition for both age groups, $ts > 1.96$.

14   However, these effects of viewing condition were larger for the young adults (sentence

15   reading time: young adults = 972-ms effect, older adults = 447-ms effect; average fixation

16   duration: young adults = 25-ms effect, older adults = 12-ms effect), compared with their older

17   counterparts. As in Experiment 1, there was significant difference in progressive saccade

18   length between unmasked and masked viewing condition for younger, but not for older

19   adults. In line with Experiment 1, results indicate that both age groups utilize parafoveal

20   information to the right of fixation, however there may be age differences in the processing

21   of parafoveal information which require further investigation.

22   The effect of font size on eye movements nicely replicate Experiment 1. Increasing

23   font size significantly decreased fixation durations and progressive saccade length. Moreover,

24   smaller font size characters produced longer reading times. The main effects of font size were

25   qualified by interactions with age-group. Follow- up contrasts revealed, in line with

1   Experiment 1, that older adults experienced exhibited longer reading times when the font was

2   smaller, while young adults reading times were consistent across font sizes.

3   Crucially, in line with Experiment 1, but in contrast to the finding of Yan et al. (2015)

4   there were no interactions between viewing condition and font size, and no three-way

5   interactions, $t_s < 1.96$. As in Experiment 1, the Bayes Factors analysis were also calculated to

6   confirm the null two-way interaction between viewing condition and font size and null three-

7   way interaction. The denominator models were again constructed based on the LMM analysis

8   for all the measures. These analyses favored a model with no three-way interaction

9   (sentences reading time: BF = 0.015, average fixation duration: BF = 0.007, progressive

10 saccade length, BF = 0.021), and no two-way interaction between viewing condition and font

11 size (sentences reading time: BF = 0.009, average fixation duration: BF = 0.004, progressive

12 saccade length: BF = 0.018). Again, the Bayes Factor analysis supports the LMM analysis

13 and suggests an absence of a font size effect on the acquirement of parafoveal information for

14 both age groups.

15   *Discussion*. Experiment 2 further investigated aging and the font size effect on

16 parafoveal processing by masking characters outside the window of normal text with

17 visually-similar characters. Crucially, in line with the findings of Experiment 1, there were no

18 two-way interactions between viewing condition and font size and no three-way interaction

19 between age, viewing condition and font size. Thus, the size of the perceptual span during the

20 reading of Chinese appears to remain largely stable across font size. The current results are

21 not consistent with Yan et al.'s (2015) study for young adults. Possible reasons for this are

22 considered in the General Discussion. These results demonstrate that older Chinese readers

23 can successfully process parafoveal information across range of font sizes. Furthermore, this

24 work extends previous findings to suggest that the font size has no effect on the acquirement

25 of parafoveal information for both young and older adult readers during Chinese reading.

1   General Discussion

2   The present study explored effects of font size on the perceptual span for older and

3   young adults during Chinese reading to test whether older adults' parafoveal processing is

4   more limited for larger font characters. We anticipated that older readers of Chinese may

5   experience particular difficulty processing large characters and that this may represent an

6   important source of age-related reading difficulty in logographic languages. To investigate

7   this, we manipulated the font size and the amount of parafoveal information available with

8   different masking stimuli in two experiments. These experiments yielded several key

9   findings: (1) Compared with young adults, older adults experience reading difficulty during

10   Chinese reading; (2) Both young and older adults read more slowly when parafoveal

11   information is limited to one character to the left of fixation and three characters to the right

12   of fixation; (3) Older adults experience greater reading difficulty when text is small, while

13   reading times are quite consistent across font sizes for young adults; (4) Both experiments

14   demonstrated that the effect of parafoveal masking is similar across font sizes for both older

15   and young adults, providing evidence that perceptual span size in Chinese is independent of

16   font size and that older adults can successfully process a similar amount of parafoveal

17   information across a range of font sizes. Each of these findings is discussed in turn.

18   In these experiments older adults read more slowly, made longer fixations, and

19   shorter progressive saccades compared with young adults. This replicates age-related

20   differences in eye movement behavior reported in earlier studies and contributes to the

21   growing body of evidence demonstrating that older readers of Chinese experience greater

22   reading difficulty than their younger counterparts (e. g., Li et al., 2018; Wang et al., 2018a, b;

23   Xie et al., 2019).

24   The results also suggest that when parafoveal information is masked by either pseudo-

25   characters or visually-similar characters, both young and older adults make substantial use of

1   parafoveal information to inform their reading. As we did not directly investigate perceptual

2   span size, we cannot make strong claims about the exact size of the span. However, it appears

3   to subtend at least four characters to the right for both older and young adults based on the

4   present findings. However, the results also suggest there may be age-group differences in the

5   extent of the perceptual span, or in the depth of processing undertaken across the span.

6   Findings from alphabetic languages have produced inconsistent results with respect to age

7   differences in parafoveal processing. It will be important for future research to establish

8   whether there are cross-linguistic differences in such effects as this will inform our

9   understanding of the generalizability of principles about how cognitive aging affects

10   language processing. Further, research using a range of mask sizes and types is needed to

11   establish whether there are truly differences in the perceptual span or whether this reflects

12   some other age differences such as sensitivity to visual information outside the masked area

13   which does not affect the perceptual span (see, e.g., Jordan, Kurtev, McGowan, & Paterson,

14   2016).

15   Both Experiments also show effects of font size on eye movement behavior. Notably

16   for young adults, reading times were invariant across font size, while older adults had shorter

17   reading times when reading larger font size characters compared with smaller characters.

18   These results therefore provide an indication that effects of font size vary across the adult

19   lifespan in Chinese reading, as in English (Akutsu et al., 1991). This is an important

20   consideration for future research, as researchers should ensure that they use a font size

21   sufficiently large for older adults to achieve their full reading performance. These results

22   likely reflect the visual and attentional changes that occur in older age. Decreased sensitivity

23   to fine visual detail (Crassini et al.,1988), may make the encoding of small characters less

24   efficient, and changes in information processing and visual attention (Madden, 2007) may

25   increase the time taken to process the large amount of information that is available in foveal

1   vision.

2   Despite older adults' shorter reading times when the font is larger, we anticipated that

3   as a result of age-related declines in parafoveal visual vision and increased sensitivity to

4   visual crowding (e.g. Crassini et al, 1988; Elliott et al.,1990), older adults would show

5   reduced effects of parafoveal masking as font size increased, indicating a smaller perceptual

6   span for large font characters. However, the absence of three-way interactions between age-

7   group, viewing condition, and font size, indicates that, contrary to expectation, older adults

8   do not have a larger font size effect on the perceptual span compared with young adults. This

9   finding provides an important indication that in spite of age-related visual difficulty, older

10 readers do not have greater difficulty processing parafoveal information when text is

11 presented in large fonts, despite these large characters appearing at greater eccentricity than

12 smaller characters. It has typically been assumed (e.g., Ball, Beard, Roenker, Miller, &

13 Griggs, 1988; Sekuler, Bennett, & Mamelak, 2000) that older adults' poorer acuity in the

14 parafovea may limit their ability to process information parafoveally and that this may slow

15 reading. These results dispute this assertion, as older adults are able to successfully

16 parafoveally process eccentric large font characters. It has previously been argued that older

17 adults of alphabetic languages may dynamically modulate the deployment of their attention

18 to compensate for age-related limitations of visual acuity (Risse & Kliegl, 2011), in order to

19 prioritize parafoveal processing (while making longer individual fixations). Such a strategy

20 may allow older adults to maintain parafoveal processing across font sizes and this may

21 represent a general strategy that is employed by older readers from a range of languages.

22 However, to more fully understand the universality of the role of acuity on parafoveal

23 processing in older age, these effects should also be investigated in alphabetic languages.

24   While we do not find evidence of an age difference in font size effects on parafoveal

25 processing, one clear difficulty in the interpretation of these results for older adults is that

1   while we did not find a three-way interaction, we also found no two-way interactions

2   between viewing condition and font size. Taken together, these results suggest that the

3   perceptual span in Chinese reading does not depend on font size, and therefore, visual acuity,

4   for either young or older adults. These results could indicate that, like alphabetic language

5   reading, a trade-off between the increase of character visibility with large font size and the

6   decrease of visual acuity with the large text becoming more eccentric results in a similar span

7   size across different font sizes (e.g. Miellet et al., 2009).

8   This suggests that in Chinese, as in English, the key factor limiting the perceptual

9   span is attentional rather than visual constraints, with the physical size of the span adapting to

10   the amount of information to be processed (as evidenced by the smaller span for Chinese

11   compared with English). However, to fully establish this, further experiments may seek to

12   modulate foveal processing demands (foveal load) during Chinese reading. Such experiments

13   may be particularly illuminating as older readers of English show greater sensitivity to foveal

14   load (e.g. Payne and Stine-Morrow, 2012). Therefore, it would be valuable to establish

15   whether any age differences in parafoveal processing may be attention, rather than acuity

16   based.

17   Yan et al reported that their results reflect the lack of spaces and greater complexity of

18   written Chinese making characters in eccentric positions (such as large font characters)

19   particularly hard to process. It has been suggested that Chinese readers may develop higher

20   parafoveal processing efficiency compared with alphabetic language readers, because of the

21   absence of spaces (Zhou, Kliegl, Yan, 2013). Thus, the lack of word boundaries in written

22   Chinese is not a major obstacle to parafoveal processing as evidence suggests that the size of

23   the perceptual span varies as a function of reading efficiency (Rayner et al., 2010), and so this

24   increased efficiency may allow both young and older skilled readers to successfully move

25   their eyes across a range of font sizes even in the absence of spaces.

1   However, it is unclear why Yan found this effect, yet we failed to. Further work is

2   needed to establish this; however we consider a few possibilities. Notably, the average

3   reading speed in Yan et al., (2015) was considerably slower than the speeds in the current

4   experiments. A recent meta-analysis (Brysbaert, 2019) estimates average word-per-minute

5   (wpm) reading rates for Chinese at 260wpm. Based on the information provided in Yan's

6   paper, we estimate the wpm reading rate in the unmasked condition as around 170 (across

7   font sizes). Whereas, when we convert our reading times to reading rates, we find rates more

8   in line with the estimates given by Brysbaert (Exp1: 272wpm; Exp2: 251wpm). Readers

9   allocate more processing resources to the foveally fixated word and engage less in parafoveal

10   processing of upcoming text when they have greater difficulty processing words (e.g.,

11   Häikiö, Bertram, Hyönä, & Niemi, 2009; Rayner, 1986; Sperlich et al., 2016; Chace, Rayner,

12   & Well, 2005; Rayner et al., 2010; Veldre & Andrews, 2014). Note, that while older adults

13   are also slower readers, they are generally considered to be skilled readers who read with

14   normal comprehension, but at a slower rate than their younger peers (Rayner et al., 2010) due

15   to age-related decline, rather than lower skill. This may indicate that the readers in Yan et al's

16   (2015) study were less efficient processers and so may have experienced greater difficulty

17   guiding their eyes across a range of font sizes in the absence of word spacing. However,

18   additional analyses considering fast and slow readers in the current experiments separately

19   (based on sentence reading times) found no evidence of a font size effect on parafoveal

20   processing for slower readers, despite our slow readers showing similar reading speeds to the

21   participants in Yan et al. (2015). As these analyses involved splitting the dataset, we cannot

22   rule out that this effect may be present with greater statistical power, but we did not observe

23   any trends within our dataset. These analyses are reported in full in the Supplemental files.

24   An alternative interpretation is that because the perceptual span is larger than the

25   masked viewing condition substantial disruption is found in all conditions. As readers could

1   preview more than three characters even when reading largest font size text, a larger viewing

2   condition may reveal more subtle font size effects obscured in this study. Overall, while we

3   cannot exclude the possibility that more subtle font size effects may exist when using

4   different masking stimuli or different mask sizes, at least when using masks that provide

5   orthographic information, with a mask size that roughly matches the typical perceptual span

6   size reported for Chinese, these effects do not appear to be present. Therefore, even if more

7   subtle effects do exist, the clear finding is that an inability to process parafoveal information

8   across a range of font sizes is unlikely to be a major contributory factor to adult age

9   differences in Chinese reading. This finding has important implications for understanding the

10   nature of adult age differences in reading across different writing systems.

11   In summary, while previous research has focused almost exclusively on alphabetic

12   languages, the present study provides novel insight into parafoveal processing across

13   adulthood during Chinese reading. The overall pattern of results suggests that during normal

14   reading, as in English, the perceptual span is independent of font size for both young and

15   older adults. Crucially, in spite of age-related visual decline, older adults' parafoveal

16   processing appears unaffected by font size. Therefore, the current experiments have furthered

17   our knowledge of effects of normative aging on Chinese reading and indicate that older

18   adults' parafoveal processing may be more robust than previously considered.

1
2   References

3   Akutsu, H., Legge, G. E., Ross, J. A., & Schuebel, K. J. (1991). Psychophysics of reading--x.

4   effects of age-related changes in vision. *Journal of Gerontology, 46*(6), P325-P331.

5   doi: 10.1093/geronj/46.6.P325

6   Apel, J. K., Henderson, J. M., & Ferreira, F. (2012). Targeting regressions: Do readers pay

7   attention to the left? *Psychonomic Bulletin & Review*, *19*, 1108–1113.

8   doi:10.3758/s13423-012-0291-1

9   Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed

10   random effects for subjects and items. *Journal of Memory and Language, 59*, 390–412.

11   http://dx.doi.org/10.1016/j.jml .2007.12.005

12   Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and

13   visual search: Expanding the useful field of view. *Journal of the Optical Society of*

14   *America A: Optics, Image Science, and Vision, 5*, 2210–2219.

15   Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for

16   confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language,*

17   *68*, 255–278. http://dx.doi.org/10.1016/j.jml .2012.11.001

18   Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models

19   using lme4. *arXiv preprint arXiv:1406*.5823. Retrieved from http://CRAN.R-

20   project.org/package=lme4

21   Brysbaert, M. (2019). How many words do we read per minute? A review and meta-analysis

22   of reading rate. *Journal of Memory and Language, 109*, 104047.

23   Chace, K. H., Rayner, K., & Well, A. D. (2005). Eye Movements and Phonological

24   Parafoveal Preview: Effects of Reading Skill. *Canadian Journal of Experimental*

25   *Psychology/Revue canadienne de psychologie expérimentale, 59*(3), 209-217.

26   http://dx.doi.org/10.1037/h0087476

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

DeDe, G., & Flax, J. K. (2016). Language comprehension in aging. *Language, Cognition and Aging,* 107-133.

Drieghe, D. (2011). Parafoveal-on-foveal effects on eye movements during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), Oxford library of psychology. The Oxford handbook of eye movements (pp. 839-855). New York, NY, US: Oxford University Press.

Elliott, D., Whitaker, D., & MacVeigh, D. (1990). Neural contribution to spatiotemporal contrast sensitivity decline in healthy ageing eyes. *Vision Research, 30*, 541–547. http://dx.doi.org/10.1016/0042-6989(90) 90066-T

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

Green, P., & MacLeod, C. J. (2016). SIMR: An R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution, 7,* 493-498.

Häikiö, T., Bertram, R., Hyönä, J., & Niemi, P. (2009). Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of Experimental Child Psychology, 102*, 167–181. http://dx.doi.org/10.1016/j.jecp.2008.04.002

Henderson, J. M., & Ferreira, F. (1990). Effects of Foveal Processing Difficulty on the Perceptual Span in Reading. *Journal of Experimental Psychology: Learning, Memory and Cognition, 16*(3), 417–429. https://doi.org/10.1037/0278-7393.16.3.417

Inhoff, A. W., & Liu, W. (1998). The Perceptual Span and Oculomotor Activity during the Reading of Chinese Sentences. *Journal of Experimental Psychology: Human Perception and Performance, 24*(1), 20–34. https://doi.org/10.1037/0096-1523.24.1.20

Kass, R. E., & Raftery, A. E. (1995). Bayes factors. *Journal of the American Statistical Association, 90*, 773–795. http://dx.doi.org/10 .1080/01621459.1995.10476572

Kemper, S., McDowd, J. (2006). Eye movements of young and older adults while reading with distraction. *Psychology and Aging, 21*(1), 32-39. http://dx.doi.org/10.1037/0882-7974.21.1.32

Kennison, S. M., & Clifton, C. (1995). Determinants of Parafoveal Preview Benefit in High and Low Working Memory Capacity Readers: Implications for Eye Movement Control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(1), 68–81. https://doi.org/10.1037/0278-7393.21.1.68

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology, 16*(1-2), 262-284. http://dx.doi.org/10.1080/09541440340000213

Li, S., Li, L., Wang, J., McGowan, V. A., & Paterson, K. B. (2018). Effects of word length on eye guidance differ for young and older Chinese readers. *Psychology and Aging, 33*(4), 685-692. http://dx.doi.org/10.1037/pag0000258

Li, X., Rayner, K., & Cave, K. R. (2009). On the segmentation of Chinese words during reading. *Cognitive Psychology, 58*(4), 525–552. https://doi.org/10.1016/j.cogpsych.2009.02.003

Madden DJ. (2007). Aging and visual attention. *Current Directions in Psychological Science*, 16, 70–74.

1   McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation

2   in reading. *Perception & Psychophysics, 17*(6), 578–586.

3   https://doi.org/10.3758/BF03203972

4   McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading.

5   *Bulletin of the Psychonomic Society, 8*(5), 365–368.

6   https://doi.org/10.3758/BF03335168

7   McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control

8   during reading: I. The location of initial eye fixations in words. *Vision Research, 28*,

9   1107–1118.

10   McGowan, V. A., White, S. J., Jordan, T. R., & Paterson, K. B. (2014). Aging and the use of

11   interword spaces during reading: Evidence from eye movements. *Psychonomic Bulletin*

12   *& Review, 21*, 740–747. http://dx.doi.org/10.3758/s13423-013-0527-8

13   Meijer, W. A., de Groot, R. H., Van Boxtel, M. P., Van Gerven, P. W., & Jolles, J. (2006).

14   Verbal learning and aging: combined effects of irrelevant speech, interstimulus interval,

15   and education. *Journals of Gerontology, 61*(5), P285-94. doi:10.1093/geronb/61.5.

16   P285

17   Miellet, S., O'Donnell, P. J., & Sereno, S. C. (2009). Parafoveal magnification: visual acuity

18   does not modulate the perceptual span in reading. *Psychological Science, 20*(6), 721-

19   728. doi: 10.1111/j.1467-9280.2009. 02364.x

20   Morey, R. D., & Rouder, J. N. (2015). BayesFactor: Computation of Bayes factors for

21   common designs. R package version 0.9.12-2. Retrieved from http://CRAN.R-

22   project.org/package=BayesFactor

23   Mund, I., Bell, R., & Buchner, A. (2010). Age differences in reading with distraction:

24   Sensory or inhibitory deficits? *Psychology and Aging, 25*(4), 886-897.

25   http://dx.doi.org/10.1037/a0019508

Nasreddine, Z.S., Phillips, N.A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I.,

Cummings, J.L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA:

a brief screening tool for mild cognitive impairment. *Journal of the American Geriatric*

Society, 53, 695- 699. http:// dx.doi.org/10.1111/j.1532-5415.2005.53221

O'Regan, J. K. (1990) Eye movements and reading. In: *Eye movements and their role in*

visual and cognitive processes, pp. 395–453, ed. E. Kowler. Elsevier. [aEDR, rKR,

RRe]

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

http://dx.doi.org/10.1016/j.visres.2010.10.020

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013a). Filtered text reveals adult age

differences in reading: Evidence from eye movements. *Psychology and Aging, 28*, 352–

364. http://dx.doi.org/10.1037/a0030350

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013b). Effects of adult aging on reading

filtered text: Evidence from eye movements. *PeerJ, 1*, e63.

http://dx.doi.org/10.7717/peerj.63

Paterson, K. B., McGowan, V. A., & Jordan, T. R. (2013c). Aging and the control of

binocular fixations during reading. *Psychology and Aging, 28,* 789–795.

doi:10.1037/a0033328

Paterson, K. B., McGowan, V. A., White, S. J., Malik, S., Abedipour, L., & Jordan, T. R.

(2014). Reading direction and the central perceptual span in Urdu and English. *Plos*

One, 21(2), 505-511. doi: 10.1371/journal.pone.0088358

Payne, B. R., & Stine-Morrow, E. A. L. (2012). Aging, parafoveal preview, and semantic

integration in sentence processing: Testing the cognitive workload of wrap-up.

Psychology and Aging, 27(3), 638–649. https://doi.org/10.1037/a0026540

R Core Team (2015). R: A language and environment for statistical computing. R foundation

1   for statistical computing, Vienna, Austria. http://www.R-project.org

2   Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers.

3   *Journal of Experimental Child Psychology, 41*(2), 211-236.

4   http://dx.doi.org/10.1016/0022-0965(86)90037-8

5   Rayner, K., Reichle, E., Stroud, M., Williams, C., & Pollatsek, A. (2006). The effect of word

6   frequency, word predictability, and font difficulty on the eye movements of young and

7   older readers. *Psychology and Aging, 21*, 448–465. doi:10.1037/0882-7974.21.3.448

8   Rayner, K., Slattery, T. J., & Bélanger, N. N. (2010). Eye movements, the perceptual span,

9   and reading speed. *Psychonomic Bulletin & Review, 17*, 834–839.

10   http://dx.doi.org/10.3758/PBR.17.6.834

11   Rayner, K., Yang, J., Schuett, S., & Slattery, T. J. (2014). The effect of foveal and parafoveal

12   masks on the eye movements of older and younger readers. *Psychology and Aging, 29*,

13   205–212. doi:10.1037/a0036015

14   Reichle, E. D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading:

15   accounting for initial fixation locations and refixations within the E-Z Reader model.

16   *Vision Research*, *39*(26), 4403–4411. https://doi.org/10.1016/S0042-6989(99)00152-2

17   Risse, S., & Kliegl, R. (2011). Adult age differences in the perceptual span during reading.

18   *Psychology and Aging, 26*(2), 451-460. http://dx.doi.org/10.1037/a0021616

19   Ryan, J.J., Sattler, J.M., & Lopez S.J. (2000). Age effects on Wechsler Adult Intelligence

20   Scale-III subtests. *Archives of Clinical Neuropsychology, 15*, 311-317.

21   Scialfa, C.T., Cordazzo, S., Bubric, K., & Lyon, J. (2013). Aging and visual crowding.

22   *Journals of Gerontology Series B: Psychological Sciences and Social Science, 6,* 522-

23   528.

24   Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on the useful field of

25   view. *Experimental Aging Research, 26*, 103–120.

1 Shu, H., Zhou, W., Yan, M., & Kliegl, R. (2011). Font size modulates saccade-target

2   selection in Chinese reading. *Attention, Perception, & Psychophysics, 73*, 482–490.

3   http://dx.doi.org/10.3758/s13414-010- 0029-y

4 Sperlich, A., Meixner, J., & Laubrock, J. (2016). Development of the perceptual span in

5   reading: A longitudinal study. *Journal of Experimental Child Psychology, 146*, 181–

6   201. doi:10.1016/j.jecp.2016.02.007

7 Stine-Morrow, E. A., & Radvansky, G. A. (2017). Discourse processing and development

8   through the adult lifespan. In M. F. Schober, D. N. Rapp, & M. A. Britt (Eds.). *The*

9   *Routledge Handbook of Discourse Processes, Second Edition* (pp. 247-268). Taylor

10   and Francis.

11 Taylor, H. R. (1978). Applying new design principles to the construction of an illiterate E

12   chart. *American Journal of Optometry and Physiological Optics, 55*, 348–351.

13 Thornton, R., & Light, L. L. (2006). Language Comprehension and Production in Normal

14   Aging. In J. E. Birren & K. W. Schaire (Eds.). *Handbook of the psychology of aging*

15   (pp. 261-287). Amsterdam, Netherlands: Elsevier. http://dx.doi.org/10.1016/B978-

16   012101264-9/50015-X

17 Trueswell, J. C., Tanenhaus, M. K., &Garnsey, S. M. (1994). Semantic influences on parsing:

18   Use of thematic role information in syntactic ambiguity resolution. *Journal of Memory*

19   *& Language*, *33*, 285–318. https://doi.org/10.1006/jmla.1994.1014

20 Vandekerckhove, J., Matzke, D., & Wagenmakers, E.-J. (2015). Model comparison and the

21   principle of parsimony. In J. Busemeyer, J. Townsend, Z. J. Wang, & A. Eidels (Eds.),

22   *Oxford Handbook of Computational and Mathematical Psychology*, (pp. 300-319).

23   Oxford: Oxford University Press.

1   Veldre, A., & Andrews, S. (2014). Lexical quality and eye movements: Individual

2   differences in the perceptual span of skilled adult readers. *The Quarterly Journal of*

3   *Experimental Psychology, 67*, 703–727. doi:10.1080/17470218.2013.826258

4   Venables, W. N., & Ripley, B. D. (2002). Modern applied statistics with S (4th ed.). New

5   York, NY: Springer. http://dx.doi.org/10.1007/978-0-387-21706-2

6   Wang, J., Li, L., Li, S., Xie, F., Chang, M., Paterson, K. B., McGowan, V. A. (2018a). Adult

7   age differences in eye movements during reading: The evidence from Chinese.

8   *Journals of Gerontology: Series B, Psychological Sciences and Social Sciences, 73*(4),

9   584-593. http://dx.doi.org/10.1093/geronb/gbw036

10   Wang, J., Li, L., Li, S., Xie, F., Liversedge, S. P., & Paterson, K. B. (2018b). Effects of aging

11   and text-stimulus quality on the word-frequency effect during Chinese reading.

12   *Psychology and Aging, 33*(4). http://dx.doi.org/10.1037/pag000025

13   Warrington, K. L., McGowan, V. A., Paterson, K. B., & White, S. J. (2018). Effects of aging,

14   word frequency, and text stimulus quality on reading across the adult lifespan: evidence

15   from eye movements. *Journal of Experimental Psychology: Learning, Memory &*

16   *Cognition, 44*, 1714-1729. doi: 10.1037/xlm0000543

17   Warrington, K.L., McGowan, V.A., Paterson, K.B., & White, S.J. (2019). Effects of adult

18   aging on letter position coding in reading: Evidence from eye movements. *Psychology*

19   *and Aging. 34*(4), 598-612. http://dx.doi.org/10.1037/pag0000342

20   Wechsler, D. (1997). WAIS-III administration and scoring manual. San Antonio, TX:

21   Psychological Corporation.

22   Wechsler, D., Chen, Y. H., & Chen, X. Y. (2002). WAIS-III Chinese version technical

23   manual. San Antonio, TX: Psychological Corporation.

Wei, W., Li, X., & Pollatsek, A. (2013). Word properties of a fixated region affect outgoing

saccade length in Chinese reading. *Vision Research*, *80*, 1–6.

https://doi.org/10.1016/j.visres.2012.11.015

Whitford, V., & Titone, D. (2016). Eye movements and the perceptual span during first- and

second-language sentence reading in bilingual older adults. *Psychology and Aging,*

31(1), 58-70. http://dx.doi.org/10.1037/a0039971

Whitford, V., & Titone, D. (2017). The effects of word frequency and word predictability

during first- and second-language paragraph reading in bilingual older and younger

adults. *Psychology and Aging, 32*(2), 158-177. http://dx.doi.org/10.1037/pag0000151

Wingfield, A., & Stine-Morrow, E. A. L. (2000). Language and speech. In F. I. M. Craik &

T. A. Salthouse (Eds.), *The handbook of aging and cognition* (pp. 359-416). Hillsdale,

NJ: Erlbaum.

Wright, C. E., & Drasdo, N. (1985). The influence of age on the spatial and temporal contrast

sensitivity function. *Documenta Ophthalmologica, 59*, 385-395.

Xie, F, Li, L., Zhao, S., Wang, J., Paterson, K. B., White, S. J., Warrington, K.L. (2019).

Aging and Pattern Complexity Effects on the Visual Span: Evidence from Chinese

Character Recognition. *Vision, 3*, 11. doi:10.3390/vision3010011

Yan, G., Zhang, Q., Zhang, L., Bai, X. (2013). The effect of masking materials on perceptual

span in Chinese reading. *Journal of Psychological Science, 36*(6), 1317-1322. doi:

10.16719/j.cnki.1671-6981.2013.06.018

Yan, M., Zhou, W., Shu, H., & Kliegl, R. (2015). Perceptual span depends on font size

during the reading of chinese sentences. *Journal of Experimental Psychology: Learning

Memory and Cognition, 41*(1), 209–219. https://doi.org/10.1037/a0038097

Zang, C., Zhang, M., Bai, X., Yan, G., Paterson, K. B., & Liversedge, S. P. (2016). Effects of

word frequency and visual complexity on eye movements of young and older Chinese

1   readers. *Quarterly Journal of Experimental Psychology, 69*(7), 1409-1425.

2   doi:10.1080/17470218.2015.1083594

3   Zhou, W., Kliegl, R., & Yan, M. (2013). A validation of parafoveal semantic information

4   extraction in reading Chinese. *Journal of Research in Reading, 36,* S51–S63.

5   doi:10.1111/j.1467-9817.2013.01556.

6

7

1   Footnotes

2   [1] Note, we do not make any claims about the role of acuity or digit span in the perceptual

3   span, as it may be that the measures of acuity and digit span employed here lack the

4   sensitivity to detect such effects in reading.

5   [2] Reading rate (average number of characters read per minute) is often the key measure of

6   interest in gaze-contingent moving-window experiments and we originally intended to report

7   this measure. However, there is evidence that calculating reading rates per-unit time can

8   result in inflation of reading rates for short sentences and reading times (Trueswell,

9   Tanenhaus, & Garnsey, 1994). As this inflation may differentially affect reading rates for

10   young and older adults, raw sentence reading times were deemed to provide a more accurate

11   reflection of the data. Reading rate analyses did, however, show the same pattern of effects

12   reported here.

1   Figure legend

2   Figure 1. An example sentence in each condition for each experiment. The asterisk indicates

3   the fixation location during reading.

4   Figure 2. Experiment 1. Sentences reading time in each condition both age groups. Error bars

5   correspond to one standard error.

6   Figure 3. Experiment 2. Sentences reading time in each condition both age groups. Error bars

7   correspond to one standard error.

8

9

1   Figure 1

Experiment 1 stimuli examples

Unmasked _56 pixels:
轻度扭伤后应立即采用冰块冷敷以减少肿胀。
                              *

Masked _ 56 pixels:
珠阅讯驭荃应立即采用廻烌样洴昰敥佮峾矫。
                              *

Unmasked _ 42 pixels:
轻度扭伤后应立即采用冰块冷敷以减少肿胀。
                              *

Masked _ 42 pixels:
珠阅讯驭荃应立即采用廻烌样洴昰敥佮峾矫。
                              *

Unmasked _ 32 pixels:
轻度扭伤后应立即采用冰块冷敷以减少肿胀。
                     *

Masked _ 32 pixels:
珠阅讯驭荃应立即采用廻烌样洴昰敥佮峾矫。
                     *

Experiment 2 stimuli examples

Unmasked _56 pixels:
电子邮件取代了纸质书信成为人们交流的工具。
                              *

Masked _ 56 pixels:
四于络阶语代了纸质书便用生了他共强和方再。
                              *

Unmasked _ 42 pixels:
电子邮件取代了纸质书信成为人们交流的工具。
                          *

Masked _ 42 pixels:
四于络阶语代了纸质书便用生了他共强和方再。
                          *

Unmasked _ 32 pixels:
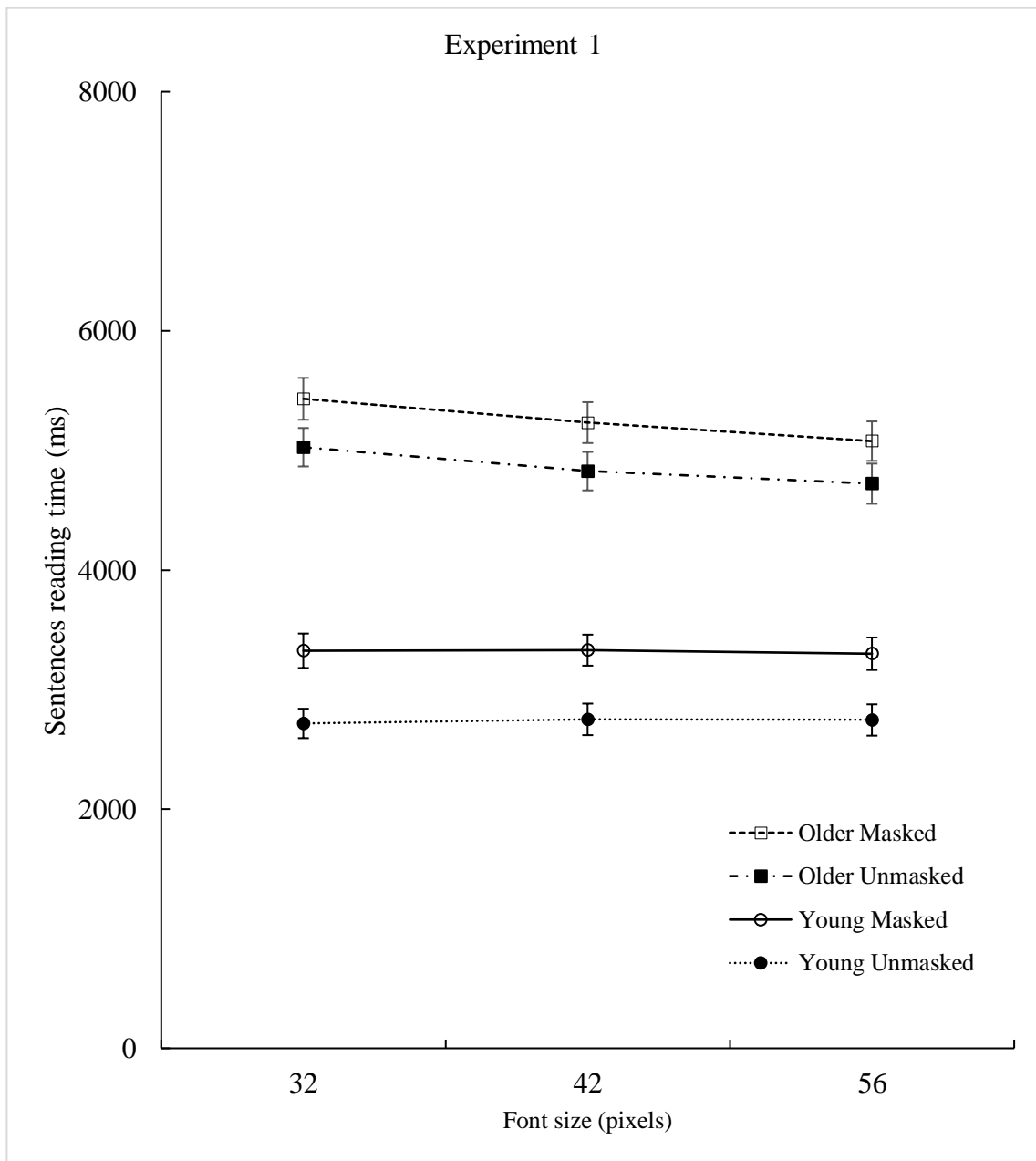电子邮件取代了纸质书信成为人们交流的工具。
                     *

Masked _ 32 pixels:
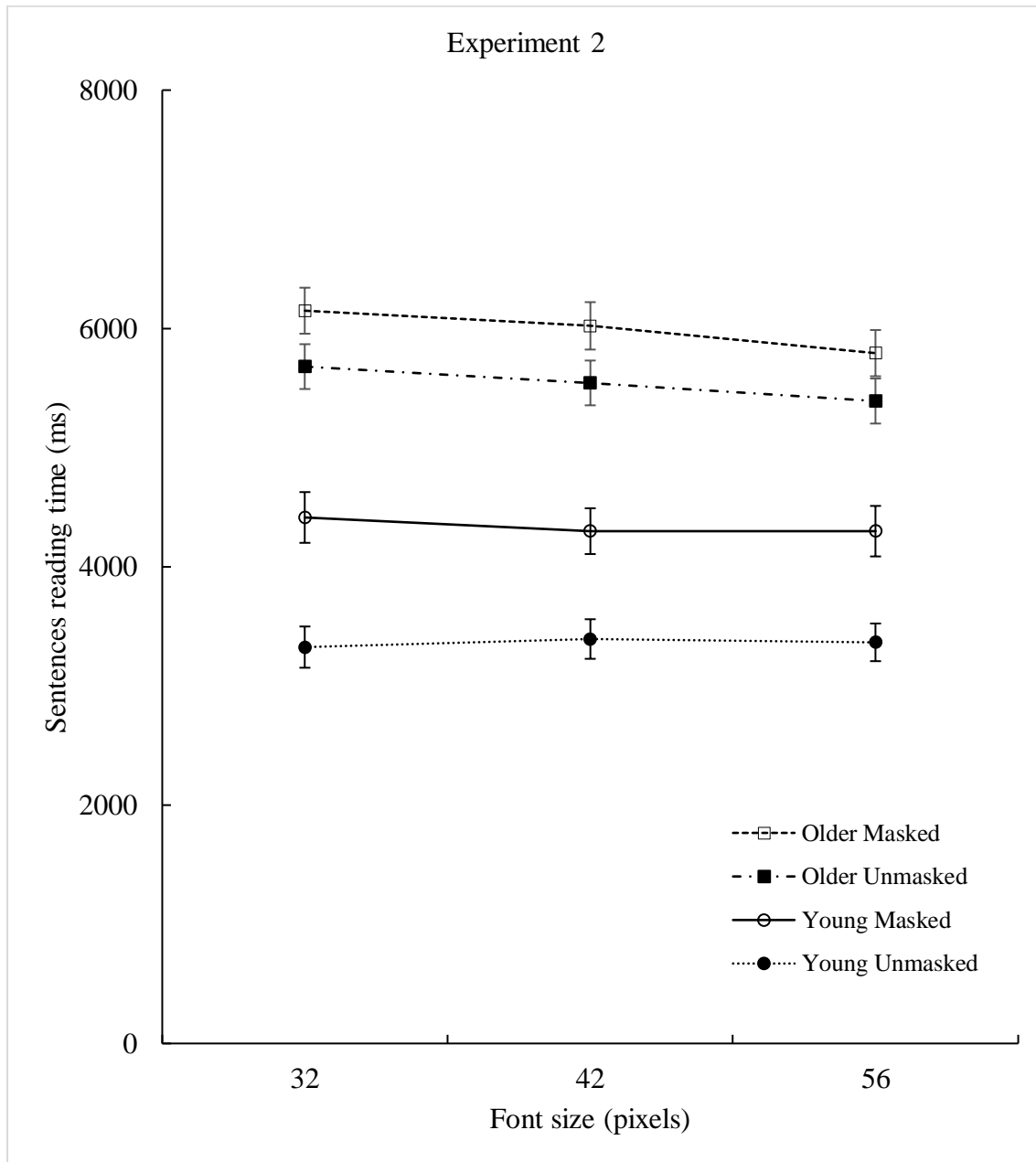四于络阶语代了纸质书便用生了他共强和方再。
                     *

2
3
4
5

1 Figure 2
2

Experiment 1

3
4
5

1 Figure 3

2

3

4

5

1   Table 1. Participant Characteristics.
2

Age Group	Age (Years)	Visual Acuity (Snellen Values)	Formal Education (Years)	Vocabulary		Digit Span (Raw scores)	
				Raw Scores	Scaled Scores	Forward	Backward
Young	19.4 (1.1)	20/24	13.7 (.97)	69.1 (5.9)	15.6 (1.8)	9.1 (.9)	6.0 (1.7)
	Range = 18-22	Range = 20/16-20/33	Range = 13-16	Range = 57-79	Range = 13-19	Range = 7-11	Range = 2-8
Older	66.9 (3.7)	20/32	12.9 (1.36)	72.0 (3.9)	15.6 (0.9)	7.7 (1.0)	4.7 (.9)
	Range = 61-76	Range = 20/19-20/40	Range = 9-16	Range = 64-78	Range = 14-17	Range = 5-10	Range = 3-7
				$t(94) = 2.83$,	$t(94) = .07$,	$t(94) = 6.90$,	$t(94) = 4.54$,
				$p = .006$	$p = .942$	$p < .001$	$p < .001$

3   *Note.* Only raw scores are presented for digit span because scaled scores can only be calculated from the combined measures. Scaled scores for

4   the combined digit span produce the same pattern as the raw scores, Young, $M = 13.8$ $SD = 2.5$, Range = 7-19; Older, $M = 12.5$, $SD = 1.6$, Range

5   = 8-16, $t(94)=3.16$, $p=.002$.

6
7

8

1 Table 2 Means and SDs and SEs for Eye Movements Measures in Experiment 1 and 2
2

	Young						Older						AE	VE	FE	
	Unmasked			Masked			Unmasked			Masked			Young vs. Older	Unmasked vs. Masked	42 vs. 56	32 vs. 42
	56	42	32	56	42	32	56	42	32	56	42	32				
Experiment 1																
Sentences reading time (ms)	2746 (131)	2751 (132)	2717 (123)	3300 (136)	3330 (130)	3325 (144)	4722 (168)	4827 (161)	5027 (161)	5078 (165)	5233 (171)	5432 (175)	-2011	-464	78	90
Average fixation duration (ms)	234 (4)	246 (4)	255 (5)	253 (4)	262 (4)	272 (4)	249 (3)	265 (3)	288 (4)	258 (3)	277 (4)	301 (4)	-19	-14	14	16
Progressive saccade length (characters)	2.1 (.06)	2.1 (.06)	2.5 (.08)	1.9 (.05)	1.9 (.04)	2.3 (.06)	1.6 (.04)	1.8 (.05)	2.1 (.06)	1.6 (.04)	1.8 (.04)	2.1 (.05)	0.3	0.2	0.1	0.3
Experiment 2																
Sentences reading time (ms)	3366 (158)	3394 (166)	3326 (173)	4299 (212)	4299 (192)	4414 (213)	5391 (189)	5543 (188)	5680 (188)	5793 (194)	6022 (199)	6149 (193)	-1911	-709	98	89

Average fixation duration (ms)	233 (3)	246 (4)	257 (4)	258 (4)	270 (4)	282 (4)	250 (3)	268 (3)	291 (4)	261 (3)	279 (3)	303 (4)	-17	-19	16	17
Progressive saccade length (characters)	2.0 (.05)	2.0 (.05)	2.4 (.07)	1.8 (.04)	1.8 (.04)	2.1 (.06)	1.6 (.04)	1.8 (.05)	2.1 (.06)	1.6 (.04)	1.7 (.05)	2.0 (.05)	0.2	0.2	0.1	0.4

1 *Note.* AE = age group effect; VE = viewing condition effect; FE = font size effect. Standard errors are shown in parentheses. SEs were calculated
2 across participant variance.

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

		Sentences reading time (ms)	Average fixation duration (ms)	Progressive saccade length （characters）
	b	4039.67	263.26	1.99
Intercept	*SE*	114.15	2.81	0.04
	t	35.39	93.76	44.69
Age group	*b*	-2026.76	-19.35	0.31
	SE	199.46	5.49	0.09
Young vs. Older	*t*	-10.16*	-3.52*	3.63*
Viewing condition	*b*	487.02	14.28	-0.14
	SE	41.89	1.27	0.02
Masked vs. Unmasked	*t*	11.63*	11.25*	-7.37*
Font size	*b*	72.31	14.09	0.08
	SE	25.68	0.71	0.01
56 vs. 42	*t*	2.82*	19.93*	7.94*
	b	88.40	16.42	0.36
42 vs. 32	*SE*	25.68	0.71	0.01
	t	3.44*	23.22*	35.83*
	b	197.74	5.81	-0.23
Age group * Viewing condition	*SE*	83.79	2.45	0.04
	t	2.36*	2.38*	-6.36*
*Age group * Font size*	*b*	-116.32	-7.23	-0.12
	SE	51.36	1.41	0.02
Age group *56 vs. 42	*t*	-2.27*	-5.11*	-5.93*
	b	-219.17	-13.17	-0.00
Age group * 42 vs. 32	*SE*	51.37	1.41	0.02
	t	-4.27*	-9.31*	-0.17
*Viewing condition * Font size*	*b*	39.57	0.77	0.00
	SE	51.36	1.41	0.02
Viewing condition * 56 vs. 42	*t*	0.77	0.55	0.21
*Viewing condition * Font size*	*b*	13.20	0.65	-0.04

Viewing condition * 42 vs. 32	SE	51.37	1.41	0.02
	t	0.26	0.46	-1.76
*Age group * Viewing condition *Font size*	b	-12.80	-7.08	-0.01
Age * Viewing condition * 56 vs. 42	SE	102.73	2.83	0.04
	t	-0.13	-2.50*	-0.23
Age * Viewing condition * 42 vs. 32	b	18.52	1.66	0.05
	SE	102.74	2.83	0.04
	t	0.18	0.59	1.14

Note. Significant fixed factor effects are indicated with an asterisk.

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

		Sentences reading time (ms)	Average fixation duration (ms)	Progressive saccade length （characters）
Intercept	b	4805.97	266.54	1.91
	SE	138.03	2.94	0.04
	t	34.82	90.54	44.68
Age group	b	-1914.48	-17.52	0.20
Young vs. Older	SE	244.72	5.81	0.08
	t	-7.82*	-3.02*	2.35*
Viewing condition	b	713.58	18.36	-0.13
Masked vs. Unmasked	SE	62.40	1.41	0.02
	t	11.44*	13.01*	-6.29*
Font size	b	103.45	15.66	0.09
56 vs. 42	SE	34.23	0.69	0.01
	t	3.02*	22.56*	8.00*
	b	76.88	17.16	0.34
42 vs. 32	SE	34.25	0.69	0.01
	t	2.25*	24.72*	30.45*
Age group * Viewing condition	b	526.49	13.49	-0.16
	SE	120.21	2.80	0.04
	t	4.38*	4.82*	-3.98*
Age group * Font size	b	-180.20	-5.66	-0.14
Age group * 56 vs. 42	SE	68.46	1.39	0.02
	t	-2.63*	-4.08*	-6.18*
	b	-107.77	-12.27	0.02
Age group * 42 vs. 32	SE	68.50	1.39	0.02
	t	-1.57	-8.84*	0.73
Viewing condition * Font size	b	27.02	-0.54	-0.04
Viewing condition * 56 vs. 42	SE	68.46	1.39	0.02
	t	0.40	-0.39	-1.75
	b	81.57	1.40	-0.00

Viewing condition * 42 vs. 32	*SE*	68.50	1.39	0.02
	t	1.19	1.01	-0.18
*Age * Viewing condition *Font size*	*b*	-105.79	-2.24	0.04
Age * Viewing condition * 56 vs. 42	*SE*	136.93	2.78	0.05
	t	-0.77	-0.81	0.82
Age * Viewing condition * 42 vs. 32	*b*	207.17	1.06	0.04
	SE	137.00	2.78	0.05
	t	1.51	0.38	0.94

Note. Significant fixed factor effects are indicated with an asterisk.