Effects of adult aging on word encoding in Chinese reading: evidence from disappearing text

Zhifang L Liu, Yun P Pan, Wen T Tong

The effect of aging on the process of word encoding for fixated words and words presented to the right of the fixation point during reading of sentences in Chinese was investigated with two disappearing text experiments. The results of Experiment 1 showed that the 40-ms onset disappearance of word n did not disrupt young adults' reading performance. However, for old readers, the disappearance of word n caused disruptions until the onset time was 120 ms. The results of Experiment 2 showed that the disappearance of word n+1 did not cause disruptions to young adults, but these conditions made old readers spend more time reading a sentence compared to the normal display condition. These results indicated a reliable aging effect on the process of word encoding when reading Chinese, and that the encoding process in the preview frame was more susceptible to normal aging compared to that in the fixation frame. We supposed that both sensory and cognitive factors are important contributors to these age-related differences.

Zhi-fang Liu[1], Yun Pan[2], Wen Tong[3],
1, Department of Psychology, Ningbo University, Ningbo, China;
2, Department of Psychology, Guizhou Normal University, Guiyang, China;
3. Department of Psychology, Shanxi Normal University, Linfen, China)
Corresponding author：Zhi-fang Liu. Email: lzhf2008@163.com.

Effects of adult aging on word encoding in reading Chinese: evidence from disappearing text

Abstract: The effect of aging on the process of word encoding for fixated words and words presented to the right of the fixation point during reading of sentences in Chinese was investigated with two disappearing text experiments. The results of Experiment 1 showed that the 40-ms onset disappearance of word n did not disrupt young adults' reading performance. However, for old readers, the disappearance of word n caused disruptions until the onset time was 120 ms. The results of Experiment 2 showed that the disappearance of word n+1 did not cause disruptions to young adults, but these conditions made old readers spend more time reading a sentence compared to the normal display condition. These results indicated a reliable aging effect on the process of word encoding when reading Chinese, and that the encoding process in the preview frame was more susceptible to normal aging compared to that in the fixation frame. We supposed that both sensory and cognitive factors are important contributors to these age-related differences.

Key words: Chinese reading, disappearing text, words encoding, aging, eye movements

INTRODUCTION

Reading is an important practiced skill for daily life. This skill is acquired in early life and remains remarkably stable in adult age. However, many studies have recently revealed some subtle age differences in reading, that is, old adults spend more time to comprehend texts, make longer fixations, and more regressions than young adults (Kemper, Crow & Kemtes, 2004; Kliegl, Grabner, Rolfs, Engbert, 2004; Stine-Morrow, Miller, & Hertzog, 2006; Rayner, Reichle, Stroud, Williams, Pollatsek, 2006; Laubrock, Kliegl,& Engbert, 2006; Rayner, Castelhano & Yang, 2009). Optical change and changes in neural transmission that occur with normal aging lead old adults to often experience a range of subtle visual deficits (Owsley, 2011), which may have a large contribution to their reading decline. Rayner et al (2006, 2009) proposed that these age-related differences are widely attributed to the sensory and cognitive decline associated with normal aging. However, the nature of this decline has not yet to be fully determined. Of particular importance for the present study is that the aging effects on word encoding may be related to both the changes in visual sensory abilities and the cognitive decline associated with normal aging. In this study, we explored the effect of aging on the time needed for encoding words both in foveal and parafoveal vision (i.e., word n and n+1) during reading of Chinese text, by comparing the reading performance of young and old adults when they read disappearing text.

The disappearing text paradigm, in which the fixated word n or word n+1 disappears after a certain fixation duration (i.e., 40, 60, or 80 ms), has been the most effective method to resolve the issue mentioned above. With this paradigm, researchers have found that most of the visual information of the fixated word necessary for reading can be acquired within the initial 50–60 ms during a fixation for young English readers, which means that young readers are able to encode all the needed visual information of a fixated word within this time frame (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Liversedge et al., 2004; Blythe, Liversedge, Joseph, White, & Rayner. 2009; Blythe, Hăikiŏ, Bertam, Liversedge, & Hyŏnă, 2011). Maybe the most striking result was that even when the word disappeared after a fixation of 60 ms, a robust frequency effect on the target words remained, which meant that word processing influenced eye movements in reading (Rayner, Liversedge, White, & Vergilino-Perez, 2003). Rayner, Liversedge, and White (2006) also investigated the visual encoding on word n+1 with disappearance experiments, and found that the disappearance of word n+1 after word n was fixated for 60 ms greatly impaired reading, which indicated not only the importance of visual coding for word n+1, but also that the time needed for encoding words in parafoveal vision is longer than for words in foveal vision when reading English.

It was found that clinical impairments are common in the old population, and these impairments have profound effects on reading performance (Paterson, McGowan, & Jordan, 2013). Further evidence has also revealed that reading performance decreases significantly with age even in people whose visual acuity is good (Lott, Schneck, Haegerstrŏm-Portnoy, Brabyn, & Gildengorin, 2001). Thus, it is safe to hypothesize that old adults may need more time to encode words during reading; of course, this notion needs to be tested. Previous research with the disappearing text paradigm has revealed that for old readers, the disappearance of the fixated word caused relatively greater reading slowdown compared to young adults, even in the 60-ms onset disappearing conditions. However, due to the absence of an interaction between age group and disappearing onset when the control condition was removed, the authors argued that the effect of disappearing onset is comparable in old and young readers (Rayner, Yang, Castelhano, & Liversedge, 2010). This is informative for revealing the age effect on visual word encoding in the foveal region phrase during reading. However, it is also important to explore the aging pattern of word encoding in parafoveal vision, as preview processing of words is common both for young and adult readers (Rayner et al., 2009; Rayner, Castelhano, & Yang, 2010). However, research on this topic is still rare.

Encoding words of alphabetic languages during reading involves the discrimination of one-dimensional, linear combinations of letters or phonological units, and then encapsulate them into more permanent representations (Reichle, Liversedge, Pollatsek, & Rayner, 2009). As mentioned above, with the disappearing text paradigm, researchers have extensively investigated the time needed for encapsulating words in foveal and parafoveal phrases (Rayner et al., 1981, 2003, 2006; Liversedge et al., 2004) and its developmental and aging issues (Blythe et al., 2009, 2011; Rayner et al., 2010). However, in contrast to the well-documented effects of disappearing text and the effects of aging on reading English, empirical studies concerning disappearing text in reading Chinese have been relatively sparse and are still in their infancy. Only one study using the disappearing text paradigm was found in which visual information of the fixated word necessary for sentence comprehension can be acquired within the initial 50–60 ms, which indicated that young adult Chinese readers could encapsulate the fixated word as quickly as young adult English readers (Liu, Zhang, & Zhao, 2011). As far as we know, there has been no research resolving the issue of the aging effect on word encoding in reading Chinese. In view of the two substantial differences between these two script types, findings from alphabetic scripts (such as English) on word encoding in reading cannot be directly extended to reading Chinese.

Firstly, Chinese writing is logographic whose written style is completely different from that of alphabetic text. Evidence has shown that the processes underlying lexical identification of Chinese words are very different from those of alphabetic languages (Zhou, & Marslen-Wilson, 2000). The prevalent assumption has been that Chinese lexical identification is a form-to-meaning process with little involvement of phonology; therefore, it appears that orthography dominates over phonology, and that orthographic encoding is a core process in Chinese word identification (Perfetti, Liu, & Tan, 2005). Zhang et al. (2012) posited that Chinese is a more thoroughly visual language compared to alphabetic scripts, and thus emphasized the role of visual processing in word recognition. Secondly, Chinese is a language with no spaces to separate words in Chinese text, and texts written in Chinese are formed by strings of box-like symbols (i.e., characters). Although series of studies conducted by Bai and colleagues have suggested the importance of words (opposed to characters) for reading and learning Chinese, which are the same as for alphabetic languages (Bai, Yan, Liversedge, Zang, & Rayner, 2008; Blythe et al., 2012; Shen et al., 2012; Bai et al., 2013), character processing is the necessary stage for multi-character word recognition (Li, Rayner, & Cave, 2009; Shen, & Li, 2012; Li, Bicknell, Liu, Wei, & Rayner, 2014). Thus, these two characteristics of Chinese text may increase the aging effect on the time needed for visual encoding of words during reading.

Thus, although previous studies have shown that young adult Chinese readers need about the same time to encode the fixated word as readers of alphabetic languages, it does not mean that both kinds of languages share the same pattern of normal aging in word encoding during reading. Here, we further examined aging effects on the time needed for encoding not only the fixated word (word n) but also the word to the right of fixation (word n+1) when reading Chinese by two disappearing text experiments, respectively. The first experiment was conducted to explore aging effects on encoding word n, in which the onset time of the word n disappearance was manipulated. In the second experiment, the same onset time of word n+1 disappearance was manipulated, and by doing this, we intended to clarify the aging effects on encoding word n+1 and compare it to the aging effects on encoding word n. The onset time of disappearance manipulations in both experiments were 40, 80, 120, and 160 ms. The logic of both experiments was straightforward. If the onset time were not sufficient for encoding before the word disappeared, normal reading performance would be impaired under this onset time of disappearing text. Moreover, if young and old adults had different requirements on the time needed for encoding the words to read normally, these differences should be revealed by the effectiveness of each onset time of disappearing manipulation at sustaining normal reading performance in each age group.

GENERAL METHOD

Participants

Sixty adults from the University of Ningbo and local community participated in the experiments. Of these, 15 young adults (M = 20.5 years, range 18–22 years) and 15 old adults (M = 66.7 years, range 60–73 years) participated in Experiment 1, and another 15 young adults (M = 20.4 years, range 18–22 years) and 15 old adults (M = 66.8 years, range 60–73 years) participated in Experiment 2. The young and old adult groups did not differ in number of years of schooling (15.8 years for the young adults and 15.4 years for the old readers). All participants were right-handed with normal or corrected-to-normal vision. They were all native Chinese speakers and were paid ¥30 for participation. None of them was aware of the purpose of the experiment or had previously participated in other similar experiments.

Apparatus

The participants' movements of the right eye were recorded with an Eye Link 1000 device manufactured by SR Research Ltd. The eye tracker is an infrared video-based tracking system, and its camera samples the pupil location and pupil size at a rate of 1000 Hz. The sentence stimuli were presented on a 19-inch DELL monitor with a 1024 × 768 pixel resolution. The refresh rate of the screen was 75 Hz. The sentences were displayed in Song font, and the size of each Chinese character was 28 × 28 pixels subtending approximately 0.63 deg of visual angle. The distance between the participant and screen was 75 cm.

Stimuli

Eighty sentences were used as stimuli in the experiments. These sentences all contained 7 or 8 two-character words. Ten college students, who did not participate in the experiments, were asked to rate the difficulty of these sentences on a 7-point scale (e.g., a score of 7 was "very difficult"). The resulting mean difficulty score was 1.65. Each sentence was shown in one of five display conditions. All eighty sentences were randomized and sampled using a Latin square, so that each participant saw sixteen sentences shown in each of the five display conditions. By doing this, we wanted to ensure that all sentences were shown equally often in the five display conditions and prevent repetition of any sentence for each participant. Sentences were shown to each participant in a randomized order across the two sessions.

There were 12 additional sentences (five of which had questions) for practice in the first session. The second session was the formal experiment. To confirm that participants were reading the sentences carefully, there were 27 filler sentences that were randomly inserted throughout the block. A Yes/No comprehension question was presented at the end of each filler sentence, and the participants were asked to answer the questions by manually pressing the buttons.

Procedure

Participants were tested individually. Before the experiment, they were informed that they would read sentences presented in different disappearing manners. The participants were instructed to read and understand the sentences and were asked to push a button box to terminate the current display when a sentence was completed. A comprehension task occasionally appeared after a sentence, and the participants were asked to answer a Yes/No question by pressing different buttons. A chin rest was inserted to ensure that the participants' heads remained still. A calibration procedure was executed prior to the beginning of the experiment in which the participant was instructed to look at each of 3 fixation points, extending in a horizontal line across the center of the screen. Once the eye tracker had been calibrated with satisfactory accuracy (mean error less than 0.5º) the sentence was presented. The calibration was checked after each trial, and the eye tracker was re-calibrated whenever necessary. The experiment was approximately 25 minutes in length.

EXPERIMENT 1

Design

The experiment followed a 2 (group: young adults *vs.* old adults) × 5 (fixated word disappearing onset: no disappearing, 40 ms, 80 ms, 120 ms, 160 ms) mixed design. The former variable was a between-subjects factor and the later was a within-subjects factor. That is, both groups of participants read the Chinese sentences in a normal condition (control) and four experimental conditions in which the word n disappeared after the designated interval (40, 80, 120, or 160 ms). An immediate re-fixation on word n did not result in its reappearance until the reader made an eye movement to a new word in disappearing manipulations. Fig. 1 shows an example of the disappearing manipulations in detail; when the reader fixated on word "垃圾," which was word n, it disappeared after 40, 80, 120, or 160 ms, and was not presented until the reader made an eye movement to a new word. When the reader made an eye movement and fixated on word "通道," the disappeared word "垃圾" reappeared; and, after 40, 80, 120, or 160 ms, "通道" disappeared (note: the sentences all contained 7 or 8 two-character words).

Figure 1 insert here

Note that the refresh rate of the screen can affect the precise timing of a display. The disappearing text manipulations were initiated when the eye fixated on word n. The refresh rate of the screen was 75 Hz in the present study, therefore, in each disappearing condition, there was a potential additional 15 ms of delay before the words disappeared after the eye moved to word n, thus the actually onset time of disappearing manipulations in both of the two experiments (Experiment 1 & 2) was 55, 95, 135 or 175 ms.

Results and Discussion

The mean accuracy of all participants for the 27 comprehension sentences exceeded 80%, and there were no significant effects of display condition and age group (*Fs* < 1.2, *ps* > 0.10). Namely, the comprehension levels were high in all situations, which indicated that participants read and fully understood the sentences. All eye movement data above or below three standard deviations from the mean were excluded; as a result, 3.7% of the data in total were removed prior to conducting the analyses. A repeated measures analysis of variance (ANOVA) on the eye movement data was carried out for the display manipulations with 5 levels and the two age groups.

For the study purpose, one word-independent measure, reading time, which was the most important measure for the study with the disappearing text paradigm (Blythe, Liversedge, Joseph, White, & Rayner, 2009), and three word-dependent measures, such as mean gaze duration (mean of gaze duration on all the words in a sentence), probability of words skipped in the initial pass when reading a sentence, and regression numbers (number of saccades made from right to left word) were analyzed as supplementary data. The reason to adopt reading time measure as the main reference independent variable is that readers may trade off fixation duration and number during disappearing text reading (Rayner et al., 1981; Liversedge et al., 2004; Liu et al., 2011), which in turn could lead to word-independent measures not being sensitive to the word encoding process. All the data are summarized in Table 1.

Table 1 insert here

Reading time yielded a significant main effect of age group; old adults spent more time reading a sentence than young adults, $F(1,28)=7.583$, $p<0.05$, $\eta^2=0.213$. Reading time also varied across the disappearing onset conditions, $F(4,112)=7.349$, $p<0.05$, $\eta^2=0.21$, with the 40-ms and 80-ms disappearing onset conditions being significantly different from the control ($ps < 0.05$). The interaction between the two variables was reliable, $F(4,112)=2.817$, $p<0.05$, $\eta^2=0.091$, which was due to the significant main effect of disappearing onset for old adults, $F(4,56)=8.509$, $p<0.001$, $\eta^2=0.365$, but this effect was not reliable for the young adults, $F(4,56)=0.997$, $p=0.417$. Pairwise comparisons for the old adults showed that the 40-ms and 80-ms disappearing onset conditions differed from the control, with the shorter disappearing onset producing longer reading times ($ps < 0.05$); however, there were no significant differences between the 120-ms and 160-ms onset and the control ($ps > 0.05$). When we removed the no-disappearing condition from the analyses and conducted a 2 (group: young adults *vs.* old adults) × 4 (disappearing onset: 40 ms, 80 ms, 120 ms, 160 ms) ANOVA, we still found a reliable interaction between the two variables, $F(3,84)=3.113$, $p<0.05$, $\eta^2=0.1$, which meant that the influence of the disappearing onset variable on reading time was greater for old adults than for young adults.

The most important aspect of the sentence reading time data is that old adults were much more disrupted by the disappearance of the fixated word than were the young adults, and that the more immediate disappearing onset was more disruptive to text processing. In particular, we found that the disappearance of word n influenced reading in the young and aged groups differently, that is, none of the fixated word disappearing conditions interrupted the reading time in the young adults. Thus, the results from this experiment replicated prior findings both in English and Chinese (Rayner et al., 1981; Liversedge et al.., 2004; Liu et al., 2011). However, for old adults, the disappearance of word n prolonged the reading time until the disappearing onset was 135 ms

(120 ms disappearing onset). That is, the period needed for visual encoding of the fixated word is 135 ms or so for old adults, which is inconsistent with findings on reading English, which found no interaction effect between age and disappearing onset, and let the authors conclude that the disappearing onset was comparable in old and young English readers (Rayner et al., 2010).

Mean gaze duration is shown in Table 1. There was a marginally reliable group effect, $F(1,28)=3.59$, $p=0.069$, $\eta^2=0.114$. The disappearing onset effect was not significant, $F(4,112)=1.575$, $p=0.186$. However, the interaction effect between these two factors was significant, $F(4,112)=4.326$, $p<0.05$, $\eta^2=0.134$. We also explored the essence of this interaction and found that young adults gazed longer in the 40-ms and 80-ms disappearing onset conditions than in the control condition ($ps < 0.05$), whereas the old adults gazed for a shorter time in the 40-ms disappearing onset conditions of word n than in the control and other disappearing conditions ($ps < 0.05$).

Probability of skipped words is also shown in Table 1. There was a marginally reliable group effect, $F(1,28)=3.818$, $p=0.06$, $\eta^2=0.12$, with young adults skipping words more often than the aged persons. The main effect of disappearing onset was also reliable, $F(4,112)=3.002$, $p<0.05$, $\eta^2=0.097$, and there was a reliable interaction between the two factors, $F(4,112)=2.425$, $p<0.05$, $\eta^2=0.08$. We explored the essence of this interaction and found that there was a main effect of disappearing onset for the aged group, $F(4, 56)=5.627$, $p<0.05$, $\eta^2=0.287$, that is, old people skipped words more often when reading disappearing text than when reading the control, with the short disappearing onset yielding the highest skip probability. The main effect of disappearing onset was not reliable for the young adults, $F(4,56)=0.108$, $p=0.979$.

Number of regressions is also shown in Table 1. The group effect was significant, $F(1,28)=7.714$, $p<0.05$, $\eta^2=0.217$, which was due to old adults being more inclined to make regressions during reading than young adults. The main effect of disappearing onset was significant, $F(4,112)=24.061$, $p<0.05$, $\eta^2=0.462$. The interaction was also reliable, $F(4,112)=9.215$, $p<0.05$, $\eta^2=0.248$, and sample analyses confirmed that the disappearing onset effect was not reliable for young adults, $F(4,56)=2.708$, $p=0.10$; but for old adults, the disappearing onset effects was reliable, $F(4,56)=31.694$, $p<0.001$, $\eta^2=0.694$. Pairwise comparisons for old group showed that all the disappearing conditions differed from the control condition, with shorter disappearing onset producing more regressions ($ps < 0.05$); however, there was no significant difference between the 120-ms and 160-ms disappearing onset ($p > 0.05$), which mimicked the reading-time data generally (see Table 1).

The three word-dependent eye movement measures provided additional evidence for the effects of normal aging on the time needed for visual encoding of fixated words. In particular, young and old adults adopted a completely different oculomotor strategy to read disappearing text. As seen from measures of mean gaze duration, skip probability, and regression number (see Table 1), young adults gazed at words of interest longer, although they skipped more words and made slightly more regressions during disappearing text reading, but the disappearing onset effects on these two measures were not reliable. The higher skip probability traded off the longer mean gaze duration, which in turn blunted the negative influence of the disappearing manipulations on sentence reading time. In contrast, for old readers, the mean gaze duration was shorter in the disappearing conditions than in the control; old adults also made more skips and regressions during disappearing text reading, which led to longer sentence reading time. The differences of both measures between the control and disappearing conditions were reliable. These findings confirmed that young adults can complete the process of encoding the fixated words in all disappearing text conditions, but old readers need more time to encode it.

EXPERIMENT 2

Design

This experiment also employed a 2 (group: young adults *vs.* old adults) × 5 (word n+1 disappearing onset: no disappearing, 40 ms, 80 ms, 120 ms, 160 ms) mixed design. The former variable was a between-subjects factor, and the later was a within-subjects factor. That is, both groups of participants read the Chinese sentences in a normal condition (control) and four experimental conditions in which the word n+1 disappeared after word n was fixated for 40, 80, 120, or 160 ms in which an immediate re-fixation on word n did not result in the re-appearance of word n+1 until the reader made an eye movement to a new word. Fig. 2 shows an example of the disappearing manipulations in detail; when the reader fixated on word "垃圾," which was word n, the word "通道," which was word n+1, disappeared after 40 ms, 80 ms, 120 ms, or 160 ms and was not presented again until the reader made an eye movement to a new word. When the reader made an eye movement and fixated on word "通道," the disappeared word reappeared, and after 40 ms, 80 ms, 120 ms, or 160 ms, "需要" disappeared.

Figure 2 insert here

Results and Discussion

The mean accuracy of all participants for the 27 comprehension sentences exceeded 80%. An ANOVA of mean accuracy was also carried out for the disappearance treatment with 5 levels and the 2 age groups. There were no reliable effects for the disappearance conditions and age groups ($Fs < 1.2$, $ps > 0.10$). All eye movement data above or below three standard deviations from the mean were excluded, and 2.9% of the data in total were removed prior to conducting the analyses. The independent measures are summarized in Table 2.

Table 2 insert here

Reading time showed a reliable age group effect, old adults required more time than young adults, $F(1,28)=34.371$, $p<0.001$, $\eta^2=0.551$. The reading time varied across the disappearing onset conditions, $F(4,112)=24.914$, $p<0.001$, $\eta^2=0.471$. The interaction was also reliable, $F(4,112)=16.36$, $p<0.001$, $\eta^2=369$, this was due to a reliable main effect of disappearing onset for old adults, $F(4,56)=25.389$, $p<0.001$, $\eta^2=0.645$, which was not evident for young adults, $F(4,56)=1.258$, $p=0.297$. Pairwise comparisons on aged adults showed that all of the disappearing conditions prolonged the total reading time compared to the control (*ps* < 0.05), and the 40-ms disappearing onset condition had a stronger effect than any of the other disappearing conditions (*ps* < 0.05). When the no-disappearing condition was removed from the analyses, there was still a reliable interaction between the two variables, $F(3,84)=6.580$, $p<0.05$, $\eta^2=0.19$, which meant that the disappearing onset variable of word n+1 influenced reading time of old adults more than that of young adults.

The aging effect on the process of encoding word n+1 in reading Chinese was explored in this experiment. It was again confirmed that old adults were disrupted much more by the disappearance manipulations than were the young adults, and that the more immediate disappearing onset was more disruptive to processing. As described in the previous paragraph, none of the word n+1 disappearance manipulations impaired the normal reading performance of young adults. However, for the old adults, the disappearing manipulations prolonged sentence reading time, with the shortest disappearing onset time (40 ms) causing the greatest interruptions. The results of the young adults are inconsistent with previous studies in English, which indicated that the 60-ms onset time disappearance of word n+1 impaired young readers' normal reading performance (Rayner et al., 2006). The results on old adults indicated that it becomes more difficult to encode word n+1 within the limited time, and even 175 ms might not be sufficient (the 160 ms onset time of word m+ disappearing condition still impair the old adults' reading performances). Thus, these data indicated that old adults' reading suffered more seriously when encoding word n+1 than when encoding the fixated word.

Mean gaze duration is shown in Table 2. There was a reliable group effect, $F(1,28)=21.030$, $p<0.01$, $\eta^2=0.429$, and a reliable disappearing onset effect $F(4,112)=6.424$, $p<0.001$, $\eta^2=0.187$, showing that the mean gaze duration was longer for aged adult readers than for young adult readers, and that all the disappearing manipulations were more effective than the no-disappearing condition (*ps* < 0.05). However, the interaction effect between the two factors was not significant, $F(4,112)=1.374$, $p>0.05$.

Probability of skipped words is also shown in Table 2. There was a reliable group effect, $F(1,28)=24.323$, $p<0.001$, $\eta^2=0.465$, showing that young adults skipped more words than old adults when reading. The disappearing onset effect was also reliable, $F(4,112)=18.033$, $p<0.001$, $\eta^2=0.392$; pairwise comparisons showed that the probability of skipped words in all disappearing conditions was higher than in the control (*ps* < 0.05). The probability in the 160-ms onset disappearing condition was lower than in the other disappearing conditions (*ps*<0.05). The interaction was not reliable, $F(4,112)=0.368$, $p=0.831$.

Number of regressions. Old adults were more inclined to make regressions during reading than young adults, $F(1,28)=19.243$, $p<0.01$, $\eta^2=0.407$. The main effect of disappearing onset was significant, $F(4,112)=18.18$, $p<0.001$, $\eta^2=0.394$. The interaction was also reliable, $F(4,112)=17.226$, $p<0.05$, $\eta^2=0.38$. Pairwise comparisons on aged adults showed that differences between any two disappearing conditions were reliable (*ps* < 0.05), except the difference between the 80-ms and 120-ms disappearing onset conditions. However, there were no differences between any of the disappearing onset conditions for the young adults (*ps* > 0.05).

The word-dependent eye movement measures provided additional evidence to support the conclusions made from the reading time data. It was found that readers also adopted a strategy of trading off gaze duration, regressions, and skips to read the sentences treated by the word n+1 disappearing manipulations. As seen in Table 2, young adults adopted a totally different oculomotor strategy to read word n+1 disappearing text compared to the old readers. In particular, the disappearance of word n+1 affected the mean gaze duration for young adults and affected the probability of skipped words equally for both young and old adults. The longer mean gaze duration during the word n+1 disappearing manipulations were traded off with a higher skip probability for both groups, that is, when reading word n+1 disappearing text, readers were inclined to fixate fewer words with longer reading time. It is quite likely that the trade-off between fixation number and time occurred similarly in this experiment, which led to longer gaze duration in the disappearing text reading for both groups; however, the reduced preview caused by the word n+1 disappearing text may have also contributed to the prolonged gaze duration of old readers. The measure of regression number further revealed the group differences. It is crucial to illustrate the differences between young and old adults in reading time and regressions, as seen from Table 2; none of the disappearance onsets of word n+1 brought on more regressions for the young adults but brought on more regression for old adults.

COMPARISON BETWEEN EXPERIMENTS

It should be pointed out that across the two experiments, the control conditions differed very little and any variability could be due to the between-participant manipulation, since different subjects participated in the two experiments. In order to better understand the age-related differences in performance when reading Chinese, a series of independent-sample t-tests were conducted to compare the differences between young and old adults in the no-disappearing conditions from the two experiments. As evident from these analyses, when reading the text under normal display conditions, old adults took more time than young adults (young adults: M=2501 ms, old adults: M=3501 ms, p<0.01), had longer gaze duration (young adults: M=258 ms, old adults: M=331 ms, p<0.01), and marginally more regressions than young adults (young adults: M=1.6, old adults: M=2.0, p=0.062), which is consistent with results from researches on the aging of alphabetic script reading (Kemper et al., 2004; Kliegl et al., 2004; Rayner et al., 2006, 2009). However, old readers skipped fewer words than young adults (young adults: M=23.3%, old adults: M=10.6%, p<0.01). This finding differs from aging effects on reading English, which suggests that compared to old English readers (Rayner et al., 2009), old Chinese adults adopted a more cautious oculomotor strategy when reading Chinese, and they were more inclined to look at the words one-by-one during reading. These findings are valuable to understand the aging effects on word encoding when reading Chinese.

As seen from the comparison of the two experiments, the time needed to encode word n+1 was equal to that of word n for young adults. Given that none of the disappearing manipulations interrupted the reading performance of young adults, and in order to better understand the difference of aging effects on word encoding between words in foveal and parafoveal locations, a 2 (disappearing treatment: word n disappearing *vs.* word n+1 disappearing) × 5 (disappearing onset: no disappearing, 40 ms, 80 ms, 120 ms, 160 ms) ANOVA was carried on reading time, and showed a reliable interaction between disappearing treatment and onset time, $F(4,112)=10.037$, $p<0.05$, $\eta^2=0.264$, which indicated that the disappearance of word n+1 impaired old adults' reading performance more seriously than the disappearance of word n. Thus, this indicated that the aging effect on encoding word n+1 was larger than that on encoding word n.

GENERAL DISCUSSION

As due to optical change and changes in neural transmission that occur with normal aging (Owsley, 2011), old adults often experience a rang of subtle visual deficits which may together with other cognitive factors impaired the words encoding during reading. With two disappearing text experiments, the aging effect on word n and n+1 encoding was investigated during reading Chinese. We further compared aging effects between these two disappearing treatments. Given that readers may trade off fixation duration and fixation number when reading disappearing text (Rayner et al., 2003; Liversedge et al., 2004), it could make the word-independent measures insensitive to the process of encoding words; therefore, sentence reading time was used as the most reliable measure to monitor the words encoding process (Blythe et al., 2009), and three word-dependent eye movement measures were further used as supplementary measures for age-related changes in the process of encoding words.

The differences in time needed for encoding word n between young adults and old adults during reading were investigated in Experiment 1. For reading time, as seen from the results and discussion section for Experiment 1, young adults can encode the visual information of a fixated word within 55-ms display time (40-ms onset disappearance of word n did not disrupt young adults' reading performance), which is generally consistent with prior research both for reading English and Chinese, suggesting that young adults can read fairly well when they see the fixated word for about 55 ms before it disappears (Rayner et al., 2003; Liversedge et al., 2004). However, the results of the old readers showed that the disappearance of word n prolonged the reading time until the onset time reached 120 ms, which was not consistent with that of old English readers (Rayner et al., 2010). Actually, Rayner et al. (2010) concluded that the effect of disappearing onset was comparable in old and young readers based on the lack of interaction between age group and disappearing onset when the control condition was removed. However, as seen from the results and discussion sections of Experiment 1, this interaction was still significant when the control condition was removed, which indeed indicated that old Chinese readers needed more time than young adults to encode the visual information of word n. Thus, it is reasonable to conclude that there was aging effect on the process of encoding word in the fixation phrase when reading Chinese.

The analyses on eye movement measures showed that the two groups adopted completely different oculomotor strategies when reading the word n disappearing text, which may indicate two groups adopted different word processing strategy when reading disappearing text. In particular, the disappearance of fixated words prolonged young adults' gaze on words, which was traded off by the higher skip probability compared to the normal display condition. However, the same manipulations led old adults to gaze at words for shorter times in the first pass of reading and led to more skips and regressions. The disappearing treatment by itself along with the increasing disappearing onset affected the reading time data and suggested that it is insufficient for old adults to visually encode the fixated word within 95-ms display of the visual information (80-ms onset disappearance of word n still disrupted old adults' reading performance), so that they abandon the recognition of the disappeared word (word n). Comparing the results of this experiment to those obtained by Rayner and colleagues (Rayner et al., 2010), it is obvious that aging has a more serious impact on encoding fixated words when reading Chinese. We suppose that visual sensory decline of aging together with two possible cognitive reasons contribute to this difference. The first is that Chinese readers may rely on preview process more than English readers. As seen from the second experiment, young Chinese readers can encode the characters in foveal and parafoveal vision parallel. The second reason is that word identification of Chinese text is a form-to-meaning process with more emphasis on visual processing (Zhou, & Marslen-Wilson, 2000l; Perfetti et al., 2005; Zhang et al., 2012). Further research is therefore needed on these issues of course.

The second experiment was conducted to explore the aging effects on the process of encoding word n+1. With the disappearing text paradigm, Rayner et al. (2006) found that the 60-ms onset disappearance of word n+1 impaired reading English equally to its immediate disappearance (0-ms onset). According to Pollatsek et al. (2006), attention plays a key role in encapsulating the visual information into a more permanent representation. By this account, 60 ms were sufficient for encoding the fixated word, but not to identify the fixated word and then shift attention to word n+1 in time for it to be encoded. Thus, this result is inconsistent with the attention gradient model, which assumes that multiple words are encoded in parallel because, if attention is allocated to both word n and word n+1, there should be sufficient time to convert the visual information of both words into an orthographic code, enabling lexical processing of either word to continue without disruption after they disappear (Reichle et al., 2009). However, as seen from the results and discussion section for Experiment 2, none of the word n+1 disappearing conditions disrupted young Chinese adults' reading time, which is also shown in Table 2. Word skipping probability was traded off with longer mean gaze duration in the disappearing manipulations compared with the control condition in young adults. Thus, the results indicated that young adults could encode the visual information of both words into an orthographic code in parallel at the character level, which is consistent with the notion that readers process characters in parallel during reading Chinese (Li, et al., 2009).

Another exciting finding was that all the disappearance of word n+1 manipulations interrupted old adults' reading performance, and that the shortest disappearing onset of word n+1 condition interrupted sentence reading performance more seriously than the other disappearance manipulations. The eye movement measures also revealed the aging effect on the process of encoding word n+1. As seen from Table 2, old adults exhibited longer gaze duration than young adults in the disappearing conditions and made more regressions when reading disappearing texts than when reading the control condition sentences. Thus, both the word-independent and word-dependent variables in the second experiment revealed that 175 ms were not sufficient to encode word n+1 for old readers (as seen from the results and discussion secession of Experiment 2, 160-ms onset disappearance of word n+1 still disrupted old adults' reading performance). Comparing the old adults' reading time measure in Experiment 1 to that in Experiment 2, it was found that the same disappearing onset of word n+1 manipulation interrupted the reading more seriously than its counterpart disappearing onset of word n condition, which meant that old adults needed more time to encode word n+1 compared to word n. We propose that both sensory and cognitive factors, which are not mutually exclusive, may contribute to this aging difference effect between the words in the two locations relative to the fixation point.

The sensory factor may be the most important contributor to this aging effect between the words in the two locations. In particular, we found that the time needed for encoding the word in the fixation frame was approximately 135 ms; however, more time was needed to encode the word in the preview frame. This finding is consistent with prior research, which has shown that visual acuity decreases with normal aging disproportionately for peripheral vision relative to regions that are closer to the fixation location (Cerella, 1985). Paterson, McGowan and Jordan (2013) also found that old adults gradually lose the ability to process detailed visual information both in foveal and parafoveal regions and rely much more than young adults on coarse-scale components and a much wider region of text when reading. Given that the perceptual span and the preview word segmentation in reading Chinese was mediated by visual factors, such as font size of characters (Yan, Zhou, Shu, & Kliegl, 2015), the deficits in parafoveal vision may lead to a smaller perceptual span for old readers. Thus, together with the previous finding, it is safe to conclude that deficits in parafoveal vision might be an important reason for the lower preview and text comprehension rate in old readers.

There are two possible cognitive reasons that might have caused the differences in time needed between encoding words in the fixation frame and preview frame for the old group. The first is related to attention. The lack of disruption from the manipulation of word n+1 disappearances for young adults indicated that this group could encode the visual information of both words (word n and n+1) in parallel. As seen from the comparison across experiments, however, old readers adopted a more conservative eye movement strategy to compensate for their lower preview processing efficiency. Thus, the longest onset time of word n+1 disappearing still impaired reading performance indicated that old readers of Chinese may serially identify the words during reading. The second reason is related to factors that are specific for Chinese. As we know, recognition of characters is necessary for the identification of multi-character words (Li et al., 2009), and Chinese word identification involves a form-to-meaning processing with more emphasis on visual processing (Zhou, & Marslen-Wilson, 2000l; Perfetti et al.,, 2005; Zhang et al., 2012). However, the recognition of Chinese multi-character word orthography is not achieved until 200 ms after presentation of the word (Zhang et al., 2012). Thus, the aging factors (i.e., perceptual speed and others) could increase the difficulty from character recognition to multi-character word identification (Salthouse, 1994). Although further research is needed on this issue, the current results demonstrate that as Chinese readers get old, they develop adaptive shifts in oculomotor strategies to compensate for their poorer word encoding ability in preview frames during reading.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

This material is sponsored by K.C. Wong Magna Fund in Ningbo University. This work was also supported by Humanities and Social Science Project from Ministry of Education of China to Zhi-fang Liu (Grant No. 15YJC190014). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Author Contributions

Zhi-fang Liu designed and performed the experiments, analysis the data, and wrote the paper. Yun Pan performed the experiments and analysis the data. Wen Tong, designed the experiments and wrote the paper.

Human Ethics

The data were anonymously analyzed. The subjects provided verbal and written informed consent by signing a form to receive money for their participation. The current study was approved by the ethics committee of the Department of Psychology of Ningbo University.

REFERENCE

Bai X, Liang F, Blythe H I, Zang C, Yan G, Liversedge S P. 2013. Interword spacing effects on the acquisition of new vocabulary for readers of Chinese as a second language. *Journal of Research in Reading 36*: S4-S17 doi:10.1111/j.1467-9817.2013.01554.x

Bai X, Yan G, Liversedge S P, Zang C, Rayner, K. 2008. Reading spaced and unspaced Chinese text: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance* 34: 1277-1287 doi:10.1037/0096-1523.34.5.1277

Blythe H I, Liang F, Zang C, Wang J, Yan G, Bai X, & Liversedge S P. 2012. Inserting spaces into Chinese text helps readers to learn new words: An eye movement study. *Journal of Memory and Language* 67: 241-254 doi:10.1016/j.jml.2012.05.004

Blythe H I, Hǎikiǒ T, Bertam R, Liversedge S P, Hyǒnǎ J. 2011. Reading disappearing text: Why do children refixate words. *Vision Research* 51, 84-92 doi:10.1016/j.visres.2010.10.003

Blythe H I, Liversedge S P, Joseph H S S L, White S J, Rayner K. 2009. Visual information capture during fixations in reading for children and adults. *Vision Research* 49: 1593-1591 doi:10.1016/j.visres.2009.03.015

Cerella J. 1985. Age-related decline in extrafoveal letter perception. *Journal of Gerontology* 40: 727-736

Ishida T, Ikeda M. 1989. Temporal properties of information extraction in reading studied by a text-replacement technique. *Journal of the Optical Society A: Optics and Image Science* 6: 1624-1632 doi: 10.1364/JOSAA.6.001624

Kemper S, Crow A, Kemtes K. 2004. Eye-fixation patterns of high and low-span young and older adults: down the garden path and back. *Psychology and A*ging 19: 157 – 170 doi: 10.1037/0882-7974.19.1.157

Kliegl R, Grabner E, Rolfs M, Engbert R. 2004. Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology* 16: 262 – 284 doi: 10.1080/09541440340000213

Laubrock J, Kliegl R, Engbert R. 2006. SWIFT explorations of age differences in eye movements during reading. *Neuroscience and Biobehavioral Reviews* 30: 872-884 doi:10.1016/j.neubiorev.2006.06.013

Li X, Bicknell K, Liu P, Wei W, Rayner K. 2014. Reading is fundamentally similar across disparate writing systems: A systematic characterization of how words and characters influence eye movements in Chinese reading. *Journal of Experimental Psychology: General* 143: 895-913 doi: 10.1037/a0033580.

Li X, Rayner K, Cave K P. 2009. On the segmentation of Chinese words during reading. *Cognitive Psychology* 58: 525-552 doi:10.1016/j.cogpsych.2009.02.003

Liversedge S P, Rayner K, White S J, Vergilino-Perez D, Findlay J M, Kentridge R W. 2004. Eye movements when reading disappearing text: is there a gap effect in reading? *Vision Research* 44: 1013-1024 doi: 10.1016/j.visres.2003.12.002

Lott L A, Schneck M E, Haegerstrŏm-Portnoy G, Brabyn J A, Gildengorin G L. 2001. Reading performance in older adults with good acuity. *Optometry & Vision Science*, 78: 316-324

Owsley C. 2011. Aging and vision. *Vision Research*, 51: 1610–1622 DOI 10.1016/j.visres.2010.10.020

Paterson K B, McGowan V A, Jordan T R. 2013. Effects of adult aging on reading filtered text: evidence from eye movements. PeerJ 1:e63 doi: 10.7717/peerj.63

Perfetti C A, Liu Y, Tan L H. 2005. The lexical constituency model: Some implications of research on Chinese for general theories of reading. *Psychological Review* 112: 43 – 59 doi.org/10.1037/0033-295X.112.1.43

Pollatsek A, Reichle E D, Rayner K. 2006. Test of the E-Z Reader mold: Exploring the interface between cognition and eye movement control. *Cognitive Psychology* 52: 1-56 doi:10.1016/j.cogpsych.2005.06.001

Rayner K, Castelhano M S, Yang J. 2009. Eye movements and the perceptual span in older and younger readers. *Psychology and Aging* 24: 755 – 760 doi: 10.1037/a0014300

Rayner K, Castelhano M S, Yang J. 2010. Preview benefit during eye fixations in reading for older and younger readers. *Psychology and Aging* 25: 714 – 718 doi: 10.1037/a0019199

Rayner K, Inhoff A, Morrison R, Slowiaczek M L, Bertera J H. 1981. Masking of foveal and parafoveal vision during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance* 7: 167-179 doi: org/10.1037/0096-1523.7.1.167

Rayner K, Liversedge S P, White S J, Vergilino-Perez D. 2003. Reading disappearing text: Cognitive control of eye movements. *Psychological Science* 14: 385-388 doi: 10.1111/1467-9280.24483

Rayner K, Reichle E D, Stroud M J, Williams C C, Pollatsek A. 2006. The effects of word frequency, word predictability, and font difficulty on the eye movements of young and elderly readers. *Psychology and Aging* 21: 448 – 465 doi: 10.1037/0882-7974.21.3.448

Reichle E D, Liversedge S P, Pollatsek A, Rayner K. 2009. Encoding multiple words simultaneously in reading is implausible. *Trend in Cognitive Sciences* 13: 115-119 doi:10.1016/j.tics.2008.12.002

Salthouse T A. 1994. The nature of the influence of speed on adult age differences in cognition. *Developmental Psychology* 30: 240-259 doi: org/10.1037/0012-1649.30.2.240

Shen D, Liversedge S P, Tian J, Zang C, Cui L, Bai X, Yan G, Rayner K. 2012. Eye movements of second language learners when reading spaced and unspaced Chinese text. *Journal of Experimental Psychology: Applied* 18: 192-202 doi: 10.1037/a0027485.

Shen W, Li X S. 2012. The uniqueness of word superiority effect in Chinese reading (in Chinese). Chinese Science Bulletin (Chinese Version) 57: 3414 – 3420.

Stine-Morrow E A L, Miller L M S, Herzog C. 2006. Aging and self-regulated language processing. *Psychological Bulletin*, 132: 582 – 606 doi: 10.1037/0033-2909.132.4.582

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: 209 – 219 doi: 10.1037/a0038097

Zhang X X, Fang Z, Du Y C, Kong L. Y, Zhang Q, Xing Q. 2012. The centro-parietal N200: An event-related potential component specific to Chinese visual word recognition. *Chinese Science Bulletin* 57: 1516-1532 doi: 10.1007/s11434-011-4932-y

Zhou X L, Marslen-Wilson W. 2000. The relative time course of semantic and phonological activation in reading Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 26: 1245-1265 doi: 10.1037//0278-7393.26.5.1245

Figure 1(on next page)

Figures

（a） 垃圾通道需要及时清理。 [beginning of fixation]
*
（b） 通道需要及时清理。 [after40/80/120/160ms]
*
（c） 垃圾通道需要及时清理。 [a new fixation]
*
（d） 垃圾 需要及时清理。 [after40/80/120/160ms]
*
（e） 垃圾 需要及时清理。 [An immediate re-fixation did’t result word reappearance]
*

Fig.1 Examples of the word n disappearance conditions (note: the asterisk indicates a fixation location).

（a） 垃圾通道需要及时清理。 [beginning of fixation]
*
（b） 垃圾 需要及时清理。 [after40/80/120/160ms]
*
（c） 垃圾通道需要及时清理。 [a new fixation]
*
（d） 垃圾通道 及时清理。 [after40/80/120/160ms]
*
（e） 垃圾通道 及时清理。 [An immediate re-fixation did’t result word reappearance]
*

Fig.2 Examples of the four word n+1 disappearance conditions (note: the asterisk indicates a fixation location).

Table 1(on next page)

Tables

Table 1:The mean and standard deviations of the measures across conditions and age groups in Experiment 1.

		RT	MeanGazeDur	Pro.Skip(%)	NO.Reg
Young adults	Control	2654(816)	254(38)	24.9(15.4)	1.7(1.1)
	40 ms	2761(822)	273(46)	25.3(15.6)	2.1(1.1)
	80 ms	2738(848)	274(56)	25.0(15.1)	1.9(0.9)
	120 ms	2625(840)	268(51)	25.5(16.9)	1.8(1.0)
	160 ms	2728(813)	269(49)	25.5(17.3)	1.7(1.0)
Aged adults	Control	3334(1001)	312(71)	13.5(8.3)	2.1(0.9)
	40 ms	3815(819)	288(55)	18.1(8.8)	3.5(0.9)
	80 ms	3632(835)	310(61)	16.5(10.1)	3.0(1.0)
	120 ms	3389(816)	304(60)	15.4(10.2)	2.7(1.0)
	160 ms	3439(835)	308(68)	16.6(9.4)	2.6(1.0)

Note: The standard deviations are given in parentheses. Control, the normal display condition; RT, sentence reading time in millisecond; MeanGazeDur, mean gaze duration in milliseconds; Pro.Sikp, probability of words skipped in the initial pass reading; NO.Reg, number of regressions.

Table 2. The mean and standard deviations of the measures across conditions and age groups in Experiment 2.

		RT	MeanGazeDur	Pro.Skip(%)	NO.Reg
Young adults	Control	2347(640)	262(31)	21.1(9.4)	1.4(0.7)
	40 ms	2498(762)	293(57)	26.8(9.4)	1.5(0.8)
	80 ms	2475(723)	287(42)	26.8(9.2)	1.6(0.8)
	120 ms	2494(691)	284(42)	24.8(8.7)	1.5(0.8)
	160 ms	2460(700)	279(39)	24.7(8.5)	1.5(0.8)
Aged adults	Control	3669(1123)	351(108)	7.6(4.6)	1.9(0.9)
	40 ms	5195(1299)	378(67)	14.3 (4.7)	4.4(2.1)
	80 ms	4784(1440)	396(80)	14.0(6.0)	3.6(1.7)
	120 ms	4687(1331)	396(75)	13.0(6.5)	3.3(1.6)
	160 ms	4544(1214)	391(83)	12.8(6.1)	3.0(1.2)