Effects of Word Frequency and Visual Complexity on Eye Movements of Young and Older Chinese Readers

Chuanli Zang[1], Manman Zhang[1], Xuejun Bai[1], Guoli Yan[1],

Kevin B. Paterson[2], & Simon P. Liversedge[3]

[1] Tianjin Normal University

[2] University of Leicester

[3] University of Southampton

Send Correspondence to:

Simon P. Liversedge,

Centre for Vision and Cognition,

School of Psychology,

Shackleton Building,

University of Southampton,

Highfield, Southampton, SO17 1BJ, UK

Email: s.p.liversedge@soton.ac.uk

Phone: +44 23 8059 9399

Fax: +44 23 8059 4597

Running Head: Eye Movements and Ageing in Chinese Reading

Abstract

Research using alphabetic languages shows that, compared to young adults, older adults employ a risky reading strategy in which they are more likely to guess word identities and skip words to compensate for their slower processing of text. However, little is known about how ageing affects reading behaviour for naturally unspaced, logographic languages like Chinese. Accordingly, to assess the generality of age-related changes in reading strategy across different writing systems we undertook an eye movement investigation of adult age differences in Chinese reading. Participants read sentences containing a target word (a single Chinese character) that had a high or low frequency of usage and was constructed from either few or many character strokes, and so either visually simple or complex. Frequency and complexity produced similar patterns of influence for both age-groups on skipping rates and fixation times for target words. Both groups therefore demonstrated sensitivity to these manipulations. But compared to the young adults, the older adults made more and longer fixations and more forward and backward eye movements overall. They also fixated the target words for longer, especially when these were visually complex. Crucially, the older adults skipped words less and made shorter progressive saccades. Therefore, in contrast with findings for alphabetic languages, older Chinese readers appear to use a careful reading strategy according to which they move their eyes cautiously along lines of text and skip words infrequently. We propose they use this more careful reading strategy to compensate for increased difficulty processing word boundaries in Chinese.

Keywords: Ageing, Eye Movements, Word Frequency, Visual Complexity, Chinese Reading.

(Word count for the main text: 6243 words)

Chinese is a logographic language in which text is printed horizontally (from left to right) as a sequence of box-like pictorial symbols (characters). Each of these characters either forms a word on its own or combines with other characters to form a word, although the boundaries between words are not demarcated using spaces or other visual cues. As with alphabetic languages (e.g., English), Chinese is read normally by making a series of saccadic eye movements across each line of text, separated by brief fixational pauses. Research investigating the spatial and temporal characteristics of these saccadic eye movements has been crucial for revealing visual and linguistic influences on where and when the eyes move during reading (e.g., Rayner, 2009), and is central to the development of sophisticated, formal computational models of eye movement control (e.g., Engbert, Nuthman, Reichter & Kleigl, 2005; Reichle, Rayner & Pollatsek, 2003). But while considerable advances have been made in understanding the mechanisms of eye movement control for reading Chinese (e.g., Li, Bicknell, Liu, Wei & Rayner, 2014), little work has investigated how eye movement behaviour changes with age for character-based, unspaced languages. Here we investigated how visual and linguistic influences on oculomotor control compare across different adult age-groups of Chinese readers, by comparing the eye movement behaviour of young (18-30 years) and older (65+ years) adult readers.

Of particular concern for the present research is the growing evidence that the written frequency of usage of words in Chinese, and the visual complexity of Chinese characters, both fundamentally influence decisions about when and where the eyes are moved during reading. In particular, words which have a low frequency of usage, and so are seldom encountered in written Chinese, are more likely to be fixated, and fixated for longer, than higher frequency words (e.g., Liversedge, Zang, Zhang, Bai, Yan, & Drieghe, 2014; Yan, Tian, Bai, & Rayner, 2006; Yang & McConkie, 1999). In addition, because Chinese characters occupy the same area of space, yet are created from a differing number of character strokes, their visual complexity varies. And this also appears to strongly influence eye movement behaviour. Indeed, research indicates that characters

that are highly visually complex (containing many strokes) are more likely to be fixated, and fixated

for longer, than less visually complex characters (e.g., Liversedge et al., 2014; Yang & McConkie,

1999). Liversedge et al. (2014) orthogonally manipulated these two variables and showed that they

each separately influenced the probability of fixating a single-character word. However, these

variables interactively influenced fixation times for words, so that low frequency words that were

visually more complex were fixated for longer than words in other conditions. This led Liversedge

et al. to argue that, while word frequency and visual complexity independently influence *where* the

eyes move, these factors jointly constrain *when* the eyes move when reading Chinese.

However, research on this topic has been concerned exclusively with the eye movement

behaviour of young adult readers and there has been little research to investigate the effects of ageing

on eye movement control during Chinese reading. Indeed, although several studies have been

published in Chinese (Bai, Guo, Cao, Gu & Yan, 2012; Wang, Bai, Yan & Wu, 2012; Wang, Shi,

Wu & Bai, 2010; Wu, Liu, Zhi & Hu, 2009; Zhang, Yan & Wang, 2011), most report data for older

adults only. Consequently, how eye movement behaviour differs across adult age-groups of readers

is unclear, although sensory and cognitive declines associated with older age may produce important

changes in eye movement behaviour for reading. Indeed, substantial changes in visual abilities occur

naturally with older age, and older adults often experience reductions in visual abilities which are

likely to affect both visual and subsequent linguistic processing of text (for a review, see Owsley,

2011). This includes a progressive loss of sensitivity to visual detail (e.g., Crassini, Brown, &

Bowman, 1988; Elliott, Yang, & Whitaker, 1995; Owsley, Sekuler, Siemsen, 1983), which has been

shown previously to affect normal reading performance for alphabetic languages (Jordan, McGowan

& Paterson, 2014; Paterson, McGowan & Jordan, 2013a,b). In addition, older adults typically

experience increased effects of visual crowding (McCarley, Yamani, Kramer, & Mounts, 2012;

Scialfa, Cordazzo, Bubric, & Lyon, 2013), characterised by reduced ability to recognise visual

objects in clutter, especially in peripheral vision (Bouma, 1971; see also Pelli & Tillman, 2008). In

addition, other research suggests that effects of visual crowding are larger for Chinese characters that are more visually complex (Wang, He & Legge, 2014; Zhang, Zhang, Xue, Liu & Yu, 2009). Consequently, compared to their younger counterparts, older Chinese readers may have greater difficulty identifying words, especially when these contain visually complex characters. However, the precise consequences of any such age-related changes in Chinese reading are unknown. A primary goal of the current work, therefore, is to establish that age-related changes in Chinese reading do actually occur, and on the assumption that they do, we were specifically interested to know how word frequency and visual complexity interact to influence eye movement control in older adult readers (as well as young adult readers).

An important further consideration is whether older Chinese readers exhibit age-related patterns of reading difficulty similar to those reported previously for alphabetic languages, as this will help reveal the extent to which age-related reading difficulty is language-specific or universal. Previous research with alphabetic languages has shown that, compared to young adults, older adults typically read more slowly, make more and longer fixational pauses, longer progressive saccades (forward eye movements), more regressions (backwards eye movements), and skip words more frequently (e.g., Jordan et al., 2014; Kemper & Liu, 2007; Kemper & McDowd, 2006; Kliegl, Grabner, Rolfs, & Engbert, 2004; McGowan, White, Jordan, & Paterson, 2014; Paterson et al., 2013a,b,c; Rayner, Castelhano, & Yang, 2009; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Rayner, Yang, Castelhano, & Liversedge, 2011; Rayner, Yang, Schuett, & Slattery, 2013; Stine-Morrow et al., 2010). In addition, older adults often show larger effects of word frequency, due to a disproportionate increase in fixation times for lower frequency words, consistent with older readers having greater difficulty identifying words (e.g., McGowan et al., 2014; Rayner et al., 2006, 2013).

These adult age differences in eye movement behaviour have previously been attributed to slowing of the lexical processing of words in older age, which is a likely consequence of sensory and

cognitive decline (e.g., Laubrock, Kliegl, & Engbert, 2006; Rayner et al., 2006; 2009; Stine-Morrow, Miller, & Hertzog, 2006). Moreover, it is widely argued that older adults compensate for such slower lexical processing by adopting a risky reading strategy with which they are more likely to infer the identities of upcoming words on the basis of prior context and only partial word information (e.g., Rayner et al., 2006, 2009). As a consequence, older adults are more likely than young adults to skip words and also tend to make longer progressive saccades. In addition, as older adults are more likely to initially misidentify these words, they tend to make more regressions to re-read text. However, Wotschack and Kliegl (2013) argued recently that the probability of a reader skipping a word is lowered if more careful reading is induced. Their study used difficult or easy comprehension questions following each sentence to induce more or less careful reading. Older readers were most strongly affected by the manipulation and, when questions were difficult, skipped words less often. In addition, McGowan et al. (2014; see also Rayner et al., 2013) compared the reading performance of young and older adults when sentences contained conventional interword spaces and when interword spaces were removed or replaced by nonlinguistic symbols. When interword spaces were absent, the older adults read more cautiously, presumably to compensate for the greater difficulty they had segmenting unspaced text. The indication, therefore, is that although older adults often may adopt a risky reading strategy, depending on the task demands they are also capable of more careful reading. An important further aim of the present research, therefore, was to determine whether older Chinese readers engage in more risky reading compared to their younger counterparts, or whether the particular task demands of reading a naturally unspaced language, such as Chinese, leads older adults to adopt a more careful reading strategy.

Investigations of the influence of word frequency and visual complexity on readers' eye movements and how this changes with older age will also inform the future development of computational models of eye movement control (e.g., Engbert et al., 2005; Reichle et al., 2003). The models that currently dominate research in this area (E-Z Reader, SWIFT) differ in their core

theoretical assumptions (e.g., serial sequential lexical processing versus parallel lexical processing). But, in both models, computations of fixation probabilities and fixation times for words are strongly influenced by word frequency and visual complexity (which, for alphabetic languages, is determined by the number of letters in a word). Both models have also been shown to successfully simulate effects of ageing on eye movement behaviour for alphabetic languages. Within the E-Z Reader model, this was achieved by adjusting parameters to slow the rate of lexical processing and increase effects of word frequency, and modifying other parameters to lower the criterion for word predictability and so increase word skipping (Rayner et al., 2006). Effects of ageing have been simulated in the SWIFT model primarily by adjusting parameters to produce generally slower rates of processing (Laubrock et al., 2006), although this model did not reproduce the increased word skipping observed for older readers of alphabetic languages. However, while efforts have been made to extend these models to eye movement control in Chinese reading (Rayner, Li, & Pollatsek, 2007), the modifications required for the models to account for adult age differences in eye movement behaviour when reading Chinese remain to be determined.

Accordingly, the present study examined the effects of word frequency and the visual complexity of words on the eye movements of young and older adults who are native Chinese readers. These participants read sentences that contained a target word formed by a single Chinese character that varied orthogonally in frequency (high frequency vs. low frequency) and visual complexity (high complexity vs. low complexity, indexed by stroke complexity). For the young adults, we expected to replicate the key findings from Liversedge et al. (2014). That is, main effects of frequency and visual complexity on the probability of skipping the target words and an interactive influence of these factors on fixation times for words. The present study is one of the first to compare the eye movements of young and older adult Chinese readers and will reveal if there are important adult age differences in Chinese reading. In particular, if older readers of Chinese, like older readers of alphabetic languages, find reading more difficult compared to their younger

counterparts, the older adults should read more slowly than the young adults, and make more and longer fixations and more regressions. The older adults may also have greater difficulty identifying words and so produce larger word frequency effects. In addition, because older readers typically have reduced visual sensitivity and experience increased effects of visual crowding, the older adults may have particular difficulty reading more visually complex words. Moreover, given the nature of sensory and cognitive declines in older age, it was possible that the combined influence of these factors would differ for the young and older adult readers. Finally, if older Chinese readers compensate for their poorer processing of text by employing a more risky reading strategy, as observed previously for older readers of alphabetic languages (e.g., Rayner et al., 2006), they may skip the target words more often than the young adults and also tend to make longer progressive saccades. However, as visual cues to the boundaries between words are lacking in written Chinese, the older readers may instead adopt a more careful reading strategy in order to compute the locations of word boundaries (e.g., McGowan et al., 2014) and so skip words less often, and tend not to make longer progressive saccades, compared to the younger readers. The present findings will also inform the development of models of eye movement control. In particular, if the effects of ageing we observe are consistent with previous findings for alphabetic languages, these might readily be accounted for by models of Chinese reading based on E-Z Reader or SWIFT. But if the present findings are very different from previous findings, it is less clear how the effects of age on eye movement behaviour when reading Chinese might be accounted for by these models.

<div align="center">Method</div>

Participants. Thirty-two younger adults (M = 22 years, range = 19-26 years) from Tianjin Normal University and 32 older adults (M = 69 years, range = 65-80 years) from the local Tianjin community participated in the experiment. All participants were native Chinese speakers who had corrected or uncorrected vision and were screened for visual and reading impairments. Participants were selected to have received at least 11 years of formal education (equivalent to receiving senior

high schooling) and all participants reported an interest in reading and that they read for several

hours (at least) each week. We undertook analyses that included years of schooling and self-reported

reading behaviour as addition statistical variables. These analyses produced the same pattern of

results as when these variables were omitted, and therefore, for the sake of simplicity, we report the

analyses without these variables included.

Materials and Design. The stimuli were the same as those used by Liversedge et al. (2014)

and consisted of 40 sets of 4 single-character target words that varied orthogonally in frequency

(high frequency vs. low frequency) and visual complexity (high complexity vs. low complexity; for

details, see Liversedge et al., 2014). The target words in each set were inserted into a sentence frame

that was identical up to the target word (see Figure 1). Sentences were on average 18 characters

long. Target words of each type did not differ in predictability in each sentence frame and sentences

containing each type of target word were equally plausible.

Insert Figure 1 about here

The experiment was a 2 (age-group: young or old adults) x 2 (word frequency: high or low) x

2 (visual complexity: high or low) mixed factorial design, with word frequency and visual

complexity as within-participants factors, and age-group as a between-participants factor. Word

frequency and visual complexity conditions were rotated across four files according to a Latin

square, so that each participant saw a given sentence frame only once but saw an equal number of

sentence frames containing a target word of each type. Each participant therefore saw a total of 40

experimental sentences. For each participant, these sentences were presented in random order,

preceded by eight practice sentences.

Apparatus and Procedure. A SR Research EyeLink 1000 eye tracker recorded participants'

right eye-movements every millisecond. The stimuli were presented on a high-resolution 19-inch

monitor as black text on a white background in Song font. Each Chinese character subtended

approximately .9° of visual angle and so of conventional size for reading.

Participants were instructed to read normally and for comprehension. At the start of the experiment, participants completed a three-point horizontal calibration procedure, and their calibration accuracy was checked before the presentation of each trial and re-calibrated as necessary (i.e., for calibration error > .35°). At the start of each trial, a fixation cross was presented on the left side of the screen. Once a stable fixation on this cross was detected, the sentence was presented (from left to right) with the first character replacing the cross. Participants pressed a response key on a button box to terminate the display once they finished reading a sentence. The sentence was then replaced by a comprehension question on 40% of trials, to which participants responded using the button box. For each participant, the experiment took approximately 20-30 minutes.

<div align="center">Results</div>

Comprehension accuracy was high for all participants, although higher for the young adults (91%) than the older adults (88%, $F(1,62) = 10.45$, $p<.01$), indicating that, while the older adults comprehended the sentences well, they did so less well than the young adults. Following standard procedures, fixations under 80ms and over 1200ms were deleted (this affected less than 5% of fixations for the lower bound, and less than .2% of fixations for the upper bound, with no difference across age groups, $ts < 1.6$, $ps >.05$). Trials were also excluded if tracker loss occurred or participants accidentally terminated the trial prematurely, or eye movement measures were more than 3SD from each participant's mean, accounting in total for only 1.1% of trials.

We computed two sets of analyses. For the global analyses, we conducted analyses of eye movements based on all the fixations by the young and older adults for each sentence; total sentence reading time, number of fixations, average fixation duration, number of progressive saccades (forward eye movements) and regressive saccades (backwards eye movements), and progressive saccade length. In addition, we conducted local analyses using measures of early word processing for the target words; the probability of skipping a word during initial processing (*SP*), the duration of the first fixation on a word (*first fixation duration* or *FFD*), the duration of the fixation on a word

receiving only one fixation during its initial processing (*single fixation duration* or *SFD*), and the sum of all fixations on a word during its initial processing (*gaze duration* or *GD*). We were specifically interested in the influence of the parafoveal processing of frequency and visual complexity on the probability of skipping a word. We therefore removed trials in which the launch site of the saccade to (or beyond) the target word was more than 3 characters from the target word (i.e., distant launch sites) (see e.g., Hand, Miellet, O'Donnell, Sereno, 2010; Liversedge et al., 2014). This exclusion criterion did not alter any of the observed effects. The number of observations before and after the exclusion of these data is listed (Table 3).

Data were analyzed by linear mixed models (LMM) using the lme 4.0 package (Bates, Maechler & Bolker, 2012) within R (R Development Core Team, 2014), specifying participants and stimuli as crossed random effects. Significance values were estimated using posterior distributions for model parameters using Markov-Chain Monte Carlo sampling and reflect both participant and stimulus variability (Baayen, Davidson & Bates, 2008). The models were run on log-transformed fixation times, and a logistic LMM model was used for the skipping rates. For the global analyses, the models included only age-group as a fixed factor. For the local analyses, all models included age-group, word frequency and visual complexity, and their interactions, and the length of the incoming saccade (i.e., launch site distance) as fixed factors. Skipping rates often are higher following a saccade from a close launch site (e.g., Liversedge et al., 2014). However, the length of the incoming saccade did not contribute to the goodness of fit of the statistical models in the present experiment and so effects of this variable are not reported.

Global Analyses

Table 1 shows means for the global measures, and Table 2 reports fixed-effect estimates for these measures and statistically significant effects are indicated using asterisks. Main effects of age-group were obtained in all measures except progressive saccade length. Compared to the younger adults, the older adults had longer reading times and made more and longer fixations, more forward

saccades and more regressions. These findings show that the older adults experienced greater

reading difficulty and are consistent with previous research on adult age differences in eye

movements when reading alphabetic languages (e.g., Rayner et al., 2006; 2009; Stine-Morrow et al.,

2006). However, in contrast with this previous research, there was no effect of age-group on

progressive saccade length in the present experiment [1], indicating that the older Chinese readers did

not produce longer forward eye movements than their younger counterparts.

Insert Table 2 about here

Local Analyses

Table 3 shows means for each local measure, and Table 4 reports fixed-effect estimates for

these measures and statistically significant effects are indicated using asterisks.

Insert Table 3 & 4 about here

Skipping Probability. There were main effects of word frequency and visual complexity on

word skipping. Readers skipped high frequency words (34% word skipping) more often than low

frequency words (31% word skipping), and low complexity words (35% word skipping) more often

than high complexity words (29% word skipping). However, there was no interaction between these

factors, which replicated the central finding from Liversedge et al. (2014). Of additional importance

was the main effect of age-group, which revealed that the young adults were more likely to skip

words (37% word skipping) than the older adults (27% word skipping). This effect of age-group did

not interact significantly with any other factors [2].

Fixation Times. There was a main effect of word frequency on gaze durations, which were

longer for low frequency words (354ms) than high frequency words (330ms). There were also main

effects of visual complexity on first fixation durations, single-fixation durations and gaze durations.

In each case, fixation times were longer for high complexity words (FFD = 326ms, SFD = 327ms,

GD = 353ms) than low complexity words (FFD = 297ms, SFD = 298ms, GD = 330ms). These

results replicate previous findings (Zang, Liversedge, Bai, & Yan, 2011). Crucially, and in contrast

to the word skipping results, word frequency and visual complexity interacted significantly in gaze durations (and produced marginal interaction effects for first fixation durations and single-fixation durations). The effect in gaze durations was due to a large effect of visual complexity for low frequency words and a negligible effect of visual complexity for high frequency words. This pattern differed from that reported previously for only young adults by Liversedge et al. (2014), who found complexity effects only for high frequency words, but nevertheless confirmed that word frequency and visual complexity interactively influence fixation times for words. We discuss possible reasons for this difference in the pattern of the interaction in the Discussion. There were no three-way interactions of age-group, word frequency, and visual complexity for the fixation time measures, indicating that the interactive effect of word frequency and visual complexity was essentially the same for the young and older readers.

Again, it was of particular importance that we also observed main effects of age-group on first fixation durations, single-fixation durations and gaze durations for the target words. In each case, this was due to the older adults fixating the target words for longer (FFD = 342ms, SFD = 346ms, GD = 385ms) than the younger adults (FFD = 277ms, SFD = 277ms, GD = 293ms). Age-group also interacted with visual complexity in first fixation durations and single-fixation durations. This was due to larger effects of visual complexity for the older adults than the young adults. For first fixation durations, the visual complexity effect was 46ms for older readers and 7ms for younger adults; and for single-fixation durations, it was 46ms for older adults and 8ms for younger adults. The same pattern in gaze durations was not significant. The indication, therefore, is that older adults had greater difficulty processing the more visually complex words.

Supplementary Analyses

The present results show that word frequency and visual complexity yield a broadly similar pattern of influence on fixation times and word skipping for the young and older adults. For both age-groups, these factors produced main effects, but no interactive influence, on the probability of

skipping a word. By comparison, for both age-groups, the two factors interacted to affect the

fixation times for the target words (observed most robustly in gaze durations). However, this

interaction differed from that reported previously by Liversedge et al. (2014) for only young adult

readers. In this previous study, an effect of visual complexity was observed only for low frequency

words, and fixation times were longer for low frequency, high complexity words compared to words

in the other conditions. In contrast, the present experiment produced a complexity effect only for

high frequency words and fixation times were shorter for high frequency, low complexity words

compared to words in the other conditions. The pattern of this interaction was broadly similar for the

young and older readers, although the older readers had longer fixation times in general (see Figure

2).

Insert Figure 2 about here

Accordingly, to assess more closely the correspondence between the present findings and

those reported previously, we conducted a further analysis that compared the gaze durations for the

young and older adults in the present experiment and those for the young adults in the Liversedge et

al. (2014) study (see Table 5a). We computed an LMM with factors participant group, word

frequency and visual complexity, and performed contrasts between the young adults in the study by

Liversedge et al. and the young and older adults in the present study (see Table 5b).

Insert Tables 5a&b about here

This analysis showed that while the older adults had the longest gaze durations, gaze

durations for the young adults in the present study were longer overall (by 25ms) compared to the

participants in the Liversedge et al. study. The interaction between word frequency and visual

complexity was marginal (and there were main effects of both factors). A contrast comparing the

interaction for the young and older adults in the present experiment showed no difference between

these two groups, confirming that the young and older adults in the present experiment produced

similar interaction effects. However, a contrast comparing the interaction effect for the young adults

in the present experiment and the participants in the Liversedge et al. study confirmed that these two groups produced different patterns of interaction.

The difference in reading performance between the two groups of young readers was surprising as participants were recruited from the same population of students. It nevertheless was striking that, as the analysis above reveals, the young adults in the present experiment produced longer fixation times on the target words compared to participants in the Liversedge et al. study. One possibility, therefore, is that subtle differences in the reading abilities of the two groups were responsible for the difference in the pattern of the interaction they produced. We examined this possibility further by comparing the sentence-level eye movements of these two groups of readers (see Table 6a). This analysis was conducted using an LMM with the factor participant group (see Table 6b).

<div align="center">Insert Tables 6a&b about here</div>

The analysis showed that the young adults in the present experiment had longer average fixation durations and made shorter progressive eye movements than the participants from the Liversedge et al. (2014) study, providing further evidence that the young adults in the present experiment had slightly poorer reading abilities. We explored possible sources of this difference in reading ability by more closely examining the make-up of these two groups. First, we considered the proportions of undergraduate and postgraduate students, as this might produce group differences in reading ability, but these were broadly similar (Liversedge et al., PG = 7.5%, UG = 92.5%; Present Study, PG = 12.5%, UG = 87.5%). We also considered the distribution of male and female students, but this too was broadly similar (Liversedge et al., male = 15%, female = 85%; present study, male = 12.5%, female = 87.5%). Moreover, LMMs that included these factors (educational level and gender) as additional covariates produced the same patterns of influence of age, word frequency and visual complexity on word-skipping and fixation times for the target words, a reliable effect of educational level on skipping (b =.18, p < .01), and only marginal effects of gender on both skipping

(b = .73, $p < .10$) and first fixation durations (b = .12, $p < .10$) and single fixation durations (b = .12, $p < .10$), due to elevated skipping rates and fixation durations for males compared to females.

Finally we considered the courses the participants studied. The Liversedge et al. group had a larger proportion of psychology students (78%) compared to the present group (47%) which included a larger proportion of students studying other science disciplines. It is unclear whether this difference is especially important, and there do not appear to be any other distinguishing features. However, an analysis that included this factor as an additional covariate, broadly defined in terms of whether the students majored in Psychology or Science, did not change the pattern of effects and showed no effect of the major subject of study. Consequently, while the difference in the pattern of the results for the young adults in the present experiment and those in the experiment by Liversedge et al. (2014) may reflect subtle differences in the reading abilities of these two groups of readers, there were no obvious differences in the composition of the participants in these two groups that might readily explain this difference in reading abilities.

Discussion

The present study assessed the eye movements of young and older adults who read sentences in Chinese, each of which included a single-character target word that varied orthogonally in frequency and visual complexity. Compared to the young adults, the older adults read more slowly, and made more and longer fixations, more progressive saccades, more regressions, and had longer fixation times for the target words. In these respects, the findings replicated key age-related differences in eye movement behaviour reported in earlier studies using alphabetic languages (e.g., Jordan et al., 2014; Kemper & Liu, 2007; Kemper & McDowd, 2006; Kliegl et al., 2004; McGowan et al., 2014; Paterson et al., 2013a,b,c; Rayner et al., 2006. 2009, 2011, 2013; Stine-Morrow et al., 2010). The present findings therefore show that, similar to findings for alphabetic languages, older readers of Chinese experience considerably more reading difficulty than their younger counterparts.

However, there were important differences between the present findings for Chinese and

those obtained previously using alphabetic languages. In particular, the older adults in the present experiment did not make longer progressive saccades compared to the young adults. In addition, it was particularly striking that the older adults were much less likely than the young adults to skip target words. This contrasts sharply with findings for alphabetic languages, in which older adults typically make longer progressive saccades and are more likely to skip words. Increased word skipping is associated with risky reading (e.g., O'Regan, 1990), and it is often argued that higher word skipping rates for older adults in previous research with alphabetic languages show that older readers use a risky reading strategy to compensate for their slower processing of text (e.g., Rayner et al., 2006, 2009). But, in contrast to these findings, other research suggests that older adults may not always use this risky reading strategy and can read more carefully when the nature of the task requires them to do so. For example, Wotschack and Kliegl (2013) found that older adults read more carefully when required to answer more difficult comprehension questions. Moreover, findings reported recently by McGowan et al. (2014; also Rayner et al., 2013) suggest that older adults adopt a more cautious reading strategy when visual cues to word boundaries are lacking.

The present findings indicate that older Chinese readers respond to the greater reading difficulty they experience, not by using a more risky reading strategy, but by reading more carefully. This may be a consequence of the specific visual and linguistic requirements of written Chinese. In particular, Chinese does not use extra spaces between characters to demarcate word boundaries, and there are no clear visual cues that might help older readers to quickly and easily determine which characters comprise a word (e.g., Bai, Yan, Liversedge, Zang, & Rayner, 2008; Zang, Liang, Bai, Yan, & Liversedge, 2013). Consequently, older adults may read Chinese more carefully than younger adults because they have particular difficulty establishing the location of the boundaries between words. Previous research with alphabetic languages also shows that older readers typically produce larger word frequency effects than younger adults due to greater difficulty identifying words during reading. This was not the case in the present experiment, and the young and older Chinese

readers produced word frequency effects that were of similar size (this pattern was maintained on

gaze duration while comparing the older adults in the present experiment and the young adult group

in the Liversedge et al. study, see Table 5b). This indicates that the older readers did not experience

particular difficulty with the more infrequent words. Moreover, it suggests that the more careful

reading strategy used by older readers to establish the boundaries between words in naturally

unspaced Chinese text may help them to lexically process words more efficiently.

Although Wotschack and Kliegl (2013) found that the difficulty of the comprehension

questions used in their study influenced reading strategy, and most of all for older readers, it was

unlikely that the use of comprehension questions led the older adults to read more carefully in the

present experiment. Indeed, the comprehension questions we used were not especially difficult and

broadly similar to those used in previous research with alphabetic languages in which older adults

exhibited risky reading (e.g., Rayner et al., 2006, young adults = 85%, older adults = 82%; Rayner et

al., 2009, young adults = 90%, older adults = 89%). What is clear, however, is that further work is

now required to more fully understand the underlying causes of the differences between the eye

movement behaviour of young and older Chinese readers, and to establish why Chinese readers use a

different strategy compared to readers of alphabetic languages to adjust to changes in their visual and

reading abilities in older adulthood.

The present results clearly show that word frequency and visual complexity yield a broadly

similar pattern of influence on fixation times and word skipping for the two age groups of readers.

For both groups, these factors produced main effects, but no interactive influence, on word-skipping.

This effect resembled that observed in previous research with only young adults (Liversedge et al.,

2014; Yang & McConkie, 1999) and both age-groups skipped high frequency words more often than

low frequency words, and low complexity words more often than high complexity words. By

comparison, for both age-groups, these two factors interacted to affect the fixation times for the

target words (observed most robustly in gaze durations). But the interaction differed from that

reported previously by Liversedge et al. (2014) for young adult readers. In this earlier study, an effect of visual complexity was observed only for lower frequency words, and fixation times were longer for low frequency, high complexity words compared to words in the other conditions. By comparison, the present experiment produced a complexity effect only for high frequency words and fixation times were shorter for high frequency, low complexity words compared to words in the other conditions. The pattern of this interaction was broadly similar for the young and older readers, although the older readers had much longer fixation times in general. Additional statistical analyses confirmed this difference in the pattern of the interaction produced in the two studies. In addition, comparisons of sentence-level measures showed that the older adults in the present experiment had longer average gaze durations and shorter progressive eye movements than the participants in the Liversedge et al. (2014) study. The indication, therefore, is that the young adults in the present study may have had slightly poorer reading abilities. To explore the source of this effect, we looked for differences in the make-up of the two groups but found no differences in the distribution of undergraduate and postgraduate participants or the ratio of male and female participants. Moreover, differences in the proportions of students majoring in Psychology (as compared to other science disciplines) did not appear to be responsible for this effect. Consequently, the precise source of the difference in performance of the two groups of young adult readers remains unclear but does not appear to reflect any obvious biases in sampling.

What does seem clear, however, is that the young adults in the present study had subtle, somewhat poorer reading abilities relative to the group in the Liversedge et al. study. This suggestion follows from analyses comparing global eye movement metrics between the two groups. This may account for the difference in the pattern of the frequency and complexity interaction produced by these two groups. However, care must be taken in reaching firm conclusions when these depend crucially upon the interpretation of complex between-participants differences. Such situations often arise in the context of cross-sectional designs that compare the performance of

different age-groups of participants (e.g., Salthouse, 2004). This type of design is nevertheless widely-used, typically in circumstances in which longitudinal or intervention-based studies are not practicable (as was the case with the present study). It will be important for future research to examine the mediating role of changes in global reading behaviour on precise interactive patterns of effects between particular variables more closely. It may also be necessary to establish the extent to which inter-generational differences, including differences in cultural and educational experiences, modulate age effects in reading behavior per se.

The present findings highlight that further research is now required to more fully investigate factors affecting the pattern of the interaction between word frequency and visual complexity during Chinese reading. Indeed, it was of particular importance for the present research that an interaction was observed for both the young and the older adult readers in the present experiment. While the exact pattern varied across participant groups, finding this interaction provides further evidence, in addition to that reported by Liversedge et al. (2014), that these two factors interactively influence how long readers fixate a word, jointly constraining decisions about when to move the eyes. By contrast, both the present findings and the earlier findings by Liversedge et al. show that these factors exert separate influences on the probability of skipping a word, indicating that frequency and complexity independently affect the targeting of saccades. Taken together, these findings support the view that decisions about when and where to move the eyes are made by different oculomotor systems (Findlay & Walker, 1999; Liversedge et al., 2014; Rayner & McConkie, 1976). But most critically, the present findings indicate, for the first time, similarities in the basic function of these two oculomotor systems for young and older adult readers.

In contrast to this commonality, other aspects of the present findings show that the older adults had specific difficulty processing more visually complex words. Indeed, not only did the older readers have generally longer fixation times, but there were interactions between age-group and visual complexity in first fixation durations and single-fixation durations for the target words. In

both cases, the older adults had greater difficulty processing more visually complex words compared to the young adults. This effect of visual complexity may reflect changes in the visual abilities of older adults. In particular, older adults typically experience reductions in visual sensitivity, especially for fine detail (e.g., Crassini et al., 1988; Elliott et al., 1995, Jordan et al., 2014; Owsley et al., 1983; Paterson et al., 2013b,c), and increased effects of visual crowding (McCarley, et al., 2012; Scialfa et al., 2013), both of which will impair the processing of text. Moreover, other research suggests that effects of visual crowding are greater for more visually complex characters (Wang et al., 2014; Zhang et al., 2009). But precisely how age-related changes in visual and reading abilities affect Chinese reading requires further investigation. For instance, effects of visual crowding are generally greater outside central vision, and so may particularly affect the parafoveal processing of text. Accordingly, further research that investigates the effects of ageing on parafoveal processing will make an important contribution to more fully revealing the nature of age-related changes in reading performance in Chinese.

Finally, the present findings reveal issues that will be important for the future development of computational models of eye movement control. The E-Z Reader and SWIFT models provide good accounts of the effects of ageing when reading alphabetic languages, such as English and German (e.g., Laubrock et al., 2006; Rayner et al., 2006). Both models implement the greater reading difficulty experienced by older adults by changing parameters within the models to slow lexical processing. In addition, within the E-Z Reader model, the more risky reading strategy employed by older readers of alphabetic languages is implemented by modifying parameters to lower the criterion for word predictability, thereby increasing word-skipping (Rayner et al., 2006). However, unlike older readers of alphabetic languages, older Chinese readers do not appear to employ a risky reading strategy. Instead, older Chinese readers appear to read more carefully than their younger counterparts, possibly because they experience greater difficulty identifying words in naturally unspaced text. A further important challenge will be to establish the extent to which different aspects of eye movement

control in reading are governed by universal principles, or principles that vary substantially across different writing systems in groups of participants of different ages.

In sum, the present research provides novel insights into effects of ageing on the eye movement behaviour of Chinese readers. As with older readers of alphabetic languages, there was clear evidence that older Chinese readers experience greater reading difficulty as a consequence of visual and cognitive declines that occur naturally in older age. However, older Chinese readers appear to adapt differently to these changes and, unlike older readers of alphabetic languages, employ a more careful reading strategy, according to which they move their eyes cautiously along lines of text and skip words infrequently. This difference in strategy may reflect the specific characteristics of the Chinese writing system.

Footnote

1. We also conducted a comparison of age group on progressive saccade length between the older

adult group in the present experiment and the young group in the Liversedge et al. (2014). The result

showed that older adults made significantly shorter progressive saccades compared to the young

adults (b = .30, *p* < .001).

2. An LMM analysis that included years of schooling as an additional factor produced the same

pattern of results, with the exception that the effect of age-group on word-skipping probability was

no longer robust. This finding, nevertheless, still contrasts sharply with findings from studies with

alphabetic languages showing that older adults typically skip words more often than younger adults

as a result of employing a more risky reading strategy.

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Table 1. Global eye movement measures for young and older adult readers. Standard deviations are provided in parentheses.

Age group	Total sentence reading time (ms)	Average fixation duration (ms)	Number of fixations	Number of forward saccades	Number of regressive saccades	Progressive saccade length (characters)
Young	3757 (1465)	258 (34)	14.5 (5.3)	10.1 (3.4)	3.6 (2.3)	2.0 (0.5)
Older	7227 (3619)	295 (53)	24.8 (12.2)	15.3 (6.2)	6.5 (4.2)	1.9 (0.5)

Table 2. Fixed effect estimates of global measures for the young and older adults.

Factor	Sentence reading time (ms)	Average fixation duration (ms)	Total number of fixations	Number of forward saccades	Number of regressive saccades	Progressive saccade length (characters)
(Intercept)	8.47***	5.61***	2.86***	2.47***	1.35***	.64 ***
Age	-.61***	-.13***	-.49***	-.41***	-.62***	.06

*** p <.001, ** p <.01, * p <.05, § p <.1

Table 3. Valid trial numbers and eye movement measures of skipping probability (SP), first fixation duration (FFD), single fixation duration (SFD) and gaze duration (GD) for target words reading in young and older adults when their eyes were less than three characters away on the preceding fixation. Standard deviations are provided in parentheses.

Measure	Age	No. of observations (close launch site/all)	High Frequency-Low Complexity	Low Frequency-Low Complexity	High Frequency-High Complexity	Low Frequency-High Complexity
SP	Young	1219/1276	.42 (.49)	.37 (.48)	.36 (.48)	.32 (.47)
	Older	1197/1272	.31 (.46)	.31 (.46)	.25 (.43)	.24 (.43)
FFD	Young	761/804	266 (98)	281 (103)	285 (105)	276 (102)
	Older	860/898	310 (111)	327 (129)	362 (155)	367 (164)
SFD	Young	709/749	267 (97)	280 (104)	287 (103)	276 (101)
	Older	757/791	312 (114)	332 (132)	363 (150)	373 (167)
GD	Young	761/802	275 (109)	306 (136)	301 (118)	289 (112)
	Older	861/899	339 (143)	395 (221)	389 (173)	417 (206)

Table 4. Fixed effect estimates of skipping probability (SP) of the target word and first fixation duration (FFD), single fixation duration (SFD) and gaze duration (GD) for the young and older adults. The reference level was the Low Complexity – High Frequency condition.

Factor	SP	FFD	SFD	GD
(Intercept)	.92***	5.63***	5.63***	5.70***
Age	.75*	-.19***	-.20***	-.24***
Complexity	-.40***	.07 ***	.07***	.06**
Frequency	-.29**	.03	.03	.06**
Complexity × Frequency	-.23	-.07§	-.06§	-.10**
Age × Complexity	.14	-.08*	-.07*	-.06
Age × Frequency	-.22	.00	-.03	-.04
Age × Complexity × Frequency	.05	-.05	-.05	-.05
Launch Site	-1.93***	.02	.02	.01

*** p <.001, ** p <.01, * p <.05, § p <.1

Table 5. (a) Target word gaze durations (with SDs) for the young adult participants (Young Group 1) in the Liversedge et al. (2014) study and the young (Young Group 2) and older adults in the present experiment, and (b) fixed-effects estimates for these groups.

a.

Measure	Group	High Frequency-Low Complexity	Low Frequency-Low Complexity	High Frequency-High Complexity	Low Frequency-High Complexity
GD	Young Group 1	267 (85)	266 (87)	262 (76)	277 (84)
	Young Group 2	275 (109)	306 (136)	301 (118)	289 (112)
	Older Adults Group	339 (143)	395 (221)	389 (173)	417 (206)

b.

Factor	GD
(Intercept)	5.65***
Contrast 1 (Young Group 2 - Young Group 1)	.06[§]
Contrast 2 (Older Adults - Young Group 2)	. 24***
Contrast 3 (Older Adults - Young Group 1)	.30***
Complexity	.04**
Frequency	.05***
Contrast 1 (Young Group 2 - Young Group 1) × Complexity	.01

Contrast 2 (Older Adults - Young Group 2) × Complexity	.06§
Contrast 3 (Older Adults - Young Group 1) × Complexity	.07*
Contrast 1 (Young Group 2 - Young Group 1) × Frequency	.01
Contrast 2 (Older Adults - Young Group 2) × Frequency	.04
Contrast 3 (Older Adults - Young Group 1) × Frequency	.05
Complexity × Frequency	-.05§
Contrast 1 (Young Group 2 - Young Group 1) × Complexity × Frequency	-.19**
Contrast 2 (Older Adults - Young Group 2) × Complexity × Frequency	.05
Contrast 3 (Older Adults - Young Group 1) × Complexity × Frequency	-.14*
Launch Site	.01

*** $p < .001$, ** $p < .01$, * $p < .05$, § $p < .1$

Table 6. (a) Global eye movement measures (with SDs) for the young adult participants (Young1) in the Liversedge et al. (2014) study and the young adult participants (Young2) in the present experiment, and (b) fixed-effects estimates for these groups.

a.

Group	Total sentence reading time (ms)	Reading rate (word /min)	Average fixation duration (ms)	Number of fixations	Number of forward saccades	Number of regressive saccades	Progressive saccade length (characters)
Young1	3504 (1457)	361 (136)	238 (36)	14.7 (5.8)	9.8 (3.5)	4.1 (2.6)	2.6 (0.7)
Young2	3757 (1465)	333 (127)	258 (34)	14.5 (5.3)	10.1 (3.4)	3.6 (2.3)	2.0 (0.5)

b.

Factor	Sentence reading time (ms)	Reading rate (word /min)	Average fixation duration (ms)	Total number of fixations	Number of forward saccades	Number of regressive saccades	Progressive saccade length (characters)
(Intercept)	8.12***	5.78***	5.50***	2.62***	2.25***	1.13***	.79***
Group	.08	-.08	.08***	-.01	.03	-.18*	-.24***

*** $p < .001$, ** $p < .01$, * $p < .05$, § $p < .1$

Figure 1. Example of the sentences used in the Experiment. Target words are shown in bold but were shown normally in the experiment.

High Frequency-Low Complexity	生活百科上提到**加**了蜂蜜的牛奶对女性有益 The household encyclopedia indicates that honey **added** to milk is good for women
Low Frequency-Low Complexity	生活百科上提到**习**过武的人身体协调性比较好 The household encyclopedia indicates that men who **learned** Kung-Fu are in better physical coordination
High Frequency-High Complexity	生活百科上提到**醒**太早可能是某些疾病的预兆 The household encyclopedia indicates that **waking** up too early may be a sign of some disease
Low Frequency-High Complexity	生活百科上提到**孵**小鸡需要保持一定的温度 The household encyclopedia indicates that **hatching** chicks need to be maintained at a certain temperature

Figure 2. Gaze durations for the target words between the young adults (Young Group 1) in the Liversedge et al. (2014) study, the young adults (Young Group 2) and older adults in the present experiment. Target words either were high-frequency and low-complexity (HF-LC), low-frequency and low-complexity (LF-LC), high-frequency and high-complexity (HF-HC), or low-frequency and high-complexity (LF-HC).