The "Risky" Reading Strategy Revisited: New Simulations Using E-Z Reader

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Running Head: The Risky Reading Strategy Revisited

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Abstract

Eye-movement studies have demonstrated that, relative to college-aged readers, older readers of alphabetic languages like English and German tend to read more slowly, making more frequent, longer fixations, longer saccades, skipping more words, but also making more frequent regressions. These findings have led to suggestions that older readers either adopt a “risky” strategy of using context to “guess” words as a way of compensating for slower rates of lexical processing (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006), or that they have a smaller and more asymmetrical perceptual span (Laubrock, Kliegl, & Engbert, 2005). Unfortunately, neither of these hypotheses seemingly explains more recent observations that older readers of Chinese seem to adopt a more “conservative” strategy, making shorter saccades and skipping less often (Wang et al., in press; Zang et al., 2016). In this paper, we use the *E-Z Reader* model of eye-movement control (Reichle, Pollatsek, & Rayner, 2012) to examine several possible accounts of the differences between college-aged and older readers of both alphabetic and non-alphabetic languages. These simulations re-confirm that the “risky” strategy may be sufficient to explain age-related differences in reader’s eye movements, with older readers of English versus Chinese being respectively more versus less inclined to guess upcoming words. The implications of these results for aging, reading, and models of eye-movement control will be discussed.

Key words: aging, computational models, E-Z Reader, reading, saccades

Word count: 4,490

In this article, the *E-Z Reader* model of eye-movement control in reading (Reichle, Pollatsek, & Rayner, 2012) is used to evaluate three hypotheses about why the eye movements of older readers (aged 65+) differ from those of younger, college-aged readers (aged 18-30). This topic is especially appropriate for this special issue honouring Keith Rayner in that he helped develop the original version of E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998) and remained active in both its development (e.g., Rayner, Ashby, Pollatsek, & Reichle, 2004) and use as a tool for understanding reading (e.g., Rayner, Li, & Pollatsek, 2007), and because he and his colleagues pioneered the early research examining eye movements of older readers (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). It is therefore fitting that this article be included among the contributions to this issue because it reports simulations using E-Z Reader to both re-evaluate the "risky" reading strategy account that was proposed by Rayner et al. to explain the patterns of eye movements observed with older readers, as well as testing two alternative accounts of these patterns.

We begin with an overview of how the eye movements of older readers differ from those of college-aged readers, and possible accounts of these differences. In particular, we will highlight recent evidence demonstrating key differences in the eye movements of older readers of alphabetic scripts (e.g., English) in comparison to older readers of non-alphabetic scripts (e.g., Chinese) and the implications of these findings for theoretical accounts of adult age differences in reading. We then briefly describe the E-Z Reader model and report simulations to evaluate these accounts.

Eye Movements of College-Aged vs. Older Readers

There is substantial evidence demonstrating age-related changes in eye-movement behaviour during reading. In particular, older readers of alphabetic languages read more slowly than their younger counterparts, make more and longer fixations, and make more regressions to revisit earlier parts of the text (Kliegl, Grabner, Rolfs, & Engbert, 2004; McGowan, White, Jordan, & Paterson, 2014; McGowan, White, & Paterson, 2015; Paterson, McGowan, & Jordan, 2013a; Rayner et al., 2006; Rayner, Yang, Castelhano, & Liversedge, 2011; Rayner, Yang, Schuett, & Slattery, 2013). Moreover, in comparison to young adult readers, older readers also skip words more frequently, and so generally move their eyes further forward in the text (McGowan et al., 2014; 2015; Paterson et al., 2013a; Rayner et al., 2006; 2011; 2013).

Intriguingly, this pattern of eye-movement behaviour observed in older readers of alphabetic languages does not resemble that of other groups of slower readers, such as developing readers (Reichle et al., 2013) or readers with dyslexia (Rayner, 1985). Instead, the indication is that the processes that control eye-movement behaviour during reading are subject to specific age-related changes. But the precise nature of these changes, and their impact upon the mechanisms that underlie eye-movement control, have yet to be fully determined.

One initially attractive suggestion (Laubrock, Kliegl, & Engbert, 2005) is that the region in which information can be sampled and used for lexical processing during a single fixation (i.e., the *perceptual span*) is more asymmetric for older than young adults. Thus, older readers process more text to the right and so skip words more often, but process less text to the left and so frequently regress back to text outside the span. This seemingly intuitive account provides a parsimonious fit with the pattern of eye movements observed in older readers (as confirmed by simulating these changes, in addition to the effects of reduced visual acuity and lexical inhibition, using the *SWIFT* model of eye-movement control during reading; Engbert, Nuthmann, Richter, & Kliegl, 2005). However, it has received little empirical support. Instead, studies which have examined age-related changes in parafoveal processing have indicated that the perceptual span of older readers is as asymmetric, or possibly even more symmetric, than that of young adult readers (Rayner, Castelhano, & Yang, 2009; 2010; Rayner, Yang, Schuett, & Slattery, 2014; Risse & Kliegl, 2011; Whitford & Titone, 2016).

A more compelling account proposed by Rayner and colleagues (Rayner et al., 2006), and previously implemented within an earlier version of the E-Z Reader model, is that older readers adopt a “riskier” reading strategy than young adults. That is, to compensate for an age-related slowdown in lexical processing (Allen, Madden & Crozier, 1991; Tainturier, Tremblay, & Lecours, 1989), older adults frequently guess the identities of upcoming words. Consequently, older readers are more likely to skip upcoming words, but are also more likely to make regressions as these guesses often prove wrong. Simulations of the risky reading strategy within E-Z Reader (implemented by modifying parameters associated with lexical processing, visual acuity, and the guessing of upcoming words) were successful in reproducing the basic pattern of eye movement behaviour in older readers: more and longer fixations, more regressions, and longer progressive saccade lengths.

However, it is currently unclear how the risky reading strategy may account for more recent findings showing a markedly different pattern of age-related changes for readers of Chinese (Wang et al., in press; Zang et al., 2016). Indeed, rather than reading more "riskily" than their younger counterparts, older readers of Chinese instead appear to adopt a more cautious reading strategy, and so skip words less frequently and move their eyes less far forward in the text. This is despite showing the same pattern of longer reading times, more and longer fixations, and more regressions as older readers of English. Consequently, any plausible explanation of adult age differences in reading will need to account for the very different pattern of eye movements between older readers of Chinese and English.

Here, we revisit the risky reading strategy and its implementation within E-Z Reader. In particular, we re-evaluate the success of the risky reading strategy in accounting for the eye movements of older readers of alphabetic languages using the current version of E-Z Reader. This version of E-Z Reader has additional assumptions (particularly in relation to higher language processing; Reichle, Warren, & McConnell, 2009) in comparison to the earlier version of E-Z Reader used to simulate age-related differences (Rayner et al., 2006), and so will not require similar ad hoc parameters in order to determine the probability of misidentifying words. More crucially, however, these simulations will also allow us to assess what additional assumptions are needed in order to account for the markedly different pattern of eye movements observed for the older readers of Chinese.

In addition to re-examining the risky reading hypothesis, we will also examine two alternative accounts that also offer plausible explanations of age-related changes in eye-movement behaviour during reading. These accounts, which we will refer to as the *visual-acuity* and *oculomotor-control hypotheses*, are derived from the large body of evidence demonstrating that even normal, healthy older age is associated with changes within the visual and oculomotor systems which may substantially impair older readers' basic visual processing and execution of eye movements (see Bruenech, 2008; Owsley, 2001). In particular, older adults experience a reduced sensitivity to fine detail, resulting in difficulty in identifying features and individual letters/characters even with appropriate optical correction (e.g., Crassini, Brown, & Bowman, 1988; Jordan, McGowan, & Paterson, 2014; Paterson, McGowan, & Jordan, 2013b; c). Older adults also experience greater effects of crowding (Scialfa, Cordazzo, Bubric, & Lyon, 2013), characterized by a difficulty in identifying visual information (such as letters or characters) when surrounded by similar visual information (Bouma, 1971), which is likely to further interfere with accurate and efficient sampling of text. These difficulties are most pronounced outside of central vision (Crassini et al, 1988; Scialfa et al., 2013), and so are likely to particularly impair parafoveal processing of text. Older adults also experience a range of oculomotor deficits, most notably reduced saccadic accuracy (e.g., Huaman & Sharpe, 1993; Irving, Steinback, Lillakas, Babu, & Hutchings, 2006; Sharpe & Zackon, 1987). This may result in older adults frequently landing in non-optimal locations, or even on words other than the intended saccade target, with a subsequent impact upon skipping rates, as well increases in the overall number of fixations and regressions due to the need to make additional corrective saccades (although see, e.g., Paterson et al., 2013 for evidence of similar landing position distributions to those of young adults). It is worth noting from the outset that we do not expect these hypotheses to account for the very different patterns of eye movements in older readers of English and Chinese without the addition of linguistic variables. Nevertheless, these simulations will provide an initial step in examining how these factors may contribute to adult age differences in reading.

Before describing the simulations, we will first provide a brief overview of the E-Z Reader model, which will be used as a framework for evaluating these different hypotheses.

E-Z Reader

For brevity, this article does not provide a detailed description of the E-Z Reader model, a justification of its theoretical assumptions, or the basis for the selection of its parameter values, but instead gives only enough detail to understand the simulations reported below. (For such a description, see Reichle et al., 2012.)[1] Figure 1 is a schematic diagram of the model, showing its various components and how information and control of processing flows among those components. The model has three core theoretical assumptions related to how word identification controls the progression of the eyes through text. The first is that lexical processing is completed on one word at a time, in a strictly serial manner. The second is that a preliminary stage of lexical processing, called the *familiarity check*, is the "trigger" to begin programming a saccade from one word to the next. The third is that the completion of a second stage of lexical processing, corresponding to *lexical access*, causes attention to shift to the next word.

Figure 1

In the model, the time (in ms) required to complete this first stage of lexical processing, $t(L_1)$, is a function of each word n's frequency in printed text (as tabulated in corpora; e.g., Francis & Kucera, 1982) and its within-sentence predictability (as measured by cloze probability; Taylor, 1965). With a probability equal to a word's cloze predictability, word n is "guessed" from its preceding context, so that $t(L_1) = 0$ ms. In the majority of cases, however, word n is not guessed and $t(L_1)$ is given by Equation 1, where $freq_n$ and $pred_n$ are the frequency and cloze predictability of word n, respectively, and α_1, α_2, and α_3 are free parameters:

$$(1) \qquad t(L_1) = \alpha_1 - \alpha_2 freq_n - \alpha_3 pred_n$$

Equation 1 specifies the mean value of $t(L_1)$ for a word of a given frequency and predictability; however, during any given Monte-Carlo simulation of the model, the actual value of $t(L_1)$ is sampled from a gamma distribution with a mean specified by Equation 1 and a standard deviation equal to some proportion, σ_γ, of the mean. (In a similar manner, the durations of the processes described below are also sampled from gamma distributions.) This time is also slowed as a function of *foveal eccentricity*, or distance between the centre of the fovea (i.e., the fixation position) and the positions of individual letters in the word that is being processed, as specified by:

$$(2) \qquad t(L_1) \leftarrow t(L_1) * \varepsilon^{\left(\sum_{i=1}^{N} |fixation - letter_i|\right)/N}$$

In Equation 2, ε is a free parameter that has as its exponent the mean absolute deviation (in character spaces) between the fixation position and each of the N letters of the word being processed. Thus, on average, the familiarity check on word n will complete rapidly for a word that is high frequency, predictable from its context, short in length, and/or fixated near its centre.

Finally, the time required to complete the second stage of lexical processing, $t(L_2)$ is given by Equation 3, where $t(L_1)$ is the value given by Equation 1 and Δ is a free parameter that modulates the additional proportion of $t(L_1)$ required to complete $t(L_2)$.

$$(3) \qquad t(L_2) = \Delta * t(L_1)$$

With the completion of lexical access, two things happen. First, after some amount of time, $t(A)$, attention shifts to the next word so that its lexical processing can begin. Second, after some other amount of time, $t(I)$, the meaning of the identified word is integrated into the sentence representation being constructed. Whether or not cloze predictability is used in identifying word n+1 is contingent upon the successful post-lexical integration of word n. In addition, failure to integrate word n prior to the lexical identification of word n+1 results in the eyes and attention being directed back (i.e., an inter-word regression) to word n with probability p_N or to word n-1 with probability $(1 - p_N)$. Post-lexical integration can also fail outright (e.g., due to the mis-parsing of a syntactically ambiguous sentence) with some probability, p_F, also resulting in an inter-word regression back to word n or n-1.

The remaining model assumptions are all related to saccadic programming and execution. First, saccades are programmed in two stages: a *labile stage* that requires $t(M_1)$ ms to complete and that can be cancelled by the initiation of a subsequent saccade, followed by a *non-labile stage* that requires $t(M_2)$ ms to complete and that cannot be cancelled. The labile stage can be further subdivided into a "preparatory" stage requiring some proportion, ξ, of $t(M_1)$ to complete and a "conversion" stage in which the spatial target is converted to distance (i.e., muscle force), with any time spent completing the preparatory stage being saved if one labile program cancels another. As a simplifying assumption, the saccades themselves are assumed to require a constant S ms to complete.

Second, the saccades are directed towards the centres of words (which affords maximal visual acuity) and their length (in character spaces) is the sum of three components: the intended saccade length, random motor error, and systematic error. The random error (in character spaces) is sampled from a Gaussian distribution with $\mu = 0$ and a standard deviation, σ, that increases linearly with the intended saccade length, ISL, as specified by:

$$(4) \qquad \sigma = \eta_1 + \eta_2\, ISL$$

In Equation 4, η_1 and η_2 are free parameters that modulate the amount of random error. The systematic error causes saccades shorter/longer than some "optimal" length, Ψ, to over/undershoot their intended targets, with this bias increasing as the launch-site fixation duration decreases. This is specified by Equation 5, where Ω_1 and Ω_2 are free parameters:

(5) $systematic\ error = (\Psi - ISL)\{[\Omega_1 - \ln(fixation\ duration)] / \Omega_2\}$

Finally, saccades move the eyes to new viewing locations, allowing the rate of lexical processing to be updated (using Equation 2) after *V* ms—the duration of the "eye-to-brain" lag. However, saccades that deviate from their intended targets are sometimes followed by "automatic" corrective saccades that are intended to move their eyes closer to their targets; the probability of this happening, *p*, is a function of the absolute distance (in character spaces) between the centre of the target word and the initial fixation position, as specified by Equation 6, with λ being a free parameter that modulates the propensity:

(6) $p = \lambda\ |\ fixation\ position - word\ centre\ |$

Although Equation 6 makes a refixation more likely following an initial fixation near either end of word *n*, the resulting labile saccade can be cancelled if the familiarity check on the word *n*+1 completes and initiates a saccadic program to move the eyes to word *n*+2. This complex interaction causes single- and first-fixation durations to be shorter when they are located near a word's beginning or end, thereby providing an account of the *Inverted Optimal Viewing Position* (*IOVP*) effect (Vitu, McConkie, Kerr, & O'Regan, 2001).

Simulations

The model as described above was used to complete four simulations. Simulation 1 was used to find a set of parameter values that allow the model to simulate a variety of eye-movement measures from college-aged readers. This "baseline" model was then used to examine three hypotheses about how aging might influence these eye-movement measures in older readers across Simulations 2-4. Although our goal was to provide a possible qualitative account of how aging affects the reading of alphabetic languages like English, the results also have interesting implications for this issue in relation to Chinese.

Simulation 1: College-aged readers. This simulation was intended to find a set of parameter values that would allow the model to both qualitatively simulate the distributions of fixation landing sites and refixation probabilities that have been reported in the literature (e.g., Rayner & Fischer, 1996) and quantitatively simulate the observed means for six word-based measures in the Schilling, Rayner, and Chumbley (1998) sentence corpus: (1) first-fixation duration; (2) single-fixation duration; (3) gaze duration; and the probabilities of: (4) making a single fixation; (5) making two or more fixations; and (6) skipping.

This was done by first adjusting the default values of parameters that control random saccadic error (i.e., η_1 and η_2) and the propensity to make "automatic" refixations (i.e., λ) to allow the model to qualitatively simulate the effects associated with initial fixation position[2]. Then, three grid searches were completed of a space defined by the parameters that control the lexical-processing rate: α_1, α_2, α_3, and Δ. (For details of how these grid searches are completed, see Reichle et al., 2012, Appendix B.) The first search used 1,000 statistical subjects per parameter permutation and varied the four parameters over the following domains using the indicated increments: (1) $\alpha_1 \in [100, 120]$, increment = 2.5; (2) $\alpha_2 \in [1, 4]$, increment = 1; (3) $\alpha_3 \in [10, 40]$, increment = 10; and (4) $\Delta \in [0.2, 0.5]$, increment = 0.1. The second search used 2,500 statistical subjects centred on the best-fitting parameter values obtained in the first search and the following increments: $\alpha_1 = 1$; $\alpha_2 = 0.5$; $\alpha_3 = 5$; and $\Delta = 0.05$. Likewise, the final search used 5,000 statistical subjects and the following increments: $\alpha_1 = 1$; $\alpha_2 = 0.1$; $\alpha_3 = 1$; and $\Delta = 0.01$.

The resulting best-fitting parameter values are shown in Table 1. The model's performance using these parameters is shown in Figure 2: Panels A and C show the model's fits to the Schilling et al. (1998) sentence corpus; Panels E, G, and I respectively show the model's capacity to simulate fixation landing-site distributions (e.g., McConkie, Kerr, Reddix, & Zola, 1988), refixation-probability distributions (e.g., McConkie, Kerr, Reddix, Zola, & Jacobs, 1989), and single-fixation durations as a function of their positions (i.e., IOVP effects; e.g., Vitu et al., 2001). Simulation 1 thus indicates that the model can explain a variety of important eye-movement measures of young adult readers. The remaining simulations are intended to test three hypotheses about how aging might influence reading as indexed by these measures.

Figure 2 & Table 1

Simulation 2: Risky reading hypothesis. One hypothesis that has been proposed to explain age-related effects on readers' eye movements is related to the slowing of lexical processing and the adoption of a compensatory strategy of using text context to "guess" upcoming words. As originally described by Rayner et al. (2006), this "risky" reading strategy affectively amounts to older readers being more reliant upon their knowledge of language to partially offset the decreased rate in reading that would otherwise result from slower lexical processing. This hypothesis was tested by Rayner et al. using an earlier version of E-Z Reader—one that required ad hoc assumptions about how the mis-identification of words results in inter-word regressions. In the present simulation, the hypothesis was tested using E-Z Reader 10 by simply including the assumption that older readers have an increased probability, κ, of "guessing" the identity of each upcoming word (i.e., the probability of "guessing" each word was set equal to the sum of that word's cloze predictability and κ)[3]. The remaining model assumptions and parameter values were exactly the same as those used in Simulation 1, with two exceptions: The values of the κ and α_1 (the parameter that controls the overall rate of lexical processing; see Equation 1) were independently adjusted to determine how both word "guessing" and a slowing of lexical processing influence readers' eye movements. The two parameters were thus adjusted across the following domains using the indicated increments: (1) $\kappa = [0, 0.1]$, increment = 0.01; and (2) $\alpha_1 = [115, 175]$, increment = 10. Thus, it was possible to examine how these two parameters modulate a pattern of behaviours that have previously been observed with older readers of alphabetic languages like English: (1) increased fixation durations; (2) longer forward saccades; (3) more fixations; (4) more word skipping; (5) more inter-word regressions; and (6) reduced reading rate.

The results of Simulation 2 are presented in Tables 2 and 3, and Figure 2. First, as Table 2 shows, the simulation replicated and extended those previously reported by Rayner et al. (2006) in demonstrating that a more complete version of E-Z Reader can accommodate the full qualitative pattern of results with only two simple assumptions: that older readers are slower at processing words but more likely to “guess” words from context. As the locations of the “E”s in Table 2 show, this qualitative pattern was evident across a range of κ and α_1 values, and as Table 3 shows, the simulated differences between younger and older adult readers were fairly pronounced. (These qualitative patterns are stable because the simulations using each permutation of parameter values are based on 1,000 statistical subjects.)

However, contrary to what was expected, some combinations of parameter values also reproduced a pattern of eye-movement behaviours that has been observed with older readers of Chinese; namely, the same pattern observed with English but with *decreases* in both forward saccade length and skipping rates. As the locations of the “C”s in Table 2 show, this second pattern occurred when there was a slow down in lexical processing but no compensatory increase in word guessing (e.g., large values of α_1 combined with very small values of κ). One interpretation of this pattern is that it reflects the normal slowdown in lexical processing that results from aging, but also a reluctance to adopt the “risky” strategy of guessing upcoming words. Given that E-Z Reader is a model of eye-movement control during the reading of English and not Chinese, however, this interpretation is obviously speculative.

Finally, Figure 2 provides a direct comparison of the model’s performance in simulating eye movements of younger versus older readers of English. As has been reported in the literature (e.g., see Paterson et al., 2013a), the fixation landing-site distributions of the two age groups do not differ noticeably (cf., Panels E & F), despite the marked differences in various fixation-duration (cf., Panels A & B) and fixation-probability (cf., Panels C & D) measures. A comparison of the refixation-probability (cf., Panels G & H) and IOVP curves (cf., Panels I & J) indicate that the model predicts more pronounced effects on both behaviours for older as compared to younger readers—predictions that have yet to be tested.

Tables 2 & 3

Simulation 3: Visual acuity hypothesis. This simulation was designed to test an alternative account of the observed aging effects: That they reflect an age-related decline in visual acuity. The simulation was thus similar to Simulation 2 except that the values of κ and ε (i.e., the parameter that controls the effect of visual acuity; see Equation 2) were manipulated instead of κ and α_1. The two parameters were thus adjusted across the following domains using the indicated increments: (1) $\kappa = [0, 0.1]$, increment = 0.01; and (2) $\varepsilon = [1.15, 1.75]$, increment = 0.1.

The results of Simulation 3 are summarized in Table 4. Contrary to what might be predicted from the visual-acuity hypothesis, a slow-down in lexical processing due to a decline in visual acuity was not sufficient to reproduce the general pattern that has been reported with older readers of English or Chinese. Although three pairs of parameter values did result in dependent measures that were qualitatively similar to those observed with older readers of English, the observed differences were very small; for example, as Table 5 shows, word skipping increased to a negligible degree.

Tables 4 & 5

Simulation 4: Oculomotor control hypothesis. This final simulation was designed to test a third account of the observed aging effects: That they reflect an age-related decline in saccade accuracy. To test this, the values of η_1 and η_2 (i.e., the parameters that modulate random saccadic error) were orthogonally varied with each other and κ using the following domains and increments: (1) $\kappa = [0, 0.1]$, increment = 0.01; (2) $\eta_1 = [0.5, 1]$, increment = 0.1; and (3) $\eta_2 = [0.1, 0.5]$, increment = 0.1.

Although none of the parameter combinations were sufficient to produce the patterns observed with older readers of English or Chinese, it is difficult to draw strong conclusions from a null finding. For example, one occulomotor account that warrants future exploration (because it is currently outside of the theoretical scope of E-Z Reader) is related to evidence that older readers are more apt to lapse into intervals of "mindless reading" (Risse & Kliegl, 2011). By this account, such intervals might be associated with more superficial text processing and thereby result in less accurate saccade targeting and the eye movements observed with older readers (e.g., longer saccades). Acknowledging this and other possible limitations, the implications of our simulation results are discussed next.

Discussion

In the present paper E-Z Reader was used to examine different accounts of why the eye movements of older readers differ from those of college-aged readers. These simulations led to the rejection of two plausible accounts of age-related differences—that they are attributable to declines in visual or oculomotor functioning during older age. Indeed, changing parameters that modulate the effects of visual acuity (ε) or random saccadic error (η_1 and η_2) failed to replicate the eye-movement patterns of either older readers of English or Chinese, suggesting that neither less efficient visual processing of text (particularly outside of central vision; e.g., Crassini et al., 1988; Scialfa et al., 2013) nor less accurate saccade targeting (e.g., Huaman & Sharpe, 1993) are sufficient to explain the eye-movement patterns of older readers.

In contrast, slowing lexical processing (α_1) and increasing the propensity to guess words (κ) produced a pattern of eye movements that closely resembled those of older readers of English, confirming that, for the reading of alphabetic languages, the risky reading strategy provides a parsimonious account of age-related changes in eye movements. And intriguingly, slower lexical processing without increased word guessing produced a pattern of eye movements that closely resembled those of the older readers of Chinese. Together, these results suggest that a slowdown in lexical processing during older age contributes to age-related changes in eye-movement behaviour in both Chinese and English. However, it is not clear why older readers of Chinese do not compensate for their slower lexical processing in a similar manner to older readers of English, especially when considering that the faster reading rates of the latter (Paterson et al., 2013; McGowan et al., 2014; 2015; Rayner et al., 2006; 2009; 2011; 2013; Wang et al., in press; Zang et al., 2016) suggest that a risky reading strategy is advantageous. Given the marked differences in the construction of Chinese and English (e.g., logographic vs. alphabetic), as well as differences in the characteristics of older readers of Chinese and English (e.g., years of education) there are many possible reasons why older Chinese readers may not guess upcoming words as frequently as older readers of English. For example, the often highly visually complex nature of written Chinese, in which characters are comprised of up to 36 strokes (Zang, Liversedge, Bai, & Yan, 2011), may create particular difficulties for older readers given the substantial decline in visual abilities that typically occurs during older age (e.g., Owsley, 2011). These difficulties in identifying words and characters may be especially pronounced in the parafovea (Wang, Bai, & Yan, 2014), where age-related visual declines are most marked (Crassini et al., 1988; Scialfa et al., 2013), and so older Chinese readers may find it particularly challenging to utilise parafoveal information when guessing upcoming words (e.g., in constraining possible lexical candidates). Alternatively, cultural differences may mean that older readers of Chinese typically have less reading experience than older readers of English, and so they may be less able to use their knowledge about language in order to rapidly and accurately guess upcoming words. Future research is clearly needed to examine these (and other) possibilities.

Finally, recent E-Z Reader simulations have also shown that decreasing the rate of lexical processing is sufficient to explain the eye-movement behaviour of developing readers—more and longer fixations, more regressions and refixations, shorter forward saccade lengths, and slower overall reading speeds (Mancheva et al., 2015; Reichle et al., 2013). These results and the present simulations together suggest that changes in lexical processing proficiency provide a parsimonious account of changes in eye-movement behaviour during reading across the lifespan.

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Endnotes

1. And for other models of eye-movement control in reading, see the 2006 special issue of *Cognitive Systems Research*.

2. The “default” values of η_1, η_2, and λ that were used in the simulations reported by Reichle et al. (2012) did not generate qualitatively robust IOVP effects and thus did not allow for an adequate test of how this benchmark finding might be modulated by age-related differences, thus necessitating their adjustment and subsequent adjustments to the lexical-processing parameters (i.e., α_1, α_2, α_3, and Δ). The value of p_N was set equal to 1.0 (rather than its default value of 0.5) because inaccurate word “guessing” might be predicted to result in specific saccade targets back to the words that were misidentified.

3. The parameter κ is conceptually similar to but simpler than the κ parameter used by Rayner et al. (2006); in the current simulations, κ represents the enhanced probability of guessing a given word rather than scaling the probability of guessing the word as a function of its frequency of occurrence.

Table 1. E-Z Reader parameters, their interpretations, and their best-fitting values.

Processes	Parameter	Interpretation	Value
Lexical	α_1	Mean maximum L_1 time (ms)	115
	α_2	Effect of word frequency on L_1 (ms)	2.2
	α_3	Effect of word predictability on L_1 (ms)	13
	Δ	Proportional difference between L_1 and L_2	0.22
Post-lexical	I	Mean integration time (ms)	25
	p_F	Probability of integration failure	0.01
	p_N	Probability of regression being directed towards prior word	1.0
Saccade programming	M_1	Mean labile saccadic programming time (ms)	125
	ξ	Proportion of M_1 allocated to “preparatory” stage	0.5
	M_2	Mean non-labile saccadic programming time (ms)	25
	λ	Modulates effect of saccadic error on refixation probability	0.25
Saccade execution	η_1	Intercept for random saccadic error (character spaces)	0.5
	η_2	Slope for random saccadic error (character spaces)	0.1
	Ψ	Optimal saccade length (character spaces)	7
	Ω_1	Intercept for launch-site fixation duration on systematic error	6
	Ω_2	Slope for launch-site fixation duration on systematic error	3
	S	Saccade duration (ms)	25
Vision & Attention	V	Eye-to-brain lag (ms)	50
	ε	Modulates effect of visual acuity	1.15
	A	Attention shift time (ms)	25
Other	σ_γ	Standard deviation of gamma distributions	0.22

Table 2. Simulation 2 parameter space and resulting older-reader eye-movement patterns.

Parameters		α_1						
		115	125	135	145	155	165	175
κ	0	-	C	C	C	C	C	C
	0.01	-	-	-	-	-	C	C
	0.02	-	E	-	-	-	-	-
	0.03	-	-	E	-	-	-	
	0.04	-	-	E	E	-	-	-
	0.05	-	-	-	E	E	E	-
	0.06	-	-	-	E	E	E	E
	0.07	-	-	-	-	E	E	E
	0.08	-	-	-	-	E	E	E
	0.09	-	-	-	-	-	E	E
	0.1	-	-	-	-	-	E	E

Note: “E” = English pattern; “C” = Chinese pattern; “-“ = non-identifiable pattern; α_1 = mean maximum L_1 time (ms); κ = modulates the “guessing” of the upcoming word.

Table 3. Examples of simulated reading patterns for young readers of English, older readers of English, and older readers of Chinese.

Dependent Measure	Simulated Population		
	Young Readers[1] (English)	Older Readers[2] (English)	Older Readers[3] (Chinese)
Mean Fixation Duration (ms)	228	268	273
Mean Forward Saccade Length (character spaces)	7.60	8.14	7.52
Mean Number Fixations (per Sentence)	8.19	8.46	9.30
Mean Probability of Skipping	0.24	0.26	0.22
Mean Probability of Making Regression	0.15	0.20	0.20
Reading Rate (Words per Minute)	332	270	245

Notes:

1. Simulation completed using $\alpha_1 = 115$ and $\kappa = 0$.
2. Simulation completed using $\alpha_1 = 175$ and $\kappa = 0.1$.
3. Simulation completed using $\alpha_1 = 175$ and $\kappa = 0$.

Table 4. Simulation 3 parameter space and resulting older-reader eye-movement patterns.

Parameters		ε						
		1.15	1.25	1.35	1.45	1.55	1.65	1.75
κ	0	-	-	-	-	-	-	-
	0.01	-	-	-	-	-	-	-
	0.02	-	-	-	-	-	-	-
	0.03	-	-	-	-	-	-	-
	0.04	-	-	-	-	-	-	-
	0.05	-	-	-	-	-	-	-
	0.06	-	E	-	-	-	-	-
	0.07	-	-	-	-	-	-	-
	0.08	-	-	E	-	-	-	-
	0.09	-	-	E	-	-	-	-
	0.1	-	-	-	-	-	-	-

Note: "E" = English pattern; "-" = non-identifiable pattern; ε = modulates the effect of visual acuity; κ = modulates the "guessing" of the upcoming word.

Table 5. Examples of simulated reading patterns for young and older readers of English.

Dependent Measure	Simulated Populations	
	Young Readers[1] (English)	Older Readers[2] (English)
Mean Fixation Duration (ms)	228	300
Mean Forward Saccade Length (character spaces)	7.60	8.27
Mean Number Fixations (per Sentence)	8.19	8.28
Mean Probability of Skipping	0.24	0.24
Mean Probability of Making Regression	0.15	0.21
Reading Rate (Words per Minute)	332	248

Notes:
1. Simulation completed using $\varepsilon = 1.15$ and $\kappa = 0$.
2. Simulation completed using $\varepsilon = 1.35$ and $\kappa = 0.09$.

Figure Captions

Figure 1. Schematic diagram of E-Z Reader, ver. 10 (Reichle et al., 2012). The thick light gray arrow shows the low spatial-frequency visual information (e.g., word boundaries) used for saccade targeting, the thick dark gray arrows indicate the high spatial-frequency visual information (e.g., letter features) used for lexical processing, and the thin black arrows indicate how control is passed among components in the model. "V" = pre-attentive visual processing, "L_1" = familiarity check, "L_2" = lexical access, "A" = attention shift, "I" = post-lexical integration, "M_1" = labile saccadic programming, and "M_2" = non-labile saccadic programming.

Figure 2. Simulation results comparing younger (Panels A, C, E, G, & I) vs. older (Panels B, D, F, H, & J) adult readers of English on 5 dependent measures. Panels A and B show mean simulated first-fixation (*FFD*), single-fixation (*SFD*), and gaze duration (*GD*) for 5 frequency classes of words, using the observed values for young adults readers (Schilling et al., 1998) for comparison. Panels C and D show mean simulated probabilities of making a single fixation (*Pr 1*), two or more fixations (*Pr 2+*), or skipping (*Pr S*), again using the Schilling et al. observed values for comparison. (Note that the observed values in Panels B and D are the same as those plotted in Panels A and B; they are re-plotted to facilitate qualitative comparisons between the data observed with younger readers and the simulated data of older readers.) Panels E and F show the initial fixation landing-site distributions for 1-8 letter words (with 0 representing the blank space preceding the words). Panels G and H show the probability of making a refixation as a function of the initial fixation position. Panels I and J show the single-fixation

durations as a function of their position (i.e., IOVP curves). (Note that older readers were simulated using $\alpha_1 = 175$ and $\kappa = 0.1$.)

Figure 1.

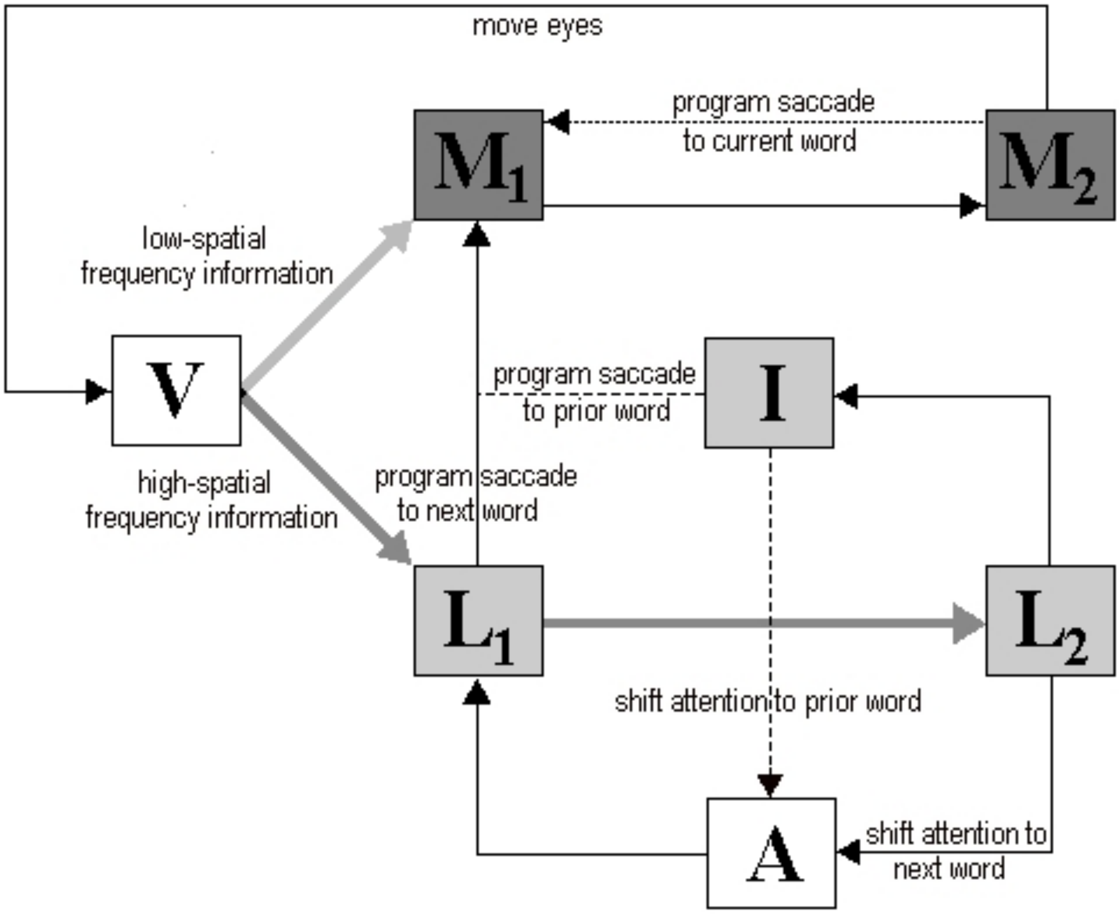
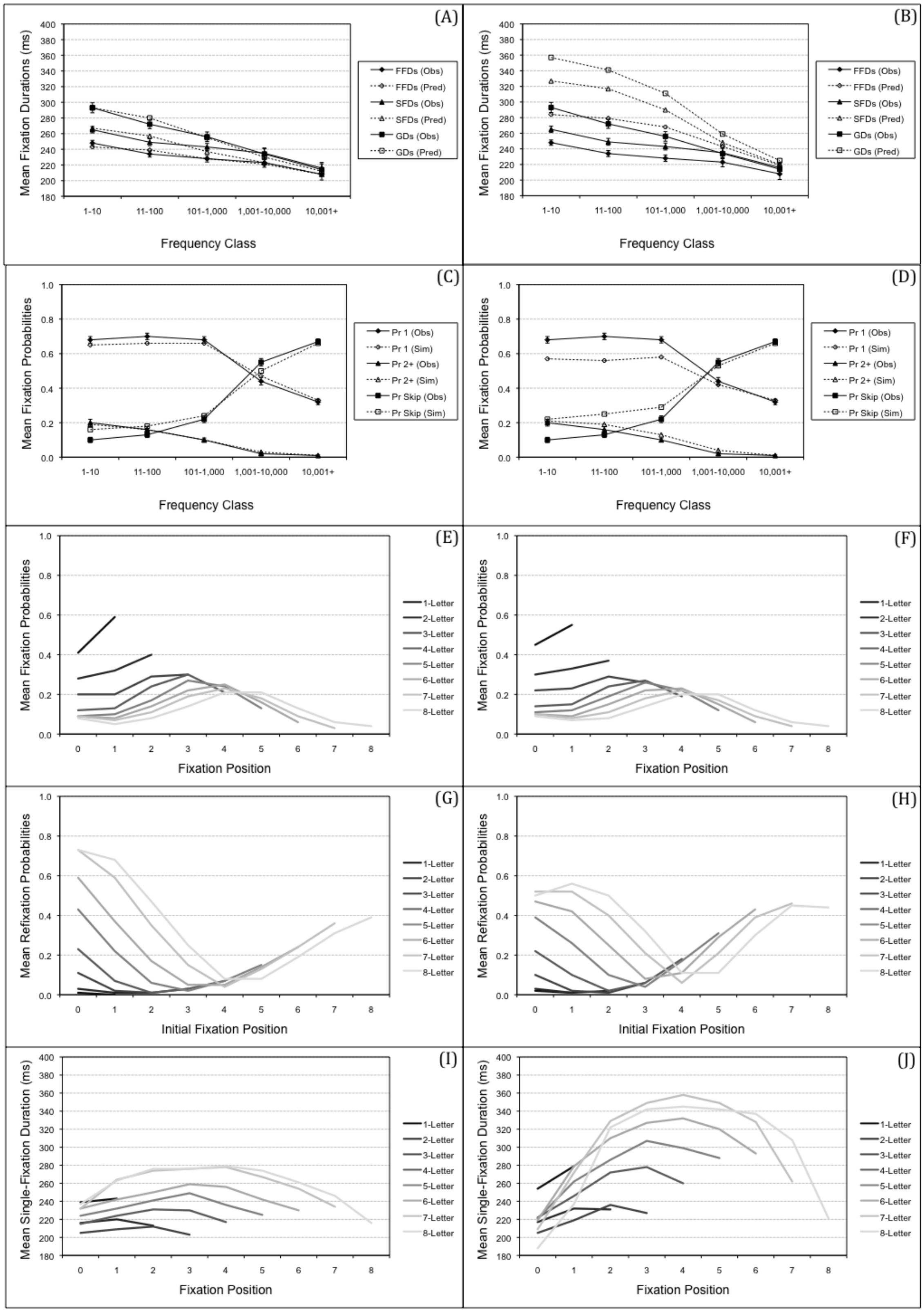

move eyes
program saccade
to current word
M1
M2
low-spatial
frequency information
V
program saccade
to prior word
I
high-spatial
frequency information
program saccade
to next word
L1
L2
shift attention to prior word
A
shift attention to
next word

Figure 2.


(A)
Mean Fixation Durations (ms)
Frequency Class
1-10
11-100
101-1,000
1,001-10,000
10,001+
FFDs (Obs)
FFDs (Pred)
SFDs (Obs)
SFDs (Pred)
GDs (Obs)
GDs (Pred)
(B)
Mean Fixation Durations (ms)
Frequency Class
FFDs (Obs)
FFDs (Pred)
SFDs (Obs)
SFDs (Pred)
GDs (Obs)
GDs (Pred)
(C)
Mean Fixation Probabilities
Frequency Class
Pr 1 (Obs)
Pr 1 (Sim)
Pr 2+ (Obs)
Pr 2+ (Sim)
Pr Skip (Obs)
Pr Skip (Sim)
(D)
Mean Fixation Probabilities
Frequency Class
Pr 1 (Obs)
Pr 1 (Sim)
Pr 2+ (Obs)
Pr 2+ (Sim)
Pr Skip (Obs)
Pr Skip (Sim)
(E)
Mean Fixation Probabilities
Fixation Position
1-Letter
2-Letter
3-Letter
4-Letter
5-Letter
6-Letter
7-Letter
8-Letter
(F)
Mean Fixation Probabilities
Fixation Position
(G)
Mean Refixation Probabilities
Initial Fixation Position
(H)
Mean Refixation Probabilities
Initial Fixation Position
(I)
Mean Single-Fixation Duration (ms)
Fixation Position
(J)
Mean Single-Fixation Duration (ms)
Fixation Position