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The Effect of Word Frequency and Parafoveal Preview on Saccade Length During the Reading of Chinese

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There are currently 2 theoretical accounts of how readers of Chinese select their saccade targets: (a) by moving their eyes to specific saccade targets (i.e., the *default-targeting hypothesis*) and (b) by adjusting their saccade lengths to accommodate lexical processing (i.e., the *dynamic-adjustment hypothesis*). In this article, we first report the results of an eye-movement experiment using a gaze-contingent boundary paradigm. This experiment demonstrates that both target-word frequency and its preview validity modulate the lengths of the saccades entering and exiting the target words, with longer saccades to/from high-frequency words when their preview was available. We then report the results of 2 simulations using computational models that instantiate the core theoretical assumptions of the default-targeting and dynamic-adjustment hypotheses. Comparisons of these simulations indicate that the dynamic-adjustment hypothesis provides a better quantitative account of the data from our experiment using fewer free parameters. We conclude by discussing evidence for dynamic saccade adjustment during the reading of alphabetic languages, and why such a heuristic may be necessary to fully explain eye-movement control during the reading of both alphabetic and nonalphabetic languages.

Keywords: Chinese, eye-movement control, preview benefit, reading, saccades

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Readers appear to prioritize ongoing lexical processing by moving their eyes to viewing locations that afford efficient identification of upcoming words. For alphabetic languages like English and German, this *preferred viewing location* is (on average) approximately one third of the way into a word (see Rayner, 1979). For nonalphabetic languages like Chinese, however, the absence of obvious visual cues between words (i.e., blank spaces) raises the question: How do readers actually select their saccade targets? This question, in combination with weak evidence for a preferred viewing location in Chinese (Li, Liu, & Rayner, 2011; Liu, Reichle, & Huang, 2015; cf., Yan, Kliegl, Richter, Nuthmann, & Shu, 2010), makes it clear that there is still much to be learned about the basic processes that guide the eyes during reading (e.g., the selection of saccade targets).

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One proposal for how Chinese readers might select their saccade targets during reading is that they first attempt to segment upcoming words from the line of text using parafoveal vision, and then move their eyes (more or less) as readers of alphabetic languages do—by selecting specific saccade targets. For example, to explain the findings that, during the reading of Chinese, words tend to get fixated near their center if they are fixated only once but tend to be fixated near their beginning if they are fixated more than once, Yan et al. (2010) suggested that Chinese readers select saccade targets depending on whether or not the upcoming (i.e., parafoveal) word has been successfully segmented. This account can be seen as a word-segmentation version of the *default-targeting hypothesis*. By this hypothesis, the eyes are directed toward the center of a word that has been segmented successfully, but toward the beginning of a word that has not. This simple "heuristic" makes some intuitive sense in that a fixation near the center of a word that has been segmented provides an optimal viewing location for rapidly identifying that word (O'Regan, 1981; Rayner & Morrison, 1981), whereas a fixation near the beginning of a word affords an opportunity to fixate the word a second time (i.e., make a *refixation*) without having to move the eyes backward (i.e., make a *regression*).

Unfortunately, the available evidence does not provide unequivocal support for Yan et al.'s (2010) hypothesis. For example, the finding of different fixation-location distributions for the single versus first-of-multiple fixations is probably an artifact of how the fixation-location distributions are analyzed: Whereas a fixation near the center of a word is less likely to be followed by another fixation on that word, and therefore more likely to be scored as a

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single fixation, a fixation near the beginning of a word is more likely to be followed by another fixation on the word and therefore more likely to be scored as the first of two (or more) fixations. Precisely how this might occur was demonstrated by Li et al. (2011) using simulations in which saccades were (on average) of constant length: Fixations near the center of a word were more likely to be scored as single fixations, whereas fixations near the beginning of a word were more likely to be scored as first-of-multiple fixations, thereby giving rise to the type of dissociation reported by Yan et al.

Two other findings are also difficult to reconcile with Yan et al.'s (2010) account. The first is that the divergence between the distributions for single versus first-of-multiple fixations persists even when blank spaces are inserted in Chinese text, thereby completely obviating the need to segment words by lexical processing in the parafovea (Zang, Liang, Bai, Yan, & Liversedge, 2013). Perhaps even more remarkable, however, is the fact that the aforementioned divergence is observed in two other nonreading tasks—one in which subjects are instructed to "read" Chinese "text" in which the characters within words have been randomly shuffled (Ma, Li, & Pollatsek, 2015), and another in which subjects search through linear arrays of Chinese character-like Landolt-*C* stimuli to locate targets (Liu et al., 2015). Together, these findings provide strong evidence against the word-segmentation version of the default-targeting hypothesis. (For an in-depth discussion of the logical problems associated with this hypothesis, see Liu, Reichle, & Li, 2015.)

Fortunately, several recent experiments have also shed additional light on the question of how readers of Chinese select their saccade targets. For example, Wei, Li, and Pollatsek (2013) found that the properties of the fixated word influence the length of saccade exiting that word. More specially, saccades leaving high-frequency words tended to be longer than those leaving low-frequency words, consistent with what has also been observed in English (e.g., Rayner, Ashby, Pollatsek, & Reichle, 2004; White & Liversedge, 2006). Extending this work, Liu, Reichle, and Li (2015) found that the degree to which a word's frequency influenced the length of the saccade exiting that word was modulated by the amount of parafoveal information that was extracted prior to the saccade. More specifically, by manipulating the frequency of the fixated word and the preview validity of all of the words immediately to its right, Liu et al. found that the frequency of the fixated word only influenced the length of saccade leaving that word if preview of the subsequent words was available. This finding suggests that the processing difficulty of the fixated word (i.e., *foveal load*) influences how much information about the next words can be extracted, and that this in turn influences the length of saccade exiting the fixated word. This finding is consistent with the well-documented interaction between foveal-processing difficulty and parafoveal preview (i.e., parafoveal words receive less processing than difficult words; Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White, Rayner, & Liversedge, 2005). Finally, there is evidence that saccades into high-frequency words tend to be longer than those into low-frequency words (Li, Bicknell, Liu, Wei, & Rayner, 2014; see also Liversedge et al., 2014). Taken together, these results collectively suggest that parafoveal processing plays an important role in determining where readers move their eyes—at least during the reading of Chinese.

This conjecture is also consistent with the growing body of evidence suggesting that readers of Chinese also engage in "deeper" parafoveal processing than do readers of alphabetic languages. For example, there is now considerable evidence that readers of Chinese extract morphosemantic information from the parafovea (Tsai, Kliegl, & Yan, 2012; Yan, Richter, Shu, & Kliegl, 2009; Yan, Risse, Zhou, & Kliegl, 2012; Yan, Zhou, Shu, Kliegl, 2012; Yang, Wang, Tong, & Rayner, 2012; Yen, Tsai, Tzeng, & Hung, 2008). And similarly, there is evidence that properties of Word $N + 1$ can modulate the amount of parafoveal processing that Word $N + 2$ receives from Word N. For example, Word $N + 2$ receives more parafoveal processing from Word N if Word $N + 1$ is high rather than low frequency (Yan, Kliegl, Shu, Pan, & Zhou, 2010; Yang, Rayner, Li, & Wang, 2012; Yang, Wang, Xu, & Rayner, 2009; see also Schotter, Reichle, & Rayner, 2014). And finally, this conjecture is consistent with one other well-established finding: that the frequency of a parafoveal word can modulate its preview (as measured by *preview benefit*, or the reduction in how long the parafoveal word is fixated when it is vs. is not previewed). For example, several experiments involving alphabetic languages have demonstrated larger reductions in first-pass reading times for previews of high- than low-frequency words (Inhoff & Rayner, 1986; Kennison & Clifton, 1995; Reingold, Reichle, Glaholt, & Sheridan, 2012; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999; Sereno & Rayner, 2000; Vitu, 1991; however, cf., Rayner, Liversedge, & White, 2006).

Although the available evidence suggests that parafoveal processing plays an important functional role in selecting saccade targets during the reading of Chinese, it is important to acknowledge that how this actually happens is still poorly understood, and that the dominant view is that specific saccade targets are selected by default during the reading of alphabetic languages like English (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2012) and German (Engbert, Nuthmann, Richter, & Kliegl, 2005), as well as nonalphabetic languages like Chinese (Pan, Yan, Laubrock, Lu, & Kliegl, 2014; Yan, Kliegl, Richter et al., 2010; Yan, Zhou, Shu, & Kliegl, 2015). In the remainder of this article, we will provide evidence that supports an alternative account based on the assumption that saccade lengths are dynamically adjusted in a manner that reflects the demands of ongoing foveal and/or parafoveal processing, so as to move the eyes to viewing locations that afford maximum processing efficiency (Li et al., 2011; Liu, Reichle, & Li, 2015; Wei et al., 2013). We call this account the *dynamic-adjustment hypothesis* (also see Bicknell, Higgins, Levy, & Rayner, 2013)[1].

Previous empirical efforts to adjudicate between our hypothesis and the dominant default-targeting hypothesis have not been successful because the two hypotheses make very similar predictions about eye-movement behavior. For example, with the addition of

[1] The dynamic-adjustment hypothesis is identical to the processing-based hypothesis that has been previously discussed in the literature (e.g., Liu, Reichle, & Li, 2015; Wei et al., 2013). We prefer the former nomenclature, however, because it provides a more transparent description of how we think readers of Chinese select their saccade targets, and because it does not suggest (e.g., through contrast) that lexical processing plays no role in the default-targeting hypothesis (i.e., according to the latter hypothesis, decisions about where to move the eyes are affected by word segmentation; Yan, Kliegl, Richter et al., 2010).

a few assumptions, the default-targeting hypothesis can also provide qualitative accounts of the findings that readers tend to: (1) move their eyes further to the right from fixations on high- than low-frequency words (Liu, Reichle, & Li, 2015; Wei et al., 2013); and (2) move their eyes further into high- than low-frequency words (Liu, Reichle, & Li, 2015). The default-targeting hypothesis can explain the first finding if one assumes that fixations on high-frequency words afford more parafoveal processing than fixations on low-frequency words, making it more likely that a word to the right of a high-frequency word will be segmented and thus the recipient of a single fixation near its center. Similarly, the default-targeting hypothesis can explain the second finding if one assumes that more saccades are intended to skip high- than low-frequency words, but that some of these intended skips then fall short due to saccadic error, causing the mean of the fixation landing-site distribution on the high-frequency words to be further to the right (i.e., near the ends of the words). Given these and similar problems of the models making similar predictions about eye-movement behavior, standard eye-movement measures and statistical methods have proven less useful for understanding how readers of Chinese select their saccade targets.

Fortunately, computational models provide another, more sophisticated method for understanding this issue, for example, by implementing the core theoretical assumptions of the two aforementioned hypotheses as computer programs and then using those programs to examine precisely how those core assumptions are related to various eye-movement measures (e.g., fixation landing-site distributions). This is the method that we adopted in the latter half of this study, and by doing so, we are able to show that the default-targeting hypothesis can actually be understood as being a discrete instantiation of the dynamic-adjustment hypothesis. That is, although both hypotheses share the assumption that parafoveal lexical processing affects the decisions about where to move the eyes (e.g., the selection of saccade targets) during Chinese reading, those decisions are made (approximately) discrete according to the default-targeting hypothesis because of the need to move the eyes to one of a few specific, default locations. In contrast, the dynamic-adjustment hypothesis predicts that saccade length should vary continuously as a function of the modulation in ongoing lexical processing difficulty. Based on the basic observation that there appears to be no preferred viewing location on words during the reading of Chinese (see Li et al., 2011; Tsai & McConkie, 2003; Yang & McConkie, 1999), we therefore hypothesized that a model based on the assumption of dynamic saccade adjustment would provide a better account of eye movements during Chinese reading than a model based on the assumption of default saccade targeting.

To provide empirical data for evaluating the two aforementioned models, it was necessary to conduct a gaze-contingent eye-movement experiment (e.g., see Rayner, 1975) in which the parafoveal processing of specific target words was modulated by manipulating two variables related to those words: their frequency and whether or not their preview was valid. In addition to the established finding of longer saccades coming into high-frequency target words (Li et al., 2014), we also predicted that the fixation landing-site distributions would be shifted further to the right on high-frequency target words, but that both of these effects would only occur with valid preview. We also predicted that both word frequency and preview validity would influence the length of the saccades exiting the target words, with longer saccades from high-frequency words (Wei et al., 2013) and from words that were the recipients of valid preview (Liu, Reichle, & Li, 2015). As indicated previously, because both the default-targeting and dynamic-adjustment hypotheses provide qualitative accounts of these results, the results are actually consistent with both hypotheses. It was therefore necessary to implement both hypotheses as computational models to evaluate how well each hypothesis could simulate the full pattern of results. Our goal, therefore, was to use these simulations to discriminate between the two hypotheses and thereby provide a more precise description of how readers of Chinese select their saccade targets.

Method

Participants

Thirty-six native Chinese-speaking students (23 males) were recruited from universities in Beijing and paid 30 Yuan (approximately $5) for their participation. All participants had normal or corrected-to-normal vision, and were naïve to the purpose of the study.

Apparatus

Stimuli were rendered in Song 20 font and displayed on a 21-in. CRT monitor (SONY Multiscan G520) with a resolution of 1024×768 pixels and a 150-Hz refresh rate. The presentation was controlled by an OpenGL-based Psychophysics Toolbox-3 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007), which incorporates the EyeLink Toolbox extensions (Cornelissen, Peters, & Palmer, 2002) in Matlab (2013a). Using this configuration, display changes can be controlled precisely and require approximately 10 ms to complete. Eye movements were recorded using an SR-Research Eyelink 1000 eye tracker (upgraded to 2,000 Hz; Kanata, ON, Canada) sampling at a 1000-Hz rate.

Stimuli and Design

The experiment used a 2 (target-word frequency: high vs. low) $\times$ 2 (target-word preview validity: valid vs. invalid) within-subject design. The stimuli have been used in previously published articles (e.g., Liu, Reichle, & Li, 2015) and consisted of 320 two-character high- (M = 121.5 per million; SD = 98.5) and low-frequency (M = 2.17 per million; SD = 1.53) target words with similar meanings (selected from the *Modern Chinese Frequency Dictionary* , 1986; more information about the properties of target words were listed in Appendix A). Each high- and low-frequency target-word pair was embedded in the same location (near the middle) within one of 160 sentence frames. Before the experiment, 10 native Chinese speakers who did not participate in the experiment attempted to guess the identities of the target words using their preceding sentence contexts; the results of this normative study indicated that target words were not predictable (i.e., the probability for guessing any target word was less than .1). Moreover, another 20 native Chinese speakers were asked to rate the naturalness of these sentences; all raters agreed that the sentences were natural (i.e., on a 5-point scale with 5 being *completely natural*, each sentence received a minimum score of at least 3 and a mean score of 4). During the actual experiment, each participant

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read each sentence displayed as a single line on the monitor. Each sentence was read only once by each participant, who read equal numbers of sentences in each condition.

As indicated, the preview validity was controlled by a modified gaze-contingent boundary paradigm (Rayner, 1975). Specifically, an invisible boundary was placed immediately before the target word so that normal preview could be allowed or prevented (see Figure 1). In the valid-preview condition, the text was displayed naturally so that readers could extract parafoveal (e.g., target word) information prior to fixating the target words. In the invalid-preview condition, all of the characters to the right of the invisible boundary were replaced by "※" symbols so that readers could not extract (useful) parafoveal information prior to fixating the target words (after which the text became visible). To prevent the possible extraction of word-boundary information prior to fixating the target word, all of the characters from the leftmost edge of the target word to the end of sentences were masked. And to minimize any disruption that might be introduced by the display changes, 80 additional sentences (which were presented without display changes) were included as fillers. Each participant therefore read a total of 240 sentences.

Procedure

The participants were seated 58 cm from the video monitor. (At this distance, one character subtended by about a 1° visual angle.) A chin/forehead rest was used to minimize head movements. Viewing was binocular, but eye-movement data were only collected from the right eye. An initial 3-point calibration and validation procedure was performed until maximal error was less than a 0.4° visual angle, and recalibration/revalidation were conducted as needed. During the experiment, participants first read 15 practice sentences (not included in our analysis) and then read the 240 experimental and filler sentences in random order. Each trial consisted of a drift check in the middle of the screen followed by a fixation box (1° × 1°, the size of a single character) at the location of the first character of the sentence. If the fixation box did not trigger or the drift check indicated more than a 0.4° error, then the participant was recalibrated. Furthermore, the eye tracker was recalibrated at regular intervals. When the fixation box was successfully fixated, the sentence appeared. Participants were instructed to read silently for comprehension, and used a button box (Microsoft SideWinder Game Pad) to terminate a sentence. Participants also used the button box to answer comprehension questions after the completion of approximately one third of the sentences and to start each trial.

High Frequency-
Valid Preview: 中国学生从英国**老师**那里学会了圣诞歌谣。
Invalid Preview: 中国学生从英国※※※※※※※※※※※。
(The Chinese students have learned a Christmas song from the British teacher.)

Low Frequency-
Valid Preview: 中国学生从英国**访客**那里学会了圣诞歌谣。
Invalid Preview: 中国学生从英国※※※※※※※※※※※。
(The Chinese students have learned a Christmas song from the British visitor.)

Figure 1. Examples of the stimuli used in the experiment (with target words in bold font for illustrative purposes).

Empirical Results

Accuracy

The mean accuracy of sentence comprehension was 98.47% and there were no differences across the four conditions (all $ps \geq .164$).

Eye-Movement Measures

Trials in which eye blinks occurred during the fixation on, immediately preceding, or immediately following the target words were excluded from analyses. Trials in which display change was triggered early by a fixation or completed more than 10 ms after the onset of the subsequent fixation were also excluded. This was done because previous research has indicated that display changes delayed by more than 10 ms cause a change in eye-movement behavior (Slattery, Angele, & Rayner, 2011). Approximately 14.48% of total trials were thus removed using those two criteria. Moreover, to avoid the inclusion of extremely long saccades (which are usually due to a track loss), any saccades longer than five characters were also excluded (<2% of the total saccades) when saccade length and fixation position were analyzed.

Our primary analyses focused on five dependent measures. To control for any possible effects of saccade launch site, our analyses of forward saccades were restricted to first progressive saccade launched from the two-character pretarget region, and that actually included two measures, conditional upon whether or not the fixation following the saccade was actually on the target word. The first, more inclusive measure included all progressive saccades from the pretarget region, irrespective of whether they actually resulted in a fixation on the target word (i.e., *progressive saccade lengths*). The second, more restrictive measure included only those progressive saccades from the pretarget region that actually resulted in a fixation on the target word (i.e., *incoming saccade lengths*). Our analyses also examined the target-word *fixation position* (being defined relative to the left edge of the target word) for each of the two types of forward saccades (i.e., progressive and incoming saccades), as well as *outgoing saccade length*, or the length of first progressive saccade that was launched from the target word and that resulted in a fixation to the right of the target word.

In addition to the aforementioned measures, we also examined the following standard eye-movement measures, calculated conditionally upon the eyes moving forward during the first pass through the text: (a) *skipping probability*, or the probability of a target word not being fixated; (b) *refixation probability*, or the probability of a target word being fixated more than once; (c) *first-fixation duration*, or the duration of the initial fixation on the target word; and (d) *gaze duration*, or the sum of all first-pass fixations on the target word. Again, to control for saccade launch site, the latter two measures (i.e., 3 and 4) were calculated using only those trials involving a single fixation in the two-character pretarget region.

Eye-movement measures were analyzed using linear mixed-effects models, except for the binomial measures (i.e., skipping and refixation probabilities), which were analyzed using generalized linear mixed models (Jaeger, 2008). To maximize the generalizability of our analyses, we used the maximal random-effects structure (Barr, Levy, Scheepers, & Tily, 2013) so that the resulting significance values would reflect variance due to participants, items, and the slopes of the fixed effects for participants and items. Target-word frequency, preview validity, and their interaction were entered as fixed-effect factors into these models. These factors were coded as sum contrasts (−0.5 vs. 0.5 for low and high frequency, and for invalid and valid preview) so that the intercepts estimated the grand mean of a given dependent variable, and the regression coefficients estimated the differences between the factor levels. To control for any possible effects of launch-site location and duration on our dependent measures, these two variables were included in our models as covariates in our analyses of saccade length and fixation position. Finally, the models were fitted using the lme4 package (Version 1.1–7; Bates, Maechler, Bolker, & Walker, 2014; Pinheiro & Bates, 2000), the p values were estimated using the lmerTest package (Version 2.0–20; Kuznetsova, Brockhoff, & Christensen, 2013), and planned contrasts were completed using the multcomp package (Version 1.4–0; Bretz, Hothorn, & Westfall, 2010) in R (Version 3.1.3; R Development Core Team, 2015). Below, we first report the primary dependent measures (i.e., those related to saccade targeting) and then report the more standard fixation-duration measures.

As can be seen by inspecting the means (see Table 1) and the linear mixed-effect models (see Table 2), both the progressive and incoming saccades were longer for high- than low-frequency target words (progressive: $b = 0.07$, $SE = 0.03$, $t = 2.76$, $p < .01$; incoming: $b = 0.04$, $SE = 0.02$, $t = 2.03$, $p < .05$), and with valid- than invalid-preview condition (progressive: $b = 0.16$, $SE = 0.04$, $t = 3.81$, $p < .001$; incoming: $b = 0.10$, $SE = 0.03$, $t = 4.00$, $p < .001$). There were also significant (or marginally significant) interactions between word frequency and preview validity on the progressive and incoming saccade length, with a larger word-frequency effect on progressive and incoming saccades in the valid- than invalid-preview condition (progressive: $b = 0.18$, $SE = 0.05$, $t = 3.78$, $p < .001$; incoming: $b = 0.06$, $SE = 0.04$, $t = 1.66$, $p < .10$). Planned contrasts indicated that saccades into (or skipping) high-frequency targets were longer than saccades into (or skipped) low-frequency targets when preview was available (progressive: $b = 0.16$, $SE = 0.03$, $z = 4.97$, $p < .001$; incoming: $b = 0.07$, $SE = 0.03$, $z = 2.75$, $p < .01$). However, saccades into (or skipping) high-frequency targets were not significantly different from those into (or skipping) low-frequency targets when preview was unavailable (both ps > 0.10). This finding that parafoveal word frequency affected progressive and incoming saccade length only with valid preview is consistent with previous results (Li et al., 2014; Liu, Reichle, & Li, 2015).

Because of the intrinsic relationship between incoming saccade length and fixation position, it is not surprising that similar word-frequency and preview effects were evident on the latter measure. Thus, fixations were further to the right on high- than low-frequency target words (progressive: $b = 0.07$, $SE = 0.03$, $t = 2.76$, $p < .01$; incoming: $b = 0.04$, $SE = 0.02$, $t = 2.03$, $p < .05$), and with valid than invalid preview (progressive: $b = 0.16$, $SE = 0.04$, $t = 3.81$, $p < .001$; incoming: $b = 0.10$, $SE = 0.03$, $t = 4.00$, $p < .001$). There were also significant (or marginally significant) interactions between word frequency and preview validity on fixation position, with a larger word-frequency effect on fixation position in the valid- than invalid-preview condition (progressive: $b = 0.18$, $SE = 0.05$, $t = 3.78$, $p < .001$; incoming: $b = 0.06$, $SE = 0.04$, $t = 1.66$, $p < .10$). Planned contrasts indicated that the fixations on high-frequency targets were further to the right than fixations on low-frequency targets when preview was available (progressive: $b = 0.16$, $SE = 0.03$, $z = 4.97$, $p < .001$; incoming: $b = 0.07$, $SE = 0.03$, $z = 2.75$, $p < .01$). However, fixations on high-frequency targets were not significantly different from those on low-frequency targets when preview was unavailable (both ps > 0.10).

As can also be seen by inspecting the means (see Table 1) and the linear mixed-effect model of the outgoing saccade length (see Table 2), saccades were longer in the high- than in the low-frequency condition ($b = 0.05$, $SE = 0.03$, $t = 1.70$, $p < .10$), and in the valid- than in the invalid-preview condition ($b = 0.09$, $SE = 0.04$, $t = 2.14$, $p < .05$). The former result is consistent with previous findings that the frequency of a fixated word can modulate the length of the saccade exiting it (Liu, Reichle, & Li, 2015; Wei et al., 2013). And finally, there was no interaction between word frequency and preview validity on outgoing saccade length ($p > .10$).

Turning now to the skipping and refixation-probability measures (see Tables 1 and 3), there was a significant interaction between word frequency and preview validity on the probability of skipping the target word ($b = 0.29$, $SE = 0.14$, $z = 2.07$, $p < .05$). A planned contrast showed that high-frequency targets were skipped more often than low-frequency targets with valid preview ($b = 0.05$, $SE = 0.02$, $z = 2.94$, $p < .05$). And similarly, high-frequency target words in the valid-preview condition were

Table 1
Means of Eye-Movement Dependent Measures (Standard Errors of the Means Are Indicated in Parentheses)

Dependent measures	Invalid preview		Valid preview	
	Low freq.	High freq.	Low freq.	High freq.
Progressive-saccade length (char.)	2.26 (.08)	2.23 (.08)	2.32 (.07)	2.49 (.09)
Progressive-fixation position (char.)	1.09 (.09)	1.06 (.09)	1.24 (.08)	1.41 (.10)
Incoming-saccade length (char.)	2.17 (.06)	2.14 (.05)	2.22 (.05)	2.32 (.06)
Incoming-fixation position (char.)	.98 (.04)	.99 (.04)	1.10 (.04)	1.14 (.04)
Outgoing-saccade length (char.)	2.40 (.08)	2.45 (.08)	2.49 (.09)	2.53 (.08)
Skipping probability	.25 (.03)	.26 (.02)	.25 (.02)	.29 (.02)
Refixation probability	.12 (.02)	.08 (.02)	.10 (.02)	.06 (.01)
First-fixation duration (ms)	322 (10)	305 (11)	280 (6)	260 (7)
Gaze duration (ms)	414 (20)	355 (15)	323 (13)	286 (10)

Note Char. = characters; freq. = frequency.

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Table 2
Results of the Linear Mixed-Effect Model Analyses of Progressive-, Incoming- and Outgoing-Saccade Length, and of Target-Word Fixation Position

Predictor	Progressive-saccade length (char.)	Incoming-saccade length (char.)	Progressive-fixation position (char.)	Incoming-fixation position (char.)	Outgoing-saccade length (char.)
Intercept	3.09^{***}	2.56^{***}	3.09^{***}	2.56^{***}	2.87^{***}
High-frequency target word	$.07^{**}$	$.04^{*}$	$.07^{**}$	$.04^{*}$	$.05^{\dagger}$
Valid preview	$.16^{***}$	$.10^{***}$	$.16^{***}$	$.10^{***}$	$.09^{*}$
High-Frequency Target Word × Valid Preview	$.18^{***}$	$.06^{\dagger}$	$.18^{**}$	$.06^{\dagger}$	$-.02$
Launch fixation location	$-.12^{***}$	$-.50^{***}$	$.88^{***}$	$.50^{***}$	$-.08^{**}$
Log(launch fixation duration)	$-.16^{***}$	$-.17^{***}$	$-.16^{***}$	$-.17^{***}$	$-.09^{*}$

Note Char. = characters.
$^{\dagger}p < .1$. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

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more likely to be skipped than those in the invalid-preview condition ($b = 0.04$, $SE = 0.02$, $z = 2.54$, $p < .05$). Finally, as Table 3 also shows, there was only a significant effect of word frequency on refixation probability, with low-frequency targets being refixated more often than high-frequency targets ($b = -0.61$, $SE = 0.13$, $z = -4.89$, $p < .001$).

Now turning to the fixation-duration measures (see Table 3), first fixations were shorter in duration on high- than low-frequency target words ($b = -19.11$, $SE = 5.12$, $t = -3.73$, $p < .001$), and with preview than without ($b = -43.18$, $SE = 6.82$, $t = -6.33$, $p < .001$), but the interaction between word frequency and preview validity on first-fixation duration was not significant ($b = -13.04$, $SE = 8.05$, $t = -1.62$, $p = .105$). The same pattern was evident for gaze durations, which were shorter on high- than low-frequency target words ($b = -51.39$, $SE = 8.74$, $t = -5.88$, $p < .001$), and with preview than without ($b = -80.29$, $SE = 12.68$, $t = -6.33$, $p < .001$), but with no interaction between word frequency and preview validity ($b = 3.00$, $SE = 14.03$, $t = 0.21$, $p = .831$).

To summarize the preceding results, our analyses indicated that the frequency of a target word and its preview availability influence the length of saccades entering and exiting that word. (Additional analyses showing that this pattern of results is evident when statistically controlling for character frequency and complexity are presented in Appendix B.) However, because this pattern is qualitatively consistent with both the default-targeting and dynamic-adjustment hypotheses, it was necessary to use computer simulations to determine how well each of the hypotheses can quantitatively fit the empirical data. To that end, in the following sections of this article, we first describe the methods used to complete two simulations—the first using a model that instantiates the basic assumption of default saccade targeting (i.e., Simulation 1), and the second using a model that instantiates the basic assumption of dynamic saccade-length adjustment (i.e., Simulation 2). The results of these two simulations were then compared to determine how well each hypothesis accounted for pattern of data reported in this article.

Computer Simulations

During each Monte-Carlo run of the two simulations reported below, a saccade launch site was first sampled from a uniform distribution covering the two-character pretarget region. (A uniform distribution was used because empirical distributions of progressive fixation positions were approximately uniform; e.g., see Li et al., 2011, Figure 3). The saccade target (in Simulation 1) or saccade length (in Simulation 2) was then specified, and the actual fixation position that resulted from the ensuing saccade was determined by adding some amount of variance to simulate saccadic error (as described below, for each simulation). This whole process was then repeated 10,000 times from each launch site. We now provide an exposition of the specific assumptions that were used to instantiate each of the two hypotheses, and then conclude with a comparison of the simulation results.

Simulation 1: Default saccade targeting. According to the default-targeting hypothesis, where readers of Chinese decide to move their eyes is dependent upon parafoveal word segmentation: If Word *N* is successfully segmented, then the eyes are directed toward its center, usually resulting in a single fixation on the word; however, if Word *N* is not successfully segmented, then the eyes are directed toward its beginning, often resulting in the word being subsequently refixated. Although Yan, Kliegl, Richter et al. (2010) did not specify what would happen if Word *N* were skipped, it is in the "spirit" of their hypothesis to assume that, in such instances,

Table 3
Linear Mixed Model Analysis for the Dependent Measures of Probability of Skipping and Refixation, and Fixation Durations

Predictor	Skipping probability	Refixation probability	First-fixation duration (ms)	Gaze duration (ms)
Intercept	-1.17^{***}	-2.95^{***}	290.35^{***}	343.22^{***}
High-frequency target word	.11	$-.61^{***}$	-19.11^{***}	-51.39^{***}
Valid preview	.11	$-.23$	-43.18^{***}	-80.29^{***}
High-Frequency Target Word × Valid Preview	$.29^{*}$	$-.05$	-13.04	3.00

Note Char. = characters.
$^{\dagger}p < .1$. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

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the eyes direct toward the beginning of word $N + 1$ because its reduced likelihood of being successfully segmented from word $N - 1$ (because of the constraints of visual acuity and the limited perceptual span, which only extends to the right of 2–3 fixated characters; see Chen & Tang, 1998; Inhoff & Liu, 1998; Tang, Au Yeung, & Chen, 1997)[2].

Because the implementation of a full-scale model of word segmentation and identification was beyond the scope of this article, we instead simply used Yan, Kliegl, Richter et al.'s (2010) aforementioned assumption about the relationship between parafoveal word segmentation and saccade targeting to estimate the probabilities of our target words having been parafoveally segmented from how often they were fixated. In other words, because single fixations tend to be located near the centers of words whereas the first-of-multiple fixations tend to be located near the beginnings of words, these two types of fixations—according to the core assumption of the default-targeting hypothesis—provide "markers" of whether or not a word was likely to have been successfully segmented from the parafovea. For that reason, the probabilities of making a single fixation versus making the first of multiple fixations can be used to estimate the probabilities of a word being segmented (with the eyes thus being directed toward the word's center) versus not (with the eyes thus being directed toward the word's beginning). Finally, it is important to emphasize that, although these estimates are just that, *estimates*, the results of Simulation 1 are robust and are not dependent upon either the precise values of these estimates or the way in which default saccade-target selection was implemented (see Appendix D).

Thus, to implement the core assumptions of the default-targeting hypothesis in the simplest way possible, second-order polynomial regression functions were used to estimate the probabilities of observing saccades of a particular length (under the assumption that the eyes are directed toward particular default targets) from each saccade launch site within the two-character pretarget region. (The SERIF model of eye-movement control in reading adopts a similar approach of using ordinal and second-order polynomial regression functions to estimate the probabilities of various saccade targets; McDonald, Carpenter, & Shillcock, 2005; see also Reilly & O'Regan, 1998.) These estimates were derived as a function of four mutually exclusive and exhaustive sequences of eye-movement behavior: (a) refixating the pretarget region; (b) fixating the target word and subsequently making a saccade from that word (because it was presumably segmented in the parafovea); (c) fixating the target word but subsequently refixating that word (because it was presumably not segmented in the parafovea); and (d) skipping the target word. The polynomial regression functions (see Equation 1) were fit to each possible saccade launch site, with the constraint that the probabilities of observing each of the four types of eye-movement behavior summed to 1. In Equation 1, x represents the distance from the pretarget saccade launch site to the leftmost edge of the target word, and κ_2, κ_1, and κ_0 respectively represent the coefficients of the 2°, 1°, and 0° polynomials (see Appendix C).

$$p(x) = \kappa_2 x^2 + \kappa_1 x + \kappa_0 \tag{1}$$

The estimated probabilities were then used to determine the saccade targets as follows: (a) If a saccade refixated the pretarget region, then the eyes were directed toward the center of that region. (b) However, if the target word was segmented from the parafovea, then the eyes were directed toward the center of the target word. (c) Alternatively, if the target word was not segmented from the parafovea, then the eyes were directed toward the beginning of the target word (i.e., the center of the target word's first character). (d) Finally, if the target word was skipped, then the eyes were directed toward the beginning of the posttarget word (i.e., the center of its first character). Because of limitations in visual acuity and the perceptual span, those rare instances in which the eyes might be deliberately moved toward the center of the posttarget word (or even toward subsequent words) were not simulated. Finally, some amount of variance was added to the saccade target to simulate the effect of saccadic error. This saccadic error was sampled from a Gaussian distribution with $\mu = 0$, and σ being a free parameter with values set to provide the best fits to the empirical fixation-position distributions of incoming saccades on the high- versus low-frequency target words. (The best fitting parameter values used to complete the simulation and the procedure used to find those values are described in Appendix C.) We will discuss the results of Simulation 1 below, in comparison to those of Simulation 2.

Simulation 2: Dynamic saccade adjustment. According to the dynamic-adjustment hypothesis, the location toward which readers of Chinese decide to move their eyes is determined dynamically, with the length of a saccade being adjusted to maximize the efficiency of foveal and/or parafoveal processing. To instantiate this hypothesis, it was again necessary to use simplifying assumptions because a detailed model of word segmentation and identification was beyond the scope of this article. For that reason, saccade length was assumed to be a linear function of target-word preview (in ms), which in the simulation was a random deviate that was sampled from a gamma distribution having a shape parameter, α, and a scale parameter, β (see Equation 2).

$$\text{preview} = \gamma(\alpha, \beta) \tag{2}$$

The precise amount of preview was also modulated by a target word's frequency, as specified by Equation 3, where the free parameters η_1 and η_0 scale α. (The weak effect of saccade launch-site distance on preview is ignored for the purpose of simplicity.) Thus, according to Equations 2 and 3, more parafoveal preview is expected (on average) for high- than low-frequency target words.

$$\alpha = \eta_1 \text{ frequency} + \eta_0 \tag{3}$$

Finally, as indicated, saccade length was modulated by preview as specified by Equation 4, with λ being a free parameter that scales this linear relationship. (Note that, in Equation 4, Equations 2 and 3 are substituted in for the rightmost term, preview, to make the relation between preview and saccade length more transparent.)

[2] Our implementation of the default-targeting assumption was directly motivated by Yan, Kliegl, Richter et al.'s (2010), description of their hypothesis: "If parafoveal word segmentation is successful . . . saccades are aimed at the word center to process the information of the to-be-fixated word in a single fixation. If not, readers aim for the beginning of the next word with . . . an increased likelihood for a forward refixation" (p. 720).

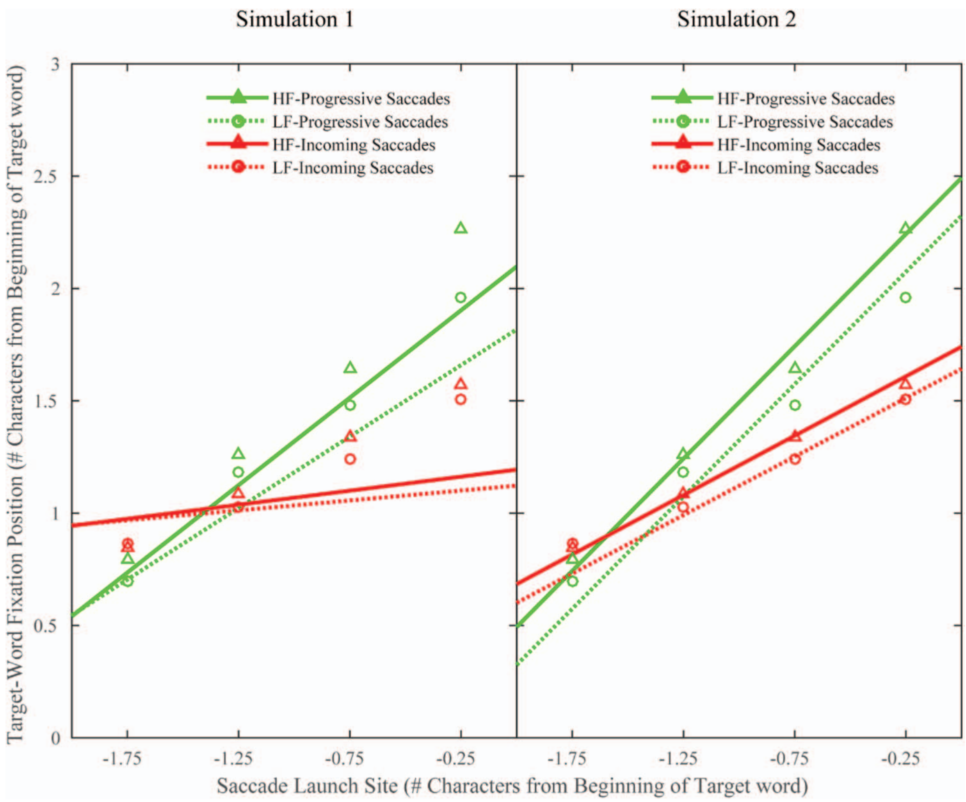

Figure 2. Observed and simulated relationship between the pretarget saccade launch site and subsequent fixation position for high- (HF) and low-frequency (LF) target words in the valid-preview condition. The symbols show the observed means and the lines show the simulated results using: (a) the default-target hypothesis (i.e., Simulation 1) and (b) the dynamic-adjustment hypothesis (i.e., Simulation 2). Note that the green (black) symbols and lines show the results using progressive saccades (i.e., regardless of whether or not the resulting fixation was on the target word), whereas the red (gray) symbols and lines show the results of the incoming saccades (i.e., progressive saccades that were followed by target-word fixations). See the online article for the color version of this figure.

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$$\begin{aligned} \text{length} &= \lambda \text{ preview} \\ &= \lambda(\alpha, \beta) \\ &= \lambda(\eta_1 \text{frequency } + \eta_0, \lambda\beta) \end{aligned} \tag{4}$$

Note that, in contrast to Simulation 1, saccadic error is intrinsic to Simulation 2, with variability in saccade length being determined by the β parameter. (The best fitting parameter values and the procedure used to find them are described in Appendix C.) We now compare the results of the two simulations and then, in the final section of this article, discuss the implications of this comparison for the basic question of how readers of Chinese select their saccade targets.

Comparison of simulation results. The results of Simulations 1 and 2, along with the empirical results to facilitate comparison, are displayed in Figures 2, 3, 4, and 5. Figure 2 shows how well the two simulations fit the observed relationships between the pretarget saccade launch site and the subsequent fixation position on high- and low-frequency target words in the valid-preview condition. A comparison of Simulations 1 and 2 indicates that the latter provides a better quantitative fit than the former. Although Simulation 1 did adequately fit the progressive saccades (i.e., regardless of whether or not the subsequent fixation landed on the target word; $MSE = 4.42 \times 10^{-2}$), it performed less well simulating incoming saccades (i.e., those saccades that subsequently resulted in a target-word fixation; $MSE = 5.89 \times 10^{-2}$). In contrast, Simulation 2 provided a better fit for both types of saccades (progressive: $MSE = 8.40 \times 10^{-3}$; incoming: $MSE = 3.10 \times 10^{-3}$).

Figure 3 shows the mean observed and simulated target-word fixation positions and saccade lengths. As the figure shows, Simulation 2 also provided better quantitative fits for both the mean fixation positions (Simulation 1: $MSE = 5.2 \times 10^{-2}$; Simulation 2: $MSE = 2.1 \times 10^{-4}$) and the mean saccade length (Simulation 1: $MSE = 3.72 \times 10^{-2}$; Simulation 2: $MSE = 2.4 \times 10^{-3}$).

Figure 4 shows the mean observed and simulated probabilities of refixating the pretarget region, fixating the target word, and skipping the target word. Between-simulation comparisons of each measure again indicate that Simulation 2 provided better quantitative fits to the data: (a) probability of refixating the pretarget word (Simulation 1: $MSE = 7.10 \times 10^{-3}$; Simulation 2: $MSE = 1.20 \times 10^{-3}$); (b) probability of fixating the target word (Simulation 1: $MSE = 1.05 \times 10^{-2}$; Simulation 2: $MSE = 7.3 \times 10^{-3}$); and (c) probability of skipping the target word (Simulation 1: $MSE = 4.75 \times 10^{-3}$; Simulation 2: $MSE = 3.1 \times 10^{-3}$).

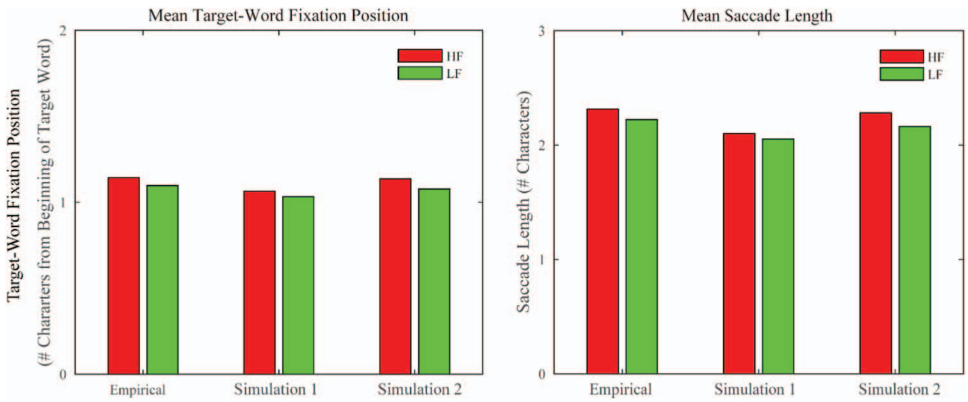

Figure 3. Mean observed and simulated (a) target-word fixation position and (b) incoming-saccade lengths for high- (HF) and low-frequency (LF) target words in the valid-preview condition. See the online article for the color version of this figure.

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Finally, to determine if our method of instantiating parafoveal processing in Simulation 2 was sufficient to explain the amount of preview benefit that was observed in our experiment, we compared the mean simulated preview benefit to the observed value. As Figure 5 shows, the simulation provided a good quantitative fit of this measure ($MSE = 0.58$).

General Discussion

In this article, we examined how parafoveal lexical processing influences eye movements during the reading of Chinese in an attempt to discriminate between two hypotheses about how Chinese readers select their saccade targets—default-saccade targeting versus dynamic-saccade adjustment. To do this, we first conducted an eye-movement experiment to determine how the frequency and preview validity of target words influenced several eye-movement measures related to the processing of those words, including the lengths of the saccades into and out of the target words, the distribution of fixation positions on the target words, and measures of fixation probability and duration. The key results from this experiment were that both target-word frequency and preview interacted to modulate the lengths of the saccades entering and exiting those words, with both types of saccades being longer for high- than low-frequency words, but only when preview of the word was available. These results provided a set of empirical "benchmarks" that were then used to evaluate the two aforementioned saccade-targeting hypotheses.

To do that, we implemented the core assumptions of the default-targeting hypothesis (i.e., Simulation 1) and dynamic-adjustment hypothesis (i.e., Simulation 2) as computational models. These two models were then used to simulate the data from our experiment. The results of these simulations confirmed our intuitions that, although the default-targeting hypothesis does provide an adequate qualitative account of how word frequency and parafoveal preview influence saccade targeting during the reading of Chinese, the dynamic-adjustment hypothesis provides a much better quantitative account of these effects. This finding, along with the finding that the dynamic-adjustment model required fewer free parameters than the default-targeting model (5 vs. 20, respectively), provides a compelling argument for why the dynamic adjustment of saccade length provides a better account of where readers of Chinese select their saccade targets than does default saccade targeting. Although this does not definitively show that the dynamic-adjustment hypothesis is correct, it does put the burden of proof on proponents of the default-targeting hypothesis to instantiate an explicit version of their hypothesis that is both parsimonious and sufficient to provide a precise account of how variables like word frequency and preview availability influence saccade targeting during Chinese reading.

It is also important to emphasize the fact that the default-targeting hypothesis can be conceptualized as a discrete version of the dynamic-adjustment hypothesis, with the full range of possible saccade lengths posited by the latter hypothesis being truncated into a small number of discrete lengths (corresponding to a few specific targets) according to the former hypothesis (i.e., we can use some thresholds to discretize the level of preview and then guide eyes to various default target positions, though this discretized operation will result in the cost of increasing free parameters and decreasing the goodness of fit. See Simulation D2 in Appendix D). That said, the absence of clearly demarcated word boundaries in Chinese and their presence in languages like English and German may play an important functional role in determining the degree to which the decisions about where to move the eyes (e.g., the selection of saccade targets) during reading can be made discrete. For that reason, we will close this article with a brief discussion of the theoretical implications of our findings for current computational models of eye-movement control in reading (see the special issue of *Cognitive Systems Research*, Reichle, 2006).

Two of the most prominent of these eye-movement models are E-Z Reader (Reichle et al., 1998, 2012; Reichle, Warren, & McConnell, 2009) and SWIFT (Engbert et al., 2005; Schad & Engbert, 2012). Although the models differ in many respects (e.g., attention is only allocated to one word at a time in E-Z Reader, but is concurrently allocated to multiple words in SWIFT), both models assume that the decisions about when to move the eyes (e.g., the selection of saccade targets) from one word to the next are coupled with lexical processing, and that saccades are (by default) directed toward the centers of upcoming (i.e., parafoveal) words. Although the latter assumption might be plausible in alphabetic

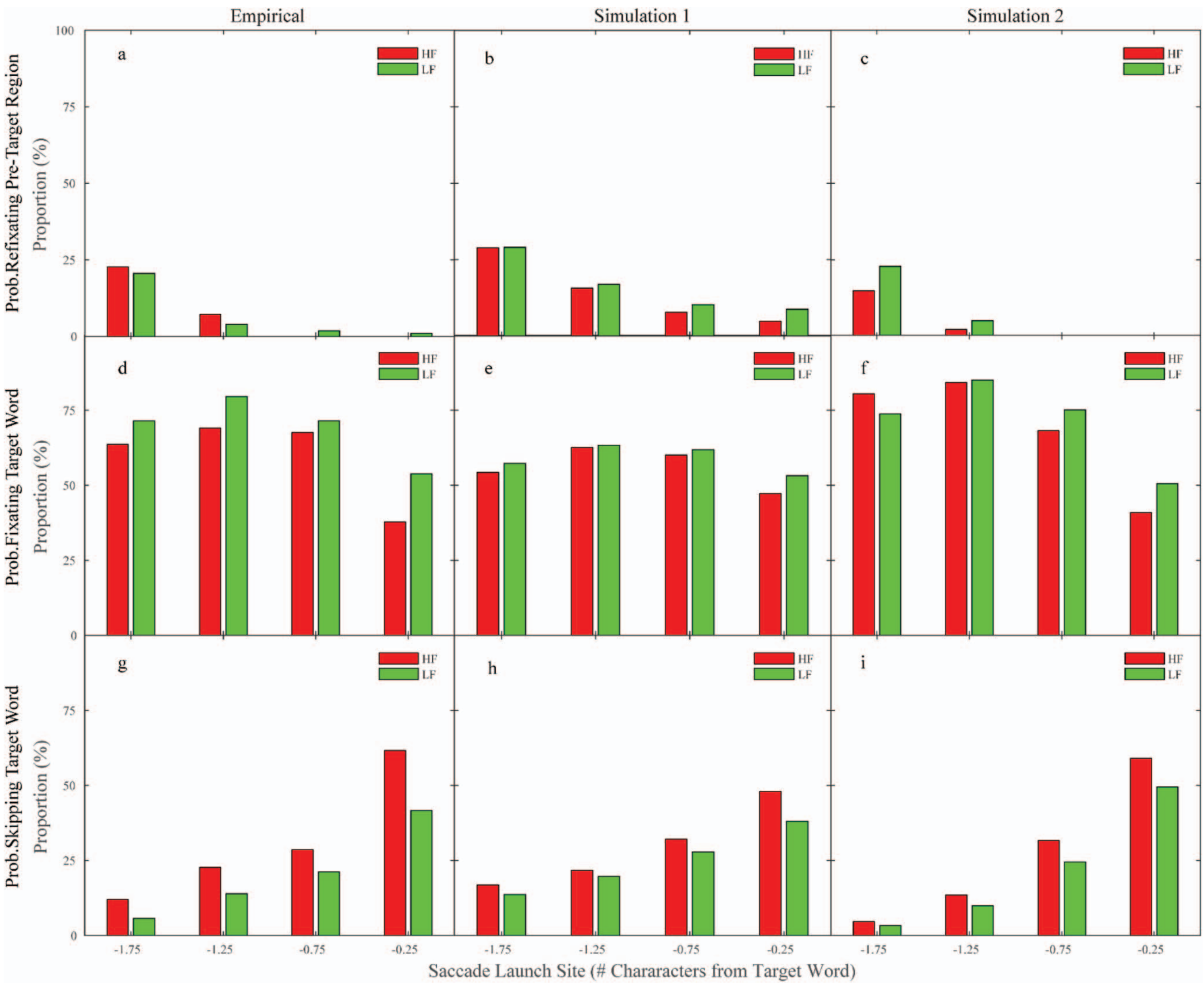

Figure 4. Mean observed and simulated probabilities of refixating the pretarget region (Panels a–c), fixating the target word (Panels d–f), and skipping the target word (Panels g–i) in the valid-preview condition. Prob. = probabilities; HF = high-frequency; LF = low-frequency. See the online article for the color version of this figure.

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languages like English and German (in which individual words are clearly demarcated by blank spaces and for which the models were developed to explain), this assumption (a) may be a gross oversimplification in the case of alphabetic languages, and/or (b) may be incorrect in the case of nonalphabetic languages like Chinese.

There are at least two important findings that are consistent with the former claim about alphabetic languages. The first consists of demonstrations that the orthographic properties of words can influence where the words are actually fixated (Hyönä, 1995; Plummer & Rayner, 2012; Radach, Inhoff, & Heller, 2004; Vonk, Radach, & van Rijn, 2000; White & Liversedge, 2004). The second consists of demonstrations that the precise nature of the morpheme constituents (e.g., their frequency) of compound words can influence saccades into and out of those constituents (Hyönä & Pollatsek, 1998, 2000). These findings together suggest that the assumption that saccades are normally directed toward the centers of upcoming words may be too simplistic for even alphabetic languages, and that some other mechanism or heuristic (e.g., the dynamic modulation of saccade length) may also play an active role in guiding where the eyes move during the reading of alphabetic languages. At least, it is worthwhile to examine this possibility by empirical or modeling works.

Additional findings supporting the second claim include both those reported in this article and several other "benchmark" findings specific to eye movements during the reading of Chinese, such as evidence that fixation-position distributions are uniform in shape (Li et al., 2011) and more recent demonstrations that properties of both foveal and parafoveal words can influence saccade length (Li et al., 2014; Liu, Reichle, & Li, 2015). These small but reliable effects suggest that there is an additional mechanism or heuristic that plays an important functional role in guiding the eye movements of readers of Chinese.

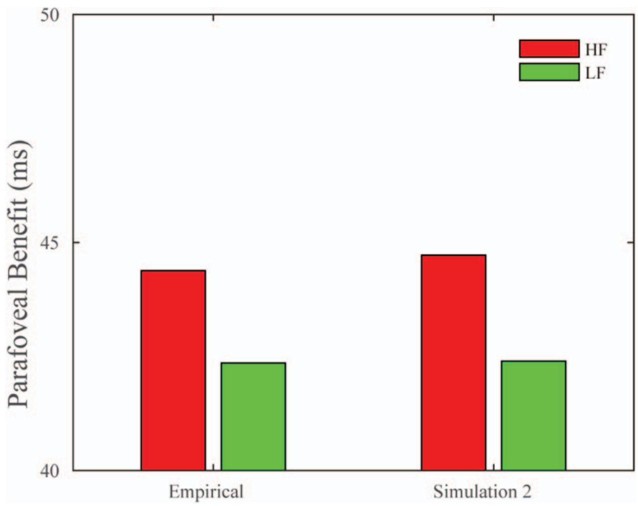

Figure 5. Mean observed and simulated preview benefit. HF = high-frequency; LF = low-frequency. See the online article for the color version of this figure.

Finally, it is obvious that the presence of clearly demarcated word boundaries in most alphabetic languages can facilitate the selection of saccade targets using simple heuristics (e.g., directing the eyes to the center of the next unidentified word) that might be adopted to help circumvent the timing constraints associated with lexical processing and saccadic programming (e.g., see Reichle & Reingold, 2013). However, as discussed above, evidence that saccade lengths are dynamically adjusted even during the reading of alphabetic languages (e.g., to facilitate the processing of individual morphemes; Hyönä & Pollatsek, 1998, 2000) suggests that readers of these languages might also employ eye-movement heuristics that are more "Chinese-like" in nature.

We therefore suspect that current eye-movement control models will need to incorporate such heuristics if they are to provide complete accounts of eye-movement behavior during the reading of nonalphabetic language like Chinese, but that—as indicated—these heuristics also be necessary to fully explain eye-movement behavior during the reading of any language. We therefore believe that future efforts should be directed toward understanding precisely how saccade length is adjusted to accommodate foveal and parafoveal processing demands during the reading of both alphabetic and nonalphabetic languages. Such comparisons will help illuminate the similarities and differences of eye-movement control across different writing systems and advance our understanding of both eye-movement control and the cognitive processes that support reading.

References

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language, 68,* 255–278. http://dx.doi.org/10.1016/j.jml.2012.11.001

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). *lme4: Linear mixed-effects models using Eigen and S4*. Retrieved from http://lme4.r-forge.r-project.org/

Bicknell, K., Higgins, E., Levy, R., & Rayner, K. (2013). Evidence for cognitively controlled saccade targeting in reading. In M. Knauff, M. Pauen, N. Sebanz, & I. Wachsmuth (Eds.), *Proceedings of the 35th Annual Conference of the Cognitive Science Society* (pp. 197–202). Austin, TX: Cognitive Science Society.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 433–436. http://dx.doi.org/10.1163/156856897X00357

Bretz, F., Hothorn, T., & Westfall, P. (2010). *Multiple comparisons using R*. Boca Raton, FL: CRC Press. http://dx.doi.org/10.1201/9781420010909

Chen, H., & Tang, C. (1998). The effective visual field in reading Chinese. *Reading and Writing, 10,* 245–254. http://dx.doi.org/10.1023/A:1008043900392

Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The Eyelink Toolbox: Eye tracking with MATLAB and the Psychophysics Toolbox. *Behavior Research Methods, Instruments & Computers, 34,* 613–617. http://dx.doi.org/10.3758/BF03195489

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review, 112,* 777–813. http://dx.doi.org/10.1037/0033-295X.112.4.777

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 417–429. http://dx.doi.org/10.1037/0278-7393.16.3.417

Hyönä, J. (1995). Do irregular letter combinations attract readers' attention? Evidence from fixation locations in words. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 68–81. http://dx.doi.org/10.1037/0096-1523.21.1.68

Hyönä, J., & Pollatsek, A. (1998). Reading Finnish compound words: Eye fixations are affected by component morphemes. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1612–1627. http://dx.doi.org/10.1037/0096-1523.24.6.1612

Hyönä, J., & Pollatsek, A. (2000). Processing of Finnish compound words in reading. In A. Kennedy, R. Radach, D. Heller, J. Pynte (Eds.), *Reading as a perceptual process* (pp. 65–87). Oxford, UK: Elsevier.

Inhoff, A. W., & Liu, W. (1998). The perceptual span and oculomotor activity during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 20–34. http://dx.doi.org/10.1037/0096-1523.24.1.20

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics, 40,* 431–439. http://dx.doi.org/10.3758/BF03208203

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language, 59,* 434–446. http://dx.doi.org/10.1016/j.jml.2007.11.007

Kennison, S. M., & Clifton, C., Jr. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 68–81. http://dx.doi.org/10.1037/0278-7393.21.1.68

Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception, 36,* 14.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2013). lmerTest: Tests in linear mixed effect models [Computer software]. Retrieved from https://cran.r-project.org/web/packages/lmerTest/index.html

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

Li, X., Liu, P., & Rayner, K. (2011). Eye movement guidance in Chinese reading: Is there a preferred viewing location? *Vision Research, 51,* 1146–1156. http://dx.doi.org/10.1016/j.visres.2011.03.004

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Liu, Y., Reichle, E. D., & Huang, R. (2015). *Eye-movement control during the reading of Chinese: An analysis using the Landolt-C Paradigm*. Retrieved from http://arxiv.org/abs/1503.07610

Liu, Y., Reichle, E. D., & Li, X. (2015). Parafoveal processing affects outgoing saccade length during the reading of Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41,* 1229–1236. http://dx.doi.org/10.1037/xlm0000057

Liversedge, S. P., Zang, C., Zhang, M., Bai, X., Yan, G., & Drieghe, D. (2014). The effect of visual complexity and word frequency on eye movements during Chinese reading. *Visual Cognition, 22,* 441–457. http://dx.doi.org/10.1080/13506285.2014.889260

Ma, G., Li, X., & Pollatsek, A. (2015). There is no relationship between the preferred viewing location and word segmentation in Chinese reading. *Visual Cognition, 23,* 399–414. http://dx.doi.org/10.1080/13506285.2014.1002554

McDonald, S. A., Carpenter, R. H. S., & Shillcock, R. C. (2005). An anatomically constrained, stochastic model of eye movement control in reading. *Psychological Review, 112,* 814–840. http://dx.doi.org/10.1037/0033-295X.112.4.814

Modern Chinese Frequency Dictionary (in Chinese). Beijing, Beijing Language and Culture University Press, 1986.

O'Regan, J. K. (1981). The "convenient viewing position" hypothesis. In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.), *Eye movements: Cognition and visual perception* (pp. 289–298). Hillsdale, NJ: Erlbaum.

Pan, J., Yan, M., Laubrock, J., Shu, H., & Kliegl, R. (2014). Saccade-target selection of dyslexic children when reading Chinese. *Vision Research, 97,* 24–30. http://dx.doi.org/10.1016/j.visres.2014.01.014

Pinheiro, J. C., & Bates, D. M. (2000). *Mixed-effects models in S and S-PLUS*. New York, NY: Springer. http://dx.doi.org/10.1007/978-1-4419-0318-1

Plummer, P., & Rayner, K. (2012). Effects of parafoveal word length and orthographic features on initial fixation landing positions in reading. *Attention, Perception, & Psychophysics, 74,* 950–963. http://dx.doi.org/10.3758/s13414-012-0286-z

R Core Team. (2015). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org

Radach, R., Inhoff, A. W., & Heller, D. (2004). Orthographic regularity gradually modulates saccade amplitudes in reading. *European Journal of Cognitive Psychology, 16,* 27–51. http://dx.doi.org/10.1080/09541440340000222

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7,* 65–81. http://dx.doi.org/10.1016/0010-0285(75)90005-5

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception, 8,* 21–30. http://dx.doi.org/10.1068/p080021

Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E. D. (2004). The effects of word frequency and predictability on eye movements in reading: Implications for the E-Z Reader model. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 720–732. http://dx.doi.org/10.1037/0096-1523.30.4.720

Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. *Vision Research, 46,* 310–323. http://dx.doi.org/10.1016/j.visres.2005.06.018

Rayner, K., & Morrison, R. E. (1981). Eye movements and identifying words in parafoveal vision. *Bulletin of the Psychonomic Society, 17,* 135–138. http://dx.doi.org/10.3758/BF03333690

Reichle, E. D. (Ed.). (2006). Models of eye-movement control in reading [Special issue]. *Cognitive Systems Research, 7,* 1–96.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological Review, 105,* 125–157. http://dx.doi.org/10.1037/0033-295X.105.1.125

Reichle, E. D., Pollatsek, A., & Rayner, K. (2012). Using E-Z Reader to simulate eye movements in nonreading tasks: A unified framework for understanding the eye–mind link. *Psychological Review, 119,* 155–185. http://dx.doi.org/10.1037/a0026473

Reichle, E. D., & Reingold, E. M. (2013). Neurophysiological constraints on the eye–mind link. *Frontiers in Human Neuroscience, 7,* 361. http://dx.doi.org/10.3389/fnhum.2013.00361

Reichle, E. D., Warren, T., & McConnell, K. (2009). Using E-Z Reader to model the effects of higher level language processing on eye movements during reading. *Psychonomic Bulletin & Review, 16,* 1–21. http://dx.doi.org/10.3758/PBR.16.1.1

Reilly, R. G., & O'Regan, J. K. (1998). Eye movement control during reading: A simulation of some word-targeting strategies. *Vision Research, 38,* 303–317. http://dx.doi.org/10.1016/S0042-6989(97)87710-3

Reingold, E. M., Reichle, E. D., Glaholt, M. G., & Sheridan, H. (2012). Direct lexical control of eye movements in reading: Evidence from a survival analysis of fixation durations. *Cognitive Psychology, 65,* 177–206. http://dx.doi.org/10.1016/j.cogpsych.2012.03.001

Schad, D. J., & Engbert, R. (2012). The zoom lens of attention: Simulating shuffled versus normal text reading using the SWIFT model. *Visual Cognition, 20,* 391–421. http://dx.doi.org/10.1080/13506285.2012.670143

Schotter, E. R., Reichle, E. D., & Rayner, K. (2014). Rethinking parafoveal processing in reading: Serial-attention models can explain semantic preview benefit and $N+2$ preview effects. *Visual Cognition, 22,* 309–333. http://dx.doi.org/10.1080/13506285.2013.873508

Schroyens, W., Vitu, F., Brysbaert, M., & d'Ydewalle, G. (1999). Eye movement control during reading: Foveal load and parafoveal processing. *The Quarterly Journal of Experimental Psychology: Section A. Human Experimental Psychology, 52,* 1021–1046. http://dx.doi.org/10.1080/713755859

Sereno, S. C., & Rayner, K. (2000). Spelling–sound regularity effects on eye fixations in reading. *Perception & Psychophysics, 62,* 402–409. http://dx.doi.org/10.3758/BF03205559

Slattery, T. J., Angele, B., & Rayner, K. (2011). Eye movements and display change detection during reading. *Journal of Experimental Psychology: Human Perception and Performance, 37,* 1924–1938. http://dx.doi.org/10.1037/a0024322

Tang, C. K., Au Yeung, L. H., & Chen, H. C. (1997). The effective visual field in Chinese reading. In H. C. Chen (Ed.), *Cognitive processing of Chinese and related Asian languages* (pp. 267–286). Hong Kong, PRC: The Chinese University Press.

Tsai, J. L., Kliegl, R., & Yan, M. (2012). Parafoveal semantic information extraction in traditional Chinese reading. *Acta Psychologica, 141,* 17–23. http://dx.doi.org/10.1016/j.actpsy.2012.06.004

Tsai, J. L., & McConkie, G. W. (2003). Where do Chinese readers send their eyes? In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 159–176). Oxford, UK: Elsevier. http://dx.doi.org/10.1016/B978-044451020-4/50010-4

Vitu, F. (1991). The influence of parafoveal preprocessing and linguistic context on the optimal landing position effect. *Perception & Psychophysics, 50,* 58–75. http://dx.doi.org/10.3758/BF03212205

Vonk, W., Radach, R., & van Rijn, H. (2000). Eye guidance and the saliency of word beginnings in reading text. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 269–299). Amsterdam, the Netherlands: North-Holland. http://dx.doi.org/10.1016/B978-008043642-5/50014-0

Wei, W., Li, X., & Pollatsek, A. (2013). Word properties of a fixated region affect outgoing saccade length in Chinese reading. *Vision Research, 80,* 1–6. http://dx.doi.org/10.1016/j.visres.2012.11.015

White, S. J., & Liversedge, S. P. (2004). Orthographic familiarity influences initial eye fixation positions in reading. *European Journal of Cognitive Psychology, 16,* 52–78. http://dx.doi.org/10.1080/09541440340000204

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White, S. J., & Liversedge, S. P. (2006). Foveal processing difficulty does not modulate non-foveal orthographic influences on fixation positions. *Vision Research, 46,* 426–437. http://dx.doi.org/10.1016/j.visres.2005.07.006

White, S. J., Rayner, K., & Liversedge, S. P. (2005). Eye movements and the modulation of parafoveal processing by foveal processing difficulty: A reexamination. *Psychonomic Bulletin & Review, 12,* 891–896. http://dx.doi.org/10.3758/BF03196782

Yan, M., Kliegl, R., Richter, E. M., Nuthmann, A., & Shu, H. (2010). Flexible saccade-target selection in Chinese reading. *The Quarterly Journal of Experimental Psychology, 63,* 705–725. http://dx.doi.org/10.1080/17470210903114858

Yan, M., Kliegl, R., Shu, H., Pan, J., & Zhou, X. (2010). Parafoveal load of word *N*+1 modulates preprocessing effectiveness of word N+2 in Chinese reading. *Journal of Experimental Psychology: Human Perception and Performance, 36,* 1669–1676. http://dx.doi.org/10.1037/a0019329

Yan, M., Richter, E. M., Shu, H., & Kliegl, R. (2009). Readers of Chinese extract semantic information from parafoveal words. *Psychonomic Bulletin & Review, 16,* 561–566. http://dx.doi.org/10.3758/PBR.16.3.561

Yan, M., Risse, S., Zhou, X., & Kliegl, R. (2012). Preview fixation duration modulates identical and semantic preview benefit in Chinese reading. *Reading and Writing, 25,* 1093–1111. http://dx.doi.org/10.1007/s11145-010-9274-7

Yan, M., Zhou, W., Shu, H., & Kliegl, R. (2012). Lexical and sublexical semantic preview benefits in Chinese reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38,* 1069–1075. http://dx.doi.org/10.1037/a0026935

Yan, M., Zhou, W., Shu, H., & Kliegl, R. (2015). Perceptual span depends on font size during the reading of Chinese sentences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41,* 209–219. http://dx.doi.org/10.1037/a0038097

Yang, H.-M., & McConkie, G. W. (1999). Reading Chinese: Some basic eye-movement characteristics. In H. C. Chen (Ed.), *Reading Chinese script: A cognitive analysis* (pp. 207–222). Mahwah, NJ: Erlbaum.

Yang, J., Rayner, K., Li, N., & Wang, S. (2012). Is preview benefit from word *n* + 2 a common effect in reading Chinese? Evidence from eye movements. *Reading and Writing, 25,* 1079–1091. http://dx.doi.org/10.1007/s11145-010-9282-7

Yang, J., Wang, S., Tong, X., & Rayner, K. (2012). Semantic and plausibility effects on preview benefit during eye fixations in Chinese reading. *Reading and Writing, 25,* 1031–1052. http://dx.doi.org/10.1007/s11145-010-9281-8

Yang, J., Wang, S., Xu, Y., & Rayner, K. (2009). Do Chinese readers obtain preview benefit from word *n* + 2? Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1192–1204. http://dx.doi.org/10.1037/a0013554

Yen, M. H., Tsai, J. L., Tzeng, O. J., & Hung, D. L. (2008). Eye movements and parafoveal word processing in reading Chinese. *Memory & Cognition, 36,* 1033–1045. http://dx.doi.org/10.3758/MC.36.5.1033

Zang, C., Liang, F., Bai, X., Yan, G., & Liversedge, S. P. (2013). Interword spacing and landing position effects during Chinese reading in children and adults. *Journal of Experimental Psychology: Human Perception and Performance, 39,* 720–734. http://dx.doi.org/10.1037/a0030097

Appendix A

Material Analyses

The properties of the target words used in the experiment and the characters from which those words are derived are displayed in Table A1. By design, high-frequency target words were higher in frequency than their low-frequency counterparts, $t = 15.30$, $p < .001$. However, as is evident in Table A1, word and character properties are not independent. For example, word frequency was positively correlated with mean character frequency, $r = .37$, $p < .001$ and was negatively correlated with the mean number of strokes per word, $r = -.21$, $p < .001$, and mean character frequency was negatively correlated with mean number of strokes per word, $r = -.35$, $p < .001$. This in turn meant that both characters of the high-frequency target words were higher in frequency than those of their low-frequency counterparts (both *t*s > 4.45, both *p*s $< .001$), and conversely, that there were fewer strokes in the characters of high- than low-frequency target words (both *t*s < -3.94, both *p*s $< .001$). However, the target words did not differ in terms of their degree of naturalness or predictability (both $|t|$s < 1.58, both *p*s $> .117$). Finally, it is important to note that, although the dynamic-adjustment hypothesis does not stipulate a clear distinction between how word and character processing modulate saccade length, the effects of word frequency on saccade length, landing position, skipping probabilities, refixation probabilities, and the various fixation-duration measures (e.g., gaze durations) remained robust after controlling for the various properties of characters (see Appendix B).

Table A1
Properties of the Target Words and Their Constituent Characters

	High-frequency		Low-frequency	
Property	*M*	*SD*	*M*	*SD*
Word frequency	121.50	98.50	2.17	1.53
Word naturalness	4.01	.41	4.06	.50
Word predictability	.01	.03	.00	.02
Character 1 number of stokes	7.59	2.91	9.11	3.34
Character 2 number of strokes	7.84	2.77	9.11	3.26
Character 1 frequency	1815.10	2208.72	787.89	1201.50
Character 2 frequency	1866.68	2910.10	774.62	1051.54

(*Appendices continue*)

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Appendix B

Additional Analyses

In this appendix, we report analyses of progressive- and incoming-saccade lengths, their corresponding fixation positions, the probabilities of skipping and refixation, and first-fixation and gaze duration after statistically controlling for two properties of the target-word characters—their frequencies and complexities (i.e., number of strokes). To avoid potential problems with collinearity, two analyses are reported, with the first controlling for the mean number of strokes and character frequencies of the target words themselves (see Tables B1 and B3), and the second controlling for the stroke number and frequency of the first character in the target words (see Tables B2 and B4). Both analyses show the interaction between target-word frequency and preview validity on progressive- and incoming-saccade length and fixation position, even after controlling for character-property covariates. Similarly, the analyses of the other measures (e.g., gaze duration) also indicate robust frequency and preview effects after controlling for character-property covariates.

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Table B1

Linear-Mixed Model for Progressive- and Incoming-Saccade Length and Their Corresponding Fixation Positions, Controlling Mean Stroke Number and Character Frequency

Predictor	Progressive-saccade length (char.)	Incoming-Saccade Length (char.)	Progressive-fixation position (char.)	Incoming-fixation position (char.)
Intercept	3.16***	2.59***	3.16***	2.59***
High-frequency target word	.05†	.03	.05†	.03
Valid preview	.16***	.10***	.16***	.10***
High-Frequency Target Word × Valid Preview	.17***	.07†	.17***	.07†
Launch fixation location	−.12***	−.50***	.88***	.50***
Log (launch fixation duration)	−.18***	−.17***	−.18***	−.17***
Mean stroke number	−.01	−.002	−.01	−.002
Mean character frequency	.02	.02†	.02	.02†

Note Char. = characters.
† $p < .1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

Table B2

Linear-Mixed Model for Progressive- and Incoming-Saccade Length and Their Corresponding Fixation Positions, Controlling the Stroke Number and Frequency of the First Character of the Target Word

Predictor	Progressive-saccade length (char.)	Incoming-saccade length (char.)	Progressive-fixation position (char.)	Incoming-fixation position (char.)
Intercept	3.17***	2.60***	3.17***	2.60***
High-frequency target word	.03	.01	.03	.01
Valid preview	.15***	.10***	.15***	.10***
High-Frequency Target Word × Valid Preview	.16***	.06†	.16***	.06†
Launch fixation location	−.12***	−.50***	.88***	.50***
Log (launch fixation duration)	−.18***	−.17***	−.18***	−.17***
First character stroke number[a]	−.03*	−.02*	−.03*	−.02*
First character frequency	.03*	.02*	.03*	.02*

Note Char. = characters.
[a] First character stroke number and frequency have been centered.
† $p < .1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

(*Appendices continue*)

Table B3
Linear Mixed Model Analysis for Skipping and Refixation Probabilities, and First-Fixation and Gaze Durations, Controlling Mean Stroke Number and Character Frequency

Predictor	Skipping probability	Refixation probability	First-fixation duration (ms)	Gaze duration (ms)
Intercept	-1.16^{***}	-2.97^{***}	290.34^{***}	343.13^{***}
High-frequency target word	.07	$-.50^{***}$	-19.21^{***}	-44.41^{***}
Valid preview	.09	−.22	-43.09^{***}	-80.23^{***}
High-Frequency Target Word × Valid Preview	$.29^{*}$	.01	−12.75	4.94
Mean stroke number[a]	−.05	$.22^{***}$	1.47	12.04^{**}
Mean character frequency[a]	.01	.04	1.38	1.01

[a]Mean stroke number and character frequency have been centered.
$^{\dagger} p < .1.$ $^{*} p < .05$ $^{**} p < .01.$ $^{***} p < .001.$

Table B4
Linear Mixed-Model Analysis for Skipping and Refixation Probabilities, and First-Fixation and Gaze Durations, Controlling the Stroke Number and Frequency of the First Character of the Target Word

Predictor	Skipping probability	Refixation probability	First-fixation duration (ms)	Gaze duration (ms)
Intercept	-1.16^{***}	-2.97^{***}	290.30^{***}	342.97^{***}
High-frequency target word	.06	$-.50^{***}$	-17.80^{**}	-45.71^{***}
Valid preview	.08	−.22	-43.12^{***}	-80.29^{***}
High-Frequency Target Word × Valid Preview	$.28^{*}$	.03	−12.23	7.09
First character stroke number[a]	$-.08^{*}$	$.20^{***}$	3.49	15.39^{***}
First character frequency[a]	.01	−.03	1.02	4.42

[a]First character stroke number and frequency have been centered.
$^{\dagger} p < .1.$ $^{*} p < .05.$ $^{**} p < .01.$ $^{***} p < .001.$

Appendix C

Simulation Parameters

Simulation 1 Parameters

We used polynomial regression functions (e.g., see Equation 1) to estimate the probabilities of observing the four different types of saccades using the method of least squares. Because these probabilities summed to 1 from each saccade launch site, only the probabilities associated with three saccade types were actually estimated; the probabilities of skipping the target word could be determined by subtracting the sum of the other three probabilities from 1. Finally, the values of σ, the parameter that controls the variability of saccadic error, were selected to maximize the goodness of fit to the empirical fixation-position distributions of incoming saccades on the high- versus low-frequency target (high-frequency: $MSE = 0.06$; low-frequency: $MSE = 0.05$). Table C1 lists the best-fitting parameter values. Figure C1 shows that these parameters accurately describe the empirical data (i.e., the probability of refixating the pretarget region: $MSE = 8.2 \times 10^{-6}$; probability of fixating the target-word center: $MSE = 2 \times 10^{-3}$; probability of fixating the target-word beginning: $MSE = 1.2 \times 10^{-5}$). Simulation 1 thus required a total of 20 free parameters.

Table C1
The Best-Fitting Parameters Used in Simulation 1

Target-word frequency	Saccade type	κ_2	κ_1	κ_0	σ
High	Refixate pre-target region	.156	.161	.031	.79
	Fixate center of target word	−.346	−.813	.195	
	Fixate beginning of target word	−.007	−.050	−.0003	
Low	Refixate pre-target region	.158	.194	.055	.86
	Fixate center of target word	−.270	−.610	.368	
	Fixate beginning of target word	.012	−.027	.024	

(*Appendices continue*)

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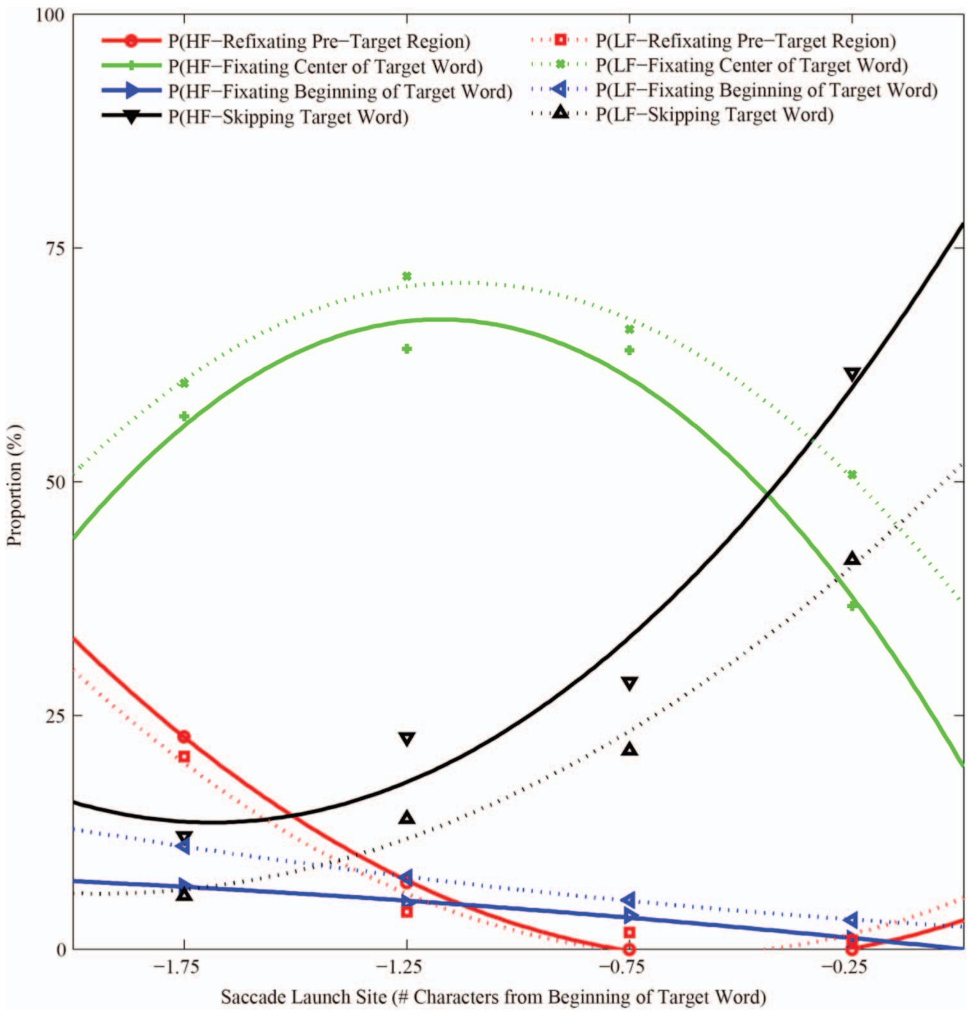

Figure C1. The observed (symbols) and estimated (lines) probabilities of refixating the pretarget region, fixating the target-word center (i.e., single fixation), fixating the target-word beginning (i.e., first-of-multiple fixations), and skipping the target word as a function of target-word frequency. HF = high-frequency; LF = low-frequency. See the online article for the color version of this figure.

Simulation 2 Parameters

The expected value of Equation 4 is $\lambda\beta(\eta_1\text{frequency} + \eta_0)$, corresponding to the value predicted using the mean progressive saccade length from the pretarget region. Thus, two groups of parameters, $\lambda\beta\eta_1$ and $\lambda\beta\eta_0$, are coefficients for a regression equation for progressive-saccade length using target-word frequency as a predictor variable (i.e., low frequency = 1, high frequency = 2). And because the variance associated with Equation 4 (i.e., the variance associated with saccadic error) is given by the quantity $\lambda^2\beta^2(\eta_1\text{frequency} + \eta_0)$, the parameter pair $\lambda\beta$ can be estimated using the empirical distribution of fixations on the target words, doing so separately for the high- and low-frequency target words. Finally, the value of λ, the parameter that scales the saccade length as a function of preview (see Equation 4), can be determined by fitting the simulated preview benefit to the observed preview benefit. Simulation 2 thus required a total of five free parameters; their final values are listed in Table C2.

Table C2
The Best-Fitting Parameters Used in Simulation 2

Target-word frequency	η_1	η_0	β	λ
High	.886	11.348	3.726	.051
Low	.801	10.267	4.118	.051

Note. Although each parameter plays a different functional role, their values are not independent and were therefore estimated in five combinations: (1) $\lambda\beta\eta_1$; (2) $\lambda\beta\eta_0$; (3) $\lambda\beta$ for high-frequency target words; (4) $\lambda\beta$ for low-frequency target words; and (5) λ.

(*Appendices continue*)

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Appendix D

Additional Simulations

The following pair of simulations provides additional evidence that the relatively poor performance of the default-targeting hypothesis is not due to how our estimates of target-word segmentation probabilities were derived (Simulation D1) or the algorithm that was used to select default saccade targets (Simulation D2).

Simulation D1

This simulation extends Simulation 1 to determine if the precise estimates of the target-word segmentation probabilities used to simulate the default-targeting hypothesis were responsible for its poor performance. To understand the logic of how this was done, imagine using x versus $1 - x$ to respectively represent the probabilities of successfully segmenting a target word (i.e., making a single fixation) versus not successfully segmenting a target word (i.e., making the first-of-multiple fixations); Simulation D1 shows that there are no values of x (across its full range of possible values, i.e., 0 to 1) that allow the default-targeting model to fit our data as well as the dynamic-adjustment model. Simulation D1 therefore used the same polynomial functions that were used in Simulation 1, but with all possible values of x to derive estimates of target-word segmentation probabilities. Figure D1 (Panel a) shows the results of this simulation, with the upper and lower edges of the shaded regions respectively showing the extreme cases in which target words were always versus never segmented from the parafovea, and with the lines showing the original fits obtained in Simulation 1 (cf., Figure 2). Inspection of the figure indicates that, regardless of the values of the target-word segmentation probabilities actually used, the default-targeting model failed to accurately predict the relationship between incoming-saccade length and the pretarget saccade launch site.

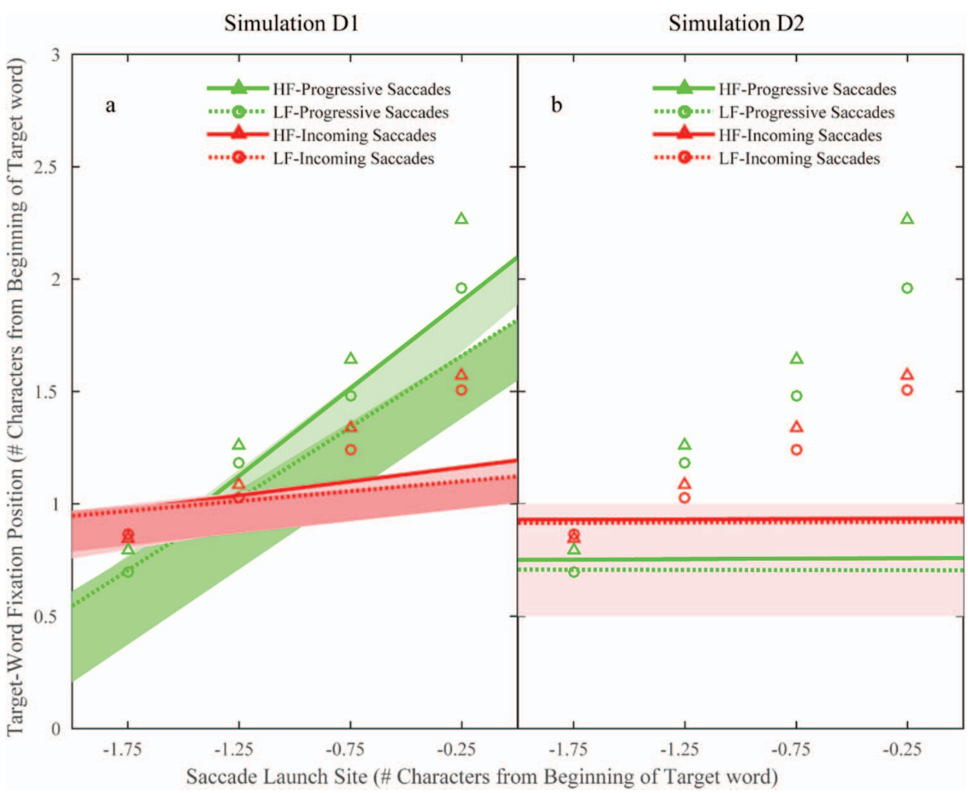

Figure D1. Observed and simulated relationship between the pretarget saccade launch site and subsequent fixation position for high- and low-frequency target words in the valid-preview condition. The symbols show the observed means, and the lines and shaded regions respectively show the intermediate and extreme cases described in the exposition of the simulations. HF = high-frequency; LF = low-frequency. See the online article for the color version of this figure.

(*Appendices continue*)

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Simulation D2

This simulation extends Simulation 2 (i.e., the dynamic-adjustment model) to determine if the algorithm used to select saccade targets in Simulation 1 might be responsible for the default-targeting model's poor performance. The logic of how this was done is simple: A threshold parameter, τ, was added to the dynamic-adjustment model (as implemented in Simulation 2) so that, if the amount of target-word preview (as specified by Equations 2 and 3) exceeded this threshold (i.e., preview $> \tau$), then the saccade was directed toward its center, under the assumption that the word would have been segmented from the parafovea; otherwise, the saccade was directed toward the beginning of the target word. (This method of selecting default saccade targets thus replaced the use of the λ parameter to scale saccade length as a function of preview, thereby avoiding the need to increase the number of parameters beyond what was used in Simulation 2.) This new assumption about saccade-target selection required the addition of saccade error (sampled from a Gaussian distribution with $\mu = 0$ and $\sigma = 1$). Finally, to exhaustively examine the model's performance, simulations were completed using values of τ spanning from 0 (i.e., the target word was always segmented from the parafovea) to $+\infty$ (i.e., the target word was never segmented from the parafovea). Intermediate values equal to the grand means of the gamma distributions corresponding to the high- and low-frequency target-word preview conditions in Simulation 2 were also used. Figure D1 (Panel b) shows the simulation results, with the upper and lower edges of the shaded regions respectively showing the model's performance with $\tau = 0$ and $\tau = +\infty$, and with the lines showing its performance using the intermediate values of τ. Inspection of the figure indicates that, relative to Simulation 1, this alternative method of selecting default saccade targets actually provided a poorer account of the relationship between both progressive- and incoming-saccade length and the pretarget launch site. In addition, it is important to note that, even if the model were made more complex (e.g., by adding parameters to allow the model to make predictions about refixations and skipping), this version of the default-targeting model would still not provide a more accurate account of the relationship between incoming-saccade length and the pretarget launch site. Thus, although Simulation D2 does not itself provide definite evidence against the default-target hypothesis, it does provide another argument against it.

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