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RESEARCH REPORT

Parafoveal Processing Affects Outgoing Saccade Length During the Reading of Chinese

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Participants' eye movements were measured while reading Chinese sentences in which target-word frequency and the availability of parafoveal processing were manipulated using a gaze-contingent boundary paradigm. The results of this study indicate that preview availability and its interaction with word frequency modulated the length of the saccades exiting the target words, suggesting important functional roles for parafoveal processing in determining where the eyes move during reading. The theoretical significance of these findings is discussed in relation to 2 current models of eye-movement control during reading, both of which assume that saccades are directed toward default targets (e.g., the center of the next unidentified word). A possible method for addressing these limitations (i.e., dynamic attention allocation) is also discussed.

Keywords: Chinese reading, parafoveal processing, eye-movement control

During reading, readers of alphabetic languages usually direct their eyes to a specific position located between the beginning and center of a word, called the *preferred-viewing location* (PVL; Rayner, 1979). Readers of most alphabetic languages have no difficulty identifying and moving their eyes to the PVL because there are low-level visual cues (i.e., blank spaces) available in parafoveal/peripheral vision that mark word boundaries. Such cues are absent in Chinese, however, thereby raising the question of how readers of Chinese decide where to move their eyes. Attempts to answer this question have failed to reach consensus.

For example, several studies have failed to demonstrate that Chinese readers choose a specific fixation position within a word during reading, suggesting that saccade targets are randomly generated (Tsai & McConkie, 2003; Yang & McConkie, 1999). However, others have argued that saccade targeting is based on the ongoing word segmentation that occurs in parafoveal vision and that Chinese readers move their eyes to the PVL if this segmentation is successful, but move their eyes to the word beginning if it is not (Yan, Kliegl, Richter, Nuthmann, & Shu, 2010). Still others have proposed that Chinese readers do not move their eyes to specific locations but that the properties of the fixated word instead affect the outgoing saccade length, with longer saccades exiting fixated words that are easier to process (Wei, Li, & Pollatsek, 2013). These differences of opinion indicate that the issue of saccade targeting in Chinese reading remains unresolved. The remainder of this article will therefore attempt to shed light on this issue by reporting the results of an eye-movement experiment that is specifically designed to examine the roles played by foveal versus parafoveal processing in guiding where the eyes move during the reading of Chinese.

As indicated, previous studies have failed to provide reliable evidence that Chinese readers select specific saccade targets during reading. These studies instead indicate the following facts about saccadic targeting during Chinese reading. First, two seminal studies of Chinese reading have showed that the PVL curves (which plot the frequency of initial fixations as a function of their within-word positions) tend to be flat, suggesting that Chinese readers do not direct their eyes toward

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specific target locations (Tsai & McConkie, 2003; Yang & McConkie, 1999).

Second, a study recently reported by Li, Liu, and Rayner (2011) found that the length of the parafoveal word did not influence the initial fixation location within that word. In this study, two- or four-character target words were embedded within the same sentence frames, with the logic being that if Chinese readers target word centers, then the peak of the PVL curve should be further to the right in the four- than two-character words. Contrary to this prediction, the PVL curves did not differ between the two conditions. Furthermore, consistent with the studies reviewed earlier, the distribution of progressive fixations on the different characters within the words (including intraword refixations) was flat (see Li et al., 2011, Figure 3). Both of these results are inconsistent with the hypothesis that Chinese readers target specific locations in words.

Finally, although Yan et al. (2010) reported a tendency for Chinese readers to fixate the PVL in single-fixation cases and near word beginnings in multiple-fixation cases (purportedly depending on whether the word was successfully segmented prior to being fixated), neither of these findings provide unequivocal evidence for saccade targeting in Chinese reading. One reason for this is that the same pattern of results was observed in a study in which subjects read Chinese text with blank spaces inserted between words, making word segmentation unnecessary (Zang, Liang, Bai, Yan, & Liversedge, 2013; see Figures 3 and 4). Another reason is that the same pattern of results was reproduced using a computer simulation in which saccades were (on average) of constant length, thereby demonstrating how behavior that might otherwise be interpreted as evidence for saccade targeting might emerge from even simpler saccade-programming assumptions (Li et al., 2011). Thus, when considered together, the studies that have just been reviewed provide no reliable evidence that readers target specific within-word positions during Chinese reading.

There are also logical reasons for questioning the saccade-targeting hypothesis in Chinese. For example, if word beginnings are the default saccade targets during Chinese reading, then the fact that written Chinese contains a large number of single-character words might cause most saccades to be short and thereby possibly reduce processing efficiency, slowing the overall reading rate. Conversely, if the PVL is the default saccade target, then it becomes necessary to explain how Chinese readers are able to successfully segment words in the parafovea, because segmentation would be necessary prior to initiating a saccadic program to move the eyes to the PVL. As already noted, because of the lack of explicit visual cues (e.g., blank spaces) denoting word boundaries in Chinese text, the process of segmenting words would likely be computationally complex, irrespective of whether it is based on some type of linguistic statistical inference (e.g., calculating differences in how often characters occur at the beginning vs. end of words to help identify the first character of an upcoming word; Yan et al., 2010) or interactive processing that allows the concurrent segmentation and identification of words (Li, Rayner, & Cave, 2009). Such logical considerations seemingly result in the following paradox: Whereas low-level (e.g., visual) processing is inadequate for word segmentation, higher level (e.g., lexical) processing would seemingly remove any need to fixate the word being processed. This paradox, in combination with the empirical results reviewed earlier, makes the hypothesis that Chinese readers select specific viewing positions implausible, thus necessitating some alternative theoretical account. That being said, we now consider possible alternative accounts.

Although the random-saccade control model (Tsai & McConkie, 2003; Yang & McConkie, 1999) is consistent with evidence suggesting that there are no specific saccade targets during the reading of Chinese, the model is inconsistent with evidence that the relationship of the parafoveal words can influence fixation durations on these words (Yan, Kliegl, Shu, Pan, & Zhou, 2010; Yang, Wang, Xu, & Rayner, 2009) and evidence that saccades move the eyes further into words rendered in small (compared to large) font (Shu, Zhou, Yan, & Kliegl, 2011). Moreover, the model is also inconsistent with evidence that the properties of a fixated word affect the length of the saccade exiting that word (e.g., saccades tend to be longer from high- than low-frequency words; Wei et al., 2013). Similar findings have also been reported in studies involving the reading of alphabetic writing systems (e.g., Rayner, Ashby, Pollatsek, & Reichle, 2004; White & Liversedge, 2006).

To explain the previously mentioned results, Wei et al. (2013) suggested a processing-based hypothesis. According to this hypothesis, readers implicitly estimate the number of characters that they can process from each fixation and then program saccades to move their eyes to locations just to the right of the estimated number of characters. The hypothesis can therefore explain why easier-to-process words are (on average) followed by longer saccades than more difficult-to-process words: Easier-to-process words allow the concurrent processing of more characters per fixation than difficult-to-process words. However, this account also raises more questions than it answers. For example, one important question is, How do Chinese readers estimate the number of characters that they can process on each fixation? One possibility is that these estimates are simply based on foveal load, or the processing difficulty associated with the currently fixated word. Because word frequency influences the relative ease of foveal processing (Reingold, Reichle, Glaholt, & Sheridan, 2012), this foveal-load hypothesis can also explain Wei et al.'s observation that saccades tend to be longer after fixations on high- than low-frequency words because the former are associated with lower foveal load than the latter. This foveal-load hypothesis provides a more specific instantiation of Wei et al.'s processing-based hypothesis, and it makes the assumption that readers do not use information from parafoveal vision in selecting saccade targets; only foveal information is used to decide where to move the eyes.

Finally, one other possible account of saccade targeting is that foveal processing affects the amount of information that can be extracted from the parafovea, which then influences the outgoing saccade length. For example, if the fixated word is easy to process, then readers might be able to extract more parafoveal information, thereby allowing them to move their eyes further into the parafovea. Consistent with this parafoveal-processing hypothesis, several studies have demonstrated that foveal load can modulate parafoveal processing (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Kliegl, 2007; Kliegl, Nuthmann, & Engbert, 2006; White, Rayner, & Liversedge, 2005). Thus, a fixation on a high-frequency word might allow more parafoveal processing of upcoming words, thereby affording a longer saccade from that word.[1]

In the present study, we attempted to adjudicate between the foveal-load and parafoveal-processing hypotheses by investigating how both foveal load and parafoveal processing might jointly determine outgoing saccade length. To examine the possible role of foveal load, we manipulated the frequency of the target word, making it either high or low frequency. To examine the possible role of parafoveal vision, we manipulated the availability of parafoveal preview using a gaze-contingent boundary paradigm to control the information being displayed on the computer screen contingent upon where our subjects were looking (e.g., Rayner, 1975). Our analyses focus mainly on the length of the saccade exiting the target word to test the following predictions derived from the two saccade-targeting hypotheses.

First, if outgoing-saccade length is mainly determined by foveal load, as the foveal-load hypothesis predicts, then the target-word frequency should influence outgoing-saccade length, and this effect should be independent of the availability of the parafoveal preview. However, if outgoing-saccade length is mainly determined by how much information can be extracted from parafoveal vision, as the parafoveal-processing hypothesis predicts, then the effect of target-word frequency on the outgoing-saccade length should only be evident with preview, resulting in an interaction between foveal load and preview. Finally, because the foveal-load and parafoveal-processing hypotheses are not necessarily mutually exclusive, both of our manipulations might affect outgoing-saccade length, lending support to both hypotheses. By this final account, a saccade exiting a high-frequency target word should be longer than the saccade exiting a low-frequency target word, with the magnitude of this difference being larger with preview than without.

Method

Participants

Thirty-two native Chinese-speaking students (five males) from universities in Beijing were paid 40 yuan (approximately $7) to participate. All participants had normal or corrected-to-normal vision.

Apparatus

Stimuli rendered in Song 20 font were displayed using EyeTrack software (http://blogs.umass.edu/eyelab/software/) on a 21-in. (53-cm) CRT monitor (SONY Multiscan G520) with a resolution of 1,024 × 768 pixels and a 150 Hz refresh rate. With this configuration, display changes required approximately 19 ms (SD = 5 ms, with 29% of trials requiring more than 19 ms) to complete, prior to the termination of a typical saccade (30 ms; see Rayner, 1998). Eye movements were recorded using a SR-Research Eyelink1000 eye tracker (Kanata, Canada) sampling at a 1,000-Hz rate. A three-point calibration procedure was used with a maximal error of 0.4° visual angle.

Stimuli and Design

The design was a 2 (target-word frequency: high vs. low) × 2 (preview type: valid vs. invalid) within-subject design. A set of 320 two-character high- (M = 120.5 per million; SD = 98.2) and low-frequency (M = 2.17 per million; SD = 1.52) target words having similar meanings were selected from the *Contemporary Chinese Dictionary*. Each high- and low-frequency target-word pair was embedded in the same location (near the middle) within 160 sentence frames. Before the experiment, 20 native Chinese speakers were asked to evaluate the naturalness of these sentences; all raters agreed that the sentences were natural. To determine the predictability of each target word, another 10 raters were asked to predict the target-word identities using their preceding sentence contexts; the results indicated that target words were not predictable (for each word, $M < 0.1$). During the actual experiment, each sentence was displayed on a single line on the monitor. Each participant read each sentence frame once and read equal numbers of sentences in each condition.

To manipulate the amount of information that participants could extract from the parafovea, an invisible boundary was placed immediately after the target word so that normal preview could be allowed or prevented using a gaze-contingent display change paradigm (see Figure 1). In the valid-preview condition, the text was displayed naturally so that readers could extract parafoveal information when they fixated 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 to the right of the target words (after which the text became visible). Because our primary interest was to determine if any effect of target-word frequency on saccade length was dependent upon parafoveal processing, we masked all of the characters following the target word. To reduce the possibility that participants noticed 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

Upon arrival, participants were given task instructions and then seated 58 cm from the video monitor. (At this distance, one character subtended about 1° of visual angle.) The participants rested their chins on a chinrest to minimize head movements during the experiment. Viewing was binocular, but eye-movement data were only collected from the right eye. The eye tracker was calibrated and validated at the beginning of the experiment, and additional calibrations and validations were conducted as necessary. After this, participants first read 15 practice sentences (not included in our analysis) and then read the 240 experimental and filler sentences in a random order. A drift-check procedure was performed before each trial; a fixation box (1° × 1° in size) was

[1] Hyönä and Pollatsek (1998, 2000) have proposed a similar account of saccade targeting, called the parafoveal-processing-difficulty hypothesis. According to this hypothesis, foveal processing difficulty reduces the extent of parafoveal processing, hence causing a reader to direct his/her saccade more towards the beginning of the next parafoveal word. Although this hypothesis has received some support (e.g., the frequency of the initial morpheme within a Finnish compound word influences the lengths of the saccades entering and exiting that morpheme; see Hyönä & Pollatsek, 1998, Table 4), the hypothesis has only been considered in the context of morphological processing and has thus been overlooked as a (potentially) more general account of saccade targeting.

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**老师**※※※※※※※※※。
(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**访客**※※※※※※※※※。
(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).

displayed at the location of the first character of the sentence, with the sentence then being displayed after the participant successfully fixated on the box. The participants were instructed to read silently and used a button box (Microsoft SideWinder Game Pad) to answer comprehension questions after approximately one third of the sentences. Participants also used the button box to start each trial.

Results

Accuracy

The accuracy of sentence comprehension was 97%, and there were no differences across the four conditions ($F < 1$).

Eye Movement Measures

Trials in which eye blinks occurred during the fixation on, immediately preceding, or immediately following target words were excluded from our analyses. Trials containing three or more blinks were also excluded, resulting in approximately 6% of the total trials being removed. Any fixation less than 80 ms in duration and within one character space of another fixation was combined with that fixation (1% of the total fixations were combined in this manner). The trials containing saccades longer than five characters were excluded because such saccades are usually due to a track loss (3% and 3% of the total trials for incoming and outgoing saccades, respectively). Finally, the trials containing saccade lengths more than 3 SDs above the mean for a given participant in a given condition were excluded (0.2% and 0.3% of the total trials for incoming and outgoing saccades, respectively).

We report the following eye-movement measures, calculated conditional upon the eyes moving forward during the first pass through the text: (a) *outgoing-saccade length* is the distance between the last fixation on the target word and the first fixation to the right of target word; (b) *incoming-saccade length* is the distance between the last fixation to the left of target word and the initial fixation on the target word; (c) *landing position* is the location of the initial fixation on the target word, relative to its beginning; (d) *first-fixation duration* is the duration of the initial fixation on the target word; (e) *single-fixation duration* is the duration of the initial fixation on the target word, conditional upon it being fixated exactly once; (6) *gaze duration* is the sum of all first-pass fixations on the target word; and (7) *posttarget fixation duration* is the first fixation duration on the region following the target word.

Eye-movement measures were analyzed with linear mixed-effects models. To maximize the generalizability of these analyses, we used the maximal random-effects structure (Barr, Levy, Scheepers, & Tily, 2013). The significance values thus reflect the variance due to participants, items, the slope of fixed effects for participants, and the covariance due to correlations among these random effects. The target-word frequency, preview type, and interaction of these two variables were entered as fixed-effect factors in 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). Therefore, the intercept estimates the grand mean of a given dependent variable, and the regression coefficients estimate the differences between factor levels. These models were fitted using the lme4 package (Version 1.1–6; Bates, Maechler, Bolker, & Walker, 2014; Pinheiro & Bates, 2000); *p* values were estimated by using the lmerTest package (Version 2.0–6; Kuznetsova, Brockhoff, & Christensen, 2013); and planned contrasts (Tukey multiple-comparisons tests) were completed using the multicomp package (Version 1.3-3; Bretz, Hothorn, & Westfall, 2010) in R (Version 3.1.0; R Development Core Team, 2014). The seven eye-movement measures for each condition are shown in Table 1; the fixed-effect estimates for each measure are shown in Table 2.

As can be seen from the average outgoing-saccade length (see Table 1) and the fixed-effect estimates of the mixed-effect models (see Table 2), the effects of word frequency, preview type, and their interaction were significant (*p*s < 0.01). The outgoing saccades launched from high-frequency target words were longer than saccades from low-frequency target words ($b = 0.14$, $SE = 0.03$, $t = 4.99$, $p < .001$). Outgoing-saccade length was also affected by the preview manipulation: Saccades were longer in the valid-preview condition (i.e., when the characters to the right of the target word were visible) than in the invalid-preview condition

Table 1
Eye-Movement Dependent Measures

Target-word frequency	Parafoveal preview	Outgoing saccade length (char.)		Incoming saccade length (char.)		Landing position (char.)		First-fixation duration (ms)		Single-fixation duration (ms)		Gaze duration (ms)		Posttarget fixation duration (ms)	
		M	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
High	Valid	2.73	0.11	2.67	0.09	0.97	0.02	255	7	255	7	276	10	258	6
	Invalid	2.37	0.10	2.62	0.09	1.03	0.03	287	8	286	8	323	13	284	9
Low	Valid	2.48	0.09	2.59	0.10	1.04	0.02	278	9	280	10	320	15	258	7
	Invalid	2.30	0.10	2.47	0.07	0.97	0.03	307	8	313	8	384	18	290	8

Note. char. = characters.

Table 2
Fixed Effect Estimates of the Eye-Movement Dependent Measures

Predictor	Outgoing saccade length (char.)	Incoming saccade length (char.)	Target landing position (char.)	Target first-fixation duration (ms)	Target single-fixation duration (ms)	Target gaze duration (ms)	Posttarget fixation duration (ms)
Intercept	2.46***	2.59***	1.00***	281.95***	283.19***	326.22***	272.62***
High-frequency target word	0.14***	0.11***	0.01	−21.56***	−25.03***	−54.50***	−4.79
Valid preview	0.25***	0.09*	0.02	−30.63***	−32.88***	−57.18***	−29.52***
High-frequency target word: valid preview	0.16**	−0.06	−0.11**	−5.42	−0.20	12.36	7.51

Note. char. = characters.
* $p < .05$. ** $p < .01$. *** $p < .001$.

(i.e., when the characters to the right of the target word were masked; $b = 0.25$, $SE = 0.06$, $t = 4.61$, $p < .001$). This second result is consistent with previous findings that parafoveal preview can modulate saccade length (Rayner, Well, Pollatsek, & Bertera, 1982). Finally, there was a significant interaction between target-word frequency and preview type (see Figure 2), with the effect of word frequency on outgoing-saccade length being larger in the valid- than in the invalid-preview condition ($b = 0.16$, $SE = 0.05$, $t = 3.13$, $p = .003$). A planned contrast (see Table 3) showed that saccades exiting high-frequency target words ($M = 2.73$ characters; $SE = 0.11$) were longer than saccades exiting low-frequency target words ($M = 2.48$ characters; $SE = 0.09$) when parafoveal information was available ($b = 0.22$, $SE = 0.04$, $z = 5.34$, $p < .001$). However, saccades exiting high-frequency target words ($M = 2.37$ characters; $SE = 0.10$) were not significantly different from those exiting low-frequency target words ($M = 2.30$ characters; $SE = 0.10$) when the parafoveal information was masked ($b = 0.06$, $SE = 0.03$, $z = 1.80$, $p = .254$).

To facilitate a comparison of our results with the eye-movement literature, we also report the incoming-saccade lengths, the target word fixation-duration measures, and the initial fixation durations in the posttarget region. The mean values of these measures are shown in Table 1; the fixed-effect estimates of the mixed-effect models are shown in Table 2.

As Table 1 shows, the incoming saccades into the target words were longer in the high- than low-frequency condition (word frequency: $b = 0.11$, $SE = 0.02$, $t = 4.51$, $p < .001$), and in the valid- than invalid-preview condition (preview type: $b = 0.09$, $SE = 0.04$, $t = 2.34$, $p = .027$). And as one would predict, all of the fixation-duration measures were reduced on high- compared to low-frequency target words (first-fixation duration: $b = -21.56$, $SE = 3.88$, $t = -5.56$, $p < .001$; single-fixation duration: $b = -25.03$, $SE = 4.39$, $t = -5.70$, $p < .001$; gaze duration: $b =$

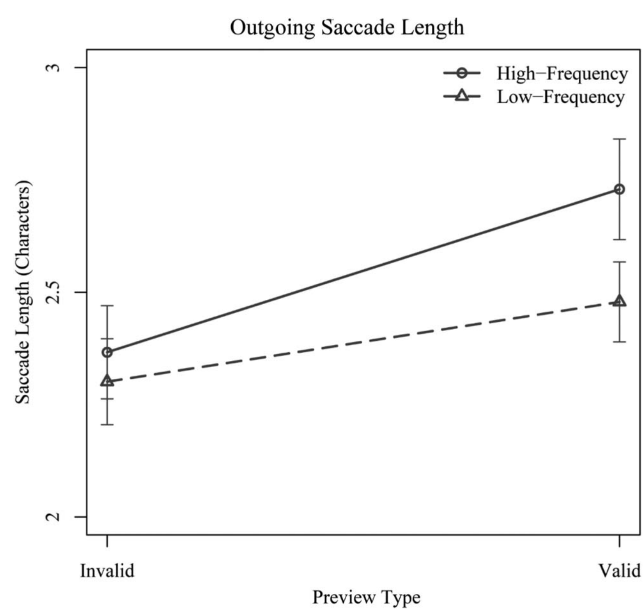

Figure 2. Outgoing-saccade length as a function of target-word frequency (low vs. high) and preview type (invalid vs. valid). The error bars indicate the standard errors of the means.

Table 3
Contrast Analysis Simple Effects for Outgoing-Saccade Length

Contrast	*b*	*SE*	*z*	*p*
high frequency: valid preview – low frequency: valid preview	0.22	0.04	5.34	<.001
high frequency: invalid preview – low frequency: invalid preview	0.06	0.03	1.80	.254
high frequency: valid preview – high frequency: invalid preview	0.33	0.06	5.86	<.001
low frequency: valid preview – low frequency: invalid preview	0.18	0.06	2.73	.029

–54.50, $SE = 8.37$, $t = –6.51$, $p < .001$), and with preview compared to without (first-fixation duration: $b = –30.63$, $SE = 5.31$, $t = –5.77$, $p < .001$; single-fixation duration: $b = –32.88$, $SE = 5.78$, $t = –5.69$, $p < .001$; gaze duration: $b = –57.18$, $SE = 11.98$, $t = –4.77$, $p < .001$). None of the interactions between word frequency and preview availability were significant for any of the aforementioned dependent measures (all $|ts| < 1.3$, all $ps \geq 0.2$).

Turning now to the two remaining dependent measures, for landing position, there were no significant effects of target-word frequency ($b = 0.01$, $SE = 0.02$, $t = 0.28$, $p = .784$) or preview type ($b = 0.02$, $SE = 0.02$, $t = 0.71$, $p = .484$), but there was a significant interaction between target-word frequency and preview type ($b = –0.11$, $SE = 0.04$, $t = –2.89$, $p = .005$), reflecting the fact that fixations tended to land closer to the beginning of the target words when they were high frequency and preview was available. For posttarget fixation duration, there was significant effect of preview type ($b = –29.52$, $SE = 5.98$, $t = –4.94$, $p < .001$), but no effect of target-word frequency ($b = –4.79$, $SE = 3.65$, $t = –1.31$, $p = .197$) or interaction between these two factors ($b = 7.51$, $SE = 7.58$, $t = 0.99$, $p = .327$).

Discussion

The present experiment examined whether the length of a saccade exiting a target word would be modulated by two variables that—based on prior studies and a priori hypotheses—might be expected to play important functional roles in saccade targeting during Chinese reading: (a) the frequency of the word from which the saccade was launched, and (b) the availability of information about parafoveal words. Our results indicated reliable effects of preview availability, with outgoing saccades being longer with valid than invalid preview. This effect also interacted with target-word frequency, however, being more pronounced from high- than low-frequency target words. Our results therefore indicate that, during the reading of Chinese, saccade targeting is influenced by parafoveal processing.

To understand exactly why this conclusion is warranted, consider the following. First, if saccade targeting is only affected by foveal processing, then we should have only observed an effect of target-word frequency on outgoing-saccade length, and not an effect of preview. Conversely, if saccade targeting is only affected by parafoveal processing, then we should have only observed an effect of preview availability on outgoing-saccade length, and not an effect of target-word frequency. Our results therefore indicate that how much information can be extracted from the parafovea influences saccade targeting but that the foveal load of the fixated word also influences the extraction of information from the parafovea, thereby exerting a secondary influence on saccade targeting. In the remainder of this article, we discuss the theoretical implications of these findings for our understanding of saccade targeting during the reading of Chinese but also during the reading of alphabetic writing systems.

We begin by again noting that, although parafoveal processing plays a universal role in eye-movement control, its utility for the purposes of saccade targeting also seems to differ across writing systems. For example, in most alphabetic writing systems, low-spatial-frequency visual information provides salient cues about the boundaries of upcoming words—cues that are used to guide a reader's eyes to the PVL. In contrast, such cues are not available in Chinese text because word boundaries are not clearly demarcated by blank spaces. However, because our results indicate that Chinese readers adjust their saccade amplitudes dynamically (as a function of parafoveal processing) rather than targeting specific locations (as might happen with alphabetic writing systems), our results suggest that Chinese readers adopt some alternative strategy for moving their eyes in a manner that supports the rapid extraction of visual information for the purposes of lexical processing. To understand what such a strategy might entail, it is useful to consider current models of eye-movement control during the reading of alphabetic writing systems (for a review, see Reichle, Rayner, & Pollatsek, 2003).

First consider the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Warren, & McConnell, 2009). According to this model, words are processed and identified one at a time, in a strictly serial manner. This lexical processing is completed in two successive stages: an early stage (called the *familiarity check*) that causes the oculomotor system to begin programming a saccade to the next word, followed by a later stage (called *lexical access*) in which the word's meaning becomes available and attention shifts to the next word. Importantly, the model assumes that saccades are always directed toward the center of the word being targeted. For example, the completion of the familiarity check on word n causes the oculomotor system to program a saccade to move the eyes toward the center of word $n + 1$. Because of systematic and random sources of saccadic error, however, the eyes will often deviate from their intended target, fixating near the outer edge of the targeted word or missing (i.e., skipping) the word completely. Importantly, because high-frequency words are processed more rapidly than low-frequency words in E-Z Reader, the model might be able to provide a partial explanation for our experimental results. For example, with all else being equal, the model would predict more overshooting of near targets following fixations on high-frequency target words because the fixations on those words will afford less time for saccadic programming (because the words are rapidly processed). Similarly, the model would predict longer outgoing saccades from high-frequency target words because fixations on those words afford more parafoveal processing, thereby increasing the likelihood of skipping the next word and producing a long saccade. What is less clear, however, is how E-Z Reader would explain the actual way in which saccade targeting is affected by the availability of parafoveal preview. This limitation of the model stems from its saccade-targeting assumption—that the default saccade target is the center of the word immediately to the right of the one being fixated.

Next consider the SWIFT model (Engbert, Nuthmann, Richter, & Kliegl, 2005). This model assumes that multiple words are processed and identified in parallel, resulting in a gradient of activation values reflecting the degree to which each word is being processed. Saccade targets are therefore selected probabilistically, with words having higher levels of lexical activation being more likely to be selected for fixation than words having lower levels of activation. Similar to E-Z Reader, SWIFT assumes that saccades are directed toward the centers of words. That being said, it is unclear how the model would handle any of the effects reported in this article because saccade targets will always (ignoring regressions) be directed toward the center of an upcoming word, with the precise (i.e., within-word) location being unaffected by either foveal load or the availability of parafoveal information. As was true of E-Z Reader, some additional assumptions are necessary to explain how foveal and parafoveal processing interact to determine where the eyes move.

An alternative approach might be to relax the strict theoretical assumption about how attention is allocated (i.e., serial vs. parallel). For example, recent simulations by Liu, Reichle, and Gao (2013) demonstrate how attention might be allocated dynamically, to exploit attention resources that become available at specific locations within a text (e.g., during the processing of sequences of easy-to-process words). Similarly, the current version of SWIFT also incorporates a "zoom lens" model of attention that can be narrowed or widened to exploit local properties of text (Schad & Engbert, 2012). Both of these conceptualizations of attention are closely related to the parafoveal-processing hypothesis in that they assume that whatever attentional resources are available for parafoveal lexical processing at any given time will depend upon the foveal load. However, it is also important to note that neither of these two conceptualizations explain how foveal and parafoveal processing jointly determine where the eyes move during reading. That being said, future simulations will be required to determine if the dynamic allocation of attention is sufficient to explain the results of our study.

Finally, because we see our results as adding to the "benchmark" findings that any viable model of eye-movement control in reading will have to explain, it is important to say something about the generality of our results. As indicated earlier, our results are novel, with the closest analog of our study being reported by White and Liversedge (2006). In that study, both foveal load (i.e., high- vs. low-frequency target words) and the relative difficulty of parafoveal processing (i.e., parafoveal words having orthographically regular vs. irregular beginnings) were manipulated, and both variables influenced outgoing-saccade length. In contrast to our study, however, the foveal and parafoveal variables did not interact, suggesting that saccade targeting may be different between alphabetic writing systems like English and the nonalphabetic Chinese writing system. For example, the spaces that separate words in most alphabetic writing systems may allow readers to more rapidly direct their eyes to the PVL in the next word, thereby weakening any interaction that foveal and parafoveal processing might otherwise have on saccade targeting.

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