The Role of Foveal Processing Load and Parafoveal Information in Saccade Target Selection in Chinese Reading: Postprint

Authors: Wang Yongsheng, Zhao Bingjie, Chen Mingjing, Li Xin, Yan Guoli, Xuejun Bai

Date: 2018-09-07T00:00:00+00:00

Abstract

The present study investigated whether the processing load of foveal words affects the amount of information acquired from the parafovea, thereby modulating subsequent saccade length during saccade target selection in Chinese readers. Using eye-tracking technology, we manipulated the word frequency (high-frequency, low-frequency) of foveal words and the stroke number (many strokes, few strokes) of parafoveal words. Results revealed that saccade length from foveal words to parafoveal words with few strokes was significantly longer than to those with many strokes, and this stroke number effect was not modulated by foveal processing load; saccade length from high-frequency foveal words to parafoveal words was significantly longer than from low-frequency foveal words. Under the present experimental conditions, these results suggest that the role of foveal processing load in saccade target selection is not achieved by modulating the amount of information acquired from the parafovea.

Full Text

Abstract

This study investigated whether the processing load of foveally fixated words influences the amount of information acquired from parafoveal words, thereby modulating subsequent saccade length during target selection in Chinese reading. Using eye-tracking technology, we manipulated the frequency of foveal words (high vs. low frequency) and the number of strokes in parafoveal words (many vs. few strokes). Results showed that saccades from foveal words to parafoveal words with few strokes were significantly longer than those to words with many strokes, and this stroke number effect was not modulated by foveal processing load. Additionally, saccades from high-frequency foveal words to parafoveal words were significantly longer than those from low-frequency words. These findings suggest that under the present experimental conditions, the role of foveal processing load in saccade target selection is not mediated by regulating the amount of information extracted from parafoveal processing.

Keywords: Chinese reading; saccade target selection; foveal processing; parafoveal processing

1. Introduction

During reading, the oculomotor control system must make real-time decisions about when to initiate a saccade and where to move the eyes—what Rayner (2009) termed the "when" and "where" problems. The "where" problem concerns saccade target selection. Research has demonstrated that readers' saccades are not random. In alphabetic scripts such as English, first fixations on words typically land between the beginning and center of the word, a position known as the preferred viewing location (PVL) (McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1979). This location approximates the optimal viewing position (OVP) for single-word recognition (O' Regan, 1992; O' Regan & Jacobs, 1992; Vitu, O' Regan, & Mittau, 1990). Information about inter-word spaces acquired during parafoveal processing guides readers' saccade target selection (Juhasz, Inhoff, & Rayner, 2005; Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982). Current influential models of eye movement control, such as the E-Z Reader model and SWIFT model, both posit the word center as the default saccade target. Readers program saccades toward the word center, though saccadic error causes fixations to land between the word beginning and center—the PVL (Liversedge, Gilchrist, & Everling, 2011; Reichle, Rayner, & Pollatsek, 2012; Schad & Engbert, 2012).

Chinese is a logographic script where the basic writing unit is the character, with each character occupying equal space. Although definitions of "words" vary among Chinese readers, both between and within individuals (Hoosain, 1992; Liu & Li, 2014; Peng & Chen, 2004), and despite the absence of explicit word boundary cues like spaces in alphabetic scripts, words play a crucial role in Chinese reading. Researchers have argued that the word serves as the fundamental processing unit in Chinese reading (Bai, Yan, Liversedge, Zang, & Rayner, 2008; Li, Bicknell, Liu, Wei, & Rayner, 2014; Yan, Tian, Bai, & Rayner, 2006).

How Chinese readers select saccade targets remains unclear. Yan, Kliegl, Richter, Nuthmann, and Shu (2010) found that when a word received only a single fixation, the fixation tended to land near the word center, similar to the PVL in alphabetic reading. When multiple fixations occurred on a word, the first fixation was more likely to land at the word beginning. The authors proposed that saccade target selection in Chinese reading depends on parafoveal word segmentation: if word segmentation is completed parafoveally, fixations land at the next word' s center; if not, they land at the next word' s beginning. However, this proposed relationship between fixation location distribution and parafoveal word segmentation has been questioned. Li, Liu, and Rayner (2011) simulated word-first-fixation location distributions using a "constant step size" strategy and obtained similar patterns. They argued that such fixation distributions might be artifacts of data analysis methods rather than reflecting readers' saccade strategies (Li et al., 2011; Ma, Li, & Pollatsek, 2015). Ma et al. (2015) examined fixation location distributions for three-character words and non-words, finding patterns similar to Yan et al. (2010) even when characters were randomly arranged. They explained that in multiple-fixation cases, first fixations appear biased toward word beginnings because the analysis only includes saccades from pre-target to target regions, excluding forward refixations within the target region. This methodological artifact inflates fixation counts near the target region' s start. In single-fixation cases, the center bias emerges because the average saccade length in Chinese reading is approximately two characters. For a three-character target region, a first fixation on the second character is more likely to be followed by a saccade exiting the region than one landing on it, whereas a first fixation on the first character is more likely to be followed by another fixation within the region. Consequently, single fixations tend to land near the target region' s center (Ma et al., 2015).

Some researchers argue that Chinese readers do not adopt the word center as a default saccade target, unlike readers of alphabetic scripts with explicit word segmentation cues, but rather engage in a dynamic adjustment process (Liu, Huang, Gao, & Reichle, 2017; Liu, Reichle, & Li, 2016). This hypothesis posits that information acquired during parafoveal processing determines subsequent saccade length: more parafoveal information yields longer saccades. Foveal processing load modulates parafoveal processing—lower foveal load enables more parafoveal information acquisition, resulting in longer subsequent saccades. Studies on parafoveal processing effects on saccade target selection support this hypothesis. For instance, Zang, Liang, Bai, Yan, and Liversedge (2013) investigated the effect of inter-word spaces on fixation positions in Chinese reading, finding that average first fixation positions were closer to word centers with spaces than without spaces, suggesting that spaces aid saccade targeting. Li et al. (2014) found that saccades into word n+1 were longer when it was high-frequency compared to low-frequency. Similarly, saccades into word n+1 were longer when the parafoveal word was highly predictable (Liu, Guo, Yu, & Reichle, 2017).

Whether foveal processing load influences saccade target selection by modulating parafoveal information acquisition remains controversial. Although previous studies show that foveal processing load affects subsequent saccade length—lower foveal load yields longer saccades (Liu, Reichle, & Li, 2015; Liu et al., 2017; Wei, Li, & Pollatsek, 2013; Wang, 2016)—researchers have proposed that this effect is mediated by parafoveal information acquisition. Liu et al. (2015) manipulated foveal word frequency (high vs. low) and parafoveal preview availability (visible vs. invisible) to examine their effects on saccade target selection. Their logic was as follows: If Chinese readers' saccade target selection is primarily influenced by foveal word characteristics, a main effect of foveal word frequency should occur regardless of parafoveal preview availability. If selection is primarily influenced by parafoveal processing, a frequency effect should only emerge when parafoveal preview is visible. If both foveal and parafoveal processing jointly regulate saccade target selection, the frequency effect should be significantly larger when parafoveal preview is visible than when invisible. Results showed that foveal word frequency only affected subsequent saccade length when parafoveal preview was visible, suggesting that Chinese readers' saccade target selection is primarily influenced by parafoveal processing. Foveal processing load affects subsequent saccade length by modulating parafoveal processing: lower foveal load yields more parafoveal information and longer subsequent saccades.

However, some studies have found that foveal processing load does not modulate parafoveal processing in Chinese reading. Yan (2015) manipulated pre-target word stroke number (many vs. few strokes) while using the boundary paradigm to manipulate target word preview type (identical, unrelated word, or non-word preview). Unlike findings in alphabetic scripts, Yan found larger preview effects when the pre-target word had high processing load (many strokes), attributing this to longer fixation durations providing more parafoveal preview time. Zhang (2015) and Wang (2016) manipulated foveal word frequency and parafoveal preview type (identical vs. pseudo-character preview), finding no modulation of foveal word frequency on parafoveal processing. Foveal processing load did not affect parafoveal preview effect magnitude.

Furthermore, in Liu et al.' s (2015) study, when participants' fixation did not cross the boundary, the sentence portion beyond the boundary was masked with "※" symbols. Because "※" differs markedly from Chinese characters and lacks a clear saccade target, this may have disrupted normal reading. Yan, Zhang, Zhang, and Bai (2013) examined the effect of using "※" versus characters as masking materials on Chinese perceptual span, finding smaller perceptual span but larger saccade amplitude with "※" masking, suggesting it interferes with normal saccade target selection. Yan (2015) and Zhang (2015) and Wang (2016) did not mask beyond-boundary text. Therefore, further investigation is needed to determine whether foveal processing load influences saccade target selection by modulating parafoveal information acquisition.

The present study manipulated foveal processing load via foveal word frequency (Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner & Raney, 1996). Research shows that fewer strokes in the first character of a two-character word leads to first fixations closer to the word center (Ma & Li, 2015; Meng, Bai, Yan, & Yao, 2014). Ma and Li (2015) proposed that stroke number information is acquired parafoveally: words with fewer strokes are processed more thoroughly in parafoveal vision, yielding longer saccades into the word and landing positions farther from the word beginning. Therefore, we simultaneously manipulated parafoveal word stroke number to investigate whether foveal processing load affects saccade target selection by modulating parafoveal information acquisition.

If foveal processing load influences saccade target selection by regulating parafoveal information acquisition, we should observe a significant interaction between foveal word frequency and parafoveal stroke number on saccade length from foveal to parafoveal words. Specifically, the stroke number effect should be larger under low foveal processing load (high-frequency words) than under high load (low-frequency words). If foveal processing load does not modulate parafoveal processing, parafoveal information acquisition should not differ across foveal load conditions, and the effect of parafoveal stroke number should not vary significantly.

2. Method

2.1 Participants

Forty undergraduate students from Tianjin Normal University participated (mean age = 20.78 years, $SD = 1.21$; 35 females, 5 males). All had normal or corrected-to-normal vision, were native Chinese speakers, right-handed, and unaware of the experimental purpose.

2.2 Design

We employed a 2 (foveal word frequency: high vs. low) × 2 (parafoveal stroke number: many vs. few) within-subjects factorial design.

2.3 Materials

We selected 76 two-character words as foveal fixation words, comprising 76 low-frequency words ($M = 7.64$ per million, $SD = 7.18$) and 76 high-frequency words ($M = 405.08$ per million, $SD = 458.04$). The frequency difference was significant ($t = 7.56$, $p < 0.001$). High- and low-frequency words did not differ significantly in total strokes, first-character strokes, or second-character strokes ($ts < 1.03$, $ps > 0.05$). However, high-frequency words had significantly higher first-character frequency ($t = 3.48$, $p = 0.001$) and second-character frequency ($t = 4.35$, $p < 0.001$) than low-frequency words.

We selected another 76 two-character words as parafoveal words. Following previous research (Ma & Li, 2015), words with 8 strokes were classified as low-stroke, and those with 12 strokes as high-stroke. Parafoveal words differed significantly in total strokes, first-character strokes, and second-character strokes ($ts > 28.20$, $ps < 0.001$), but did not differ in word frequency, first-character frequency, or second-character frequency ($ts < 1.47$, $ps > 0.05$). See Table 1 for details.

Foveal and parafoveal word pairs were combined within similar sentence frames (15–20 characters). The text preceding the foveal word was identical across conditions.

Table 1 shows the material characteristics. Note: Values in parentheses are standard deviations.

We conducted norming studies. First, 40 university students rated sentence naturalness on a 7-point scale (1 = very unnatural, 7 = very natural). Mean naturalness was 6.4 (SD = 0.38), with no significant differences across conditions ($Fs < 0.43$, $ps > 0.05$), meeting experimental requirements. Next, 28 students completed a predictability task, providing the foveal word given the preceding sentence context. Predictability did not differ between high-frequency (M = 0.32, SD = 1.61) and low-frequency (M = 0.31, SD = 1.99) conditions ($t = -0.001$, $p = 1.00$). Table 2 provides example materials. Note: Italics indicate foveal words; bold indicates parafoveal words (both presented normally during the experiment).

2.4 Apparatus

We used an Eyelink 1000 eye tracker (sampling rate = 1000 Hz) with a display change delay of 6–12 ms. The monitor refreshed at 120 Hz with 1024×768 pixel resolution. Viewing distance was 70 cm. Stimuli were presented in 28-point Song font, with each character subtending approximately 1.18° of visual angle (37×37 pixels).

2.5 Procedure

Participants were tested individually. After a brief laboratory introduction, participants read instructions, which the experimenter then summarized to ensure comprehension. A three-point calibration was performed (average error $< 0.2°$ indicated successful calibration). Participants then read experimental sentences, beginning with 8 practice trials. The experiment comprised 4 material sets, each containing 76 experimental sentences (19 per condition). Sentences were randomized within each set, with each participant completing one set. In addition to 76 experimental sentences, there were 8 practice and 20 filler sentences. Thirty sentences were followed by yes/no comprehension questions (mean accuracy = 93.2%, indicating attentive performance). The experiment lasted 20–30 minutes, with recalibration as needed.

2.6 Data Analysis

Following previous research (Rayner, 1998, 2009), fixations shorter than 80 ms or longer than 800 ms were excluded. Data were also excluded if: (1) fewer than 4 fixations occurred on a sentence; (2) track loss occurred due to blinking or head movement; or (3) values exceeded 3 SD from the mean. Excluded data comprised 2.64% of total data.

Analyses of saccade target selection included launch position, saccade length from foveal to parafoveal words, fixation position on parafoveal words, and skipping rate. Fixation time analyses included first fixation duration, gaze duration, single fixation duration, and total fixation duration. All saccade target selection analyses used character-based units (Yan et al., 2013).

We analyzed data using linear mixed models (LMM) in R (R Development Core Team, 2014) with the lme4 package (Bates, Maechler, & Bolker, 2012), specifying participants and items as crossed random effects. Significance estimates were derived from Markov-Chain Monte Carlo posterior distributions, simultaneously accounting for participant and item variability (Baayen, Davidson, & Bates, 2008). Dependent variables were log-transformed, and skipping rates were analyzed using logistic LMM. Fixed effects included foveal word frequency, parafoveal stroke number, and their interaction. Because high-frequency words had significantly higher first- and second-character frequencies, we included first- and second-character frequencies as covariates in saccade target selection analyses. When interactions were significant, we conducted simple effects analyses comparing parafoveal low- versus high-stroke words under high-frequency foveal conditions.

3. Results

3.1 Saccade Target Selection Analysis

Descriptive and analytic results for saccade target selection appear in Table 3 and Table 4 , respectively.

Table 3 shows means and standard deviations (in parentheses) for parafoveal word measures (units = characters).

Table 4 presents fixed-effect estimates. Note: ***p < 0.001,*** *p < 0.01,* p < 0.05, §p < 0.1.

For launch position from foveal to parafoveal words, neither main effects nor the interaction were significant (ts < 0.88, ps > 0.05).

For saccade length from foveal to parafoveal words, the main effect of foveal word frequency was significant (b = −0.037, SE = 0.013, t = −2.80, p = 0.006), with longer saccades from high- than low-frequency words. The main effect of parafoveal stroke number was also significant (b = 0.029, SE = 0.013, t = 2.10, p = 0.042), with longer saccades to low-stroke than high-stroke words. The interaction was not significant (b = 0.026, SE = 0.028, t = 0.94, p > 0.05).

For forward saccade length from foveal words, foveal word frequency showed a significant main effect (b = −0.034, SE = 0.014, t = −2.49, p = 0.015), with longer forward saccades from high-frequency words. Parafoveal stroke number also showed a significant main effect (b = 0.055, SE = 0.016, t = 3.35, p = 0.002), with longer forward saccades when the parafoveal word had few strokes. The interaction was not significant (b = −0.023, SE = 0.031, t = 0.76, p > 0.05).

For fixation position measures, foveal word frequency showed a marginally significant effect only on first fixation position in multiple-fixation cases (b = −0.078,

$SE = 0.046$, $t = -1.70$, $p = 0.09$), with no effects on average first fixation position or single-fixation position. Parafoveal stroke number showed marginally significant effects on average first fixation position ($b = 0.046$, $SE = 0.025$, $t = 1.82$, $p = 0.074$) and single-fixation position ($b = 0.051$, $SE = 0.026$, $t = 1.96$, $p = 0.055$), but not on first fixation position in multiple-fixation cases ($ts < 1.7$, $ps > 0.05$). No interactions were significant for any fixation position measures ($ts < 1.16$, $ps > 0.05$).

We conducted Bayesian analyses to verify the reliability of null interactions. Comparing full models (with main effects and interaction) to main-effects-only models, results favored no interaction for saccade length from foveal to parafoveal words (9.63:1) and forward saccade length (4.65:1).

When first- and second-character frequencies were included as covariates, the interaction between first-character frequency and word frequency was significant for saccade length from foveal to parafoveal words ($b = -0.030$, $SE = 0.011$, $t = -2.79$, $p = 0.006$). Simple effects analysis revealed that for low-frequency foveal words, higher character frequency yielded longer saccades ($b = 0.098$, $SE = 0.037$, $t = 2.66$, $p = 0.008$). Second-character frequency showed a significant main effect ($b = 0.018$, $SE = 0.006$, $t = 3.16$, $p = 0.002$) and a marginally significant interaction with parafoveal stroke number ($b = -0.017$, $SE = 0.009$, $t = -1.88$, $p = 0.06$). Simple effects showed that the stroke number effect was smaller when the foveal word' s second character was high-frequency (1.97 vs. 2.00; $b = 0.057$, $SE = 0.029$, $t = 1.94$, $p = 0.052$) than when it was low-frequency (1.86 vs. 1.91; $b = 0.053$, $SE = 0.027$, $t = 1.96$, $p = 0.05$). Similar patterns emerged for forward saccade length.

To rule out character frequency confounds, we selected 52 item sets with significant word frequency differences ($t = 10.38$, $p < 0.001$) but no differences in first- or second-character strokes or frequencies ($ts < 1.90$, $p > 0.05$), while parafoveal stroke number differed significantly ($ts > 21.55$, $p < 0.001$). Results showed a marginally significant word frequency effect on saccade length from foveal to parafoveal words ($b = 0.031$, $SE = 0.017$, $t = 1.81$, $p = 0.075$), with longer saccades from high-frequency words, and no significant interaction ($b = 0.025$, $SE = 0.033$, $t = 0.77$, $p = 0.44$).

Thus, while foveal word frequency and parafoveal stroke number both affected saccade target selection, we found no interaction between them, suggesting that foveal processing load does not influence saccade target selection by modulating parafoveal processing.

3.2 Fixation Time Analysis

We analyzed fixation times on foveal and parafoveal words (see Table 5 and Table 6).

Table 5 shows means and standard deviations for fixation measures.

Table 6 presents fixed-effect estimates.

For foveal words, word frequency showed significant main effects: high-frequency words had shorter fixation times than low-frequency words (first fixation: $b = 0.053$, $SE = 0.013$, $t = 4.04$, $p < 0.001$; gaze: $b = 0.095$, $SE = 0.019$, $t = 4.98$, $p < 0.001$; single fixation: $b = 0.052$, $SE = 0.013$, $t = 3.93$, $p < 0.001$; total time: $b = 0.139$, $SE = 0.023$, $t = 6.05$, $p < 0.001$). Parafoveal stroke number showed a significant effect on foveal first fixation duration ($b = 0.024$, $SE = 0.012$, $t = 2.04$, $p = 0.04$), with shorter times when the parafoveal word had many strokes, and a marginally significant effect on single fixation duration ($b = 0.025$, $SE = 0.014$, $t = 1.83$, $p = 0.07$). No effects were found for gaze or total time ($ts < 1.75$, $ps > 0.05$). No interactions were significant ($ts < 1.14$, $ps > 0.05$), nor were main effects on skipping rates ($ts < 0.51$, $ps > 0.05$).

For parafoveal words, stroke number showed a marginally significant effect on first fixation duration ($b = -0.027$, $SE = 0.016$, $t = -1.71$, $p = 0.095$) and significant effects on gaze duration ($b = -0.047$, $SE = 0.017$, $t = -2.62$, $p = 0.011$), single fixation duration ($b = -0.039$, $SE = 0.016$, $t = -2.39$, $p = 0.022$), and total time ($b = -0.077$, $SE = 0.028$, $t = -2.65$, $p = 0.009$), with longer fixations on high-stroke words. Foveal word frequency significantly affected parafoveal total time ($b = 0.066$, $SE = 0.024$, $t = 2.75$, $p = 0.008$), with longer times following low-frequency foveal words. No interactions were significant ($ts < 0.77$, $ps > 0.05$). For skipping rates, parafoveal stroke number showed a significant effect ($b = 0.610$, $SE = 0.181$, $t = 3.36$, $p < 0.001$), with higher skipping rates for low-stroke words, while foveal frequency and the interaction were not significant ($ts < 0.51$, $ps > 0.05$).

The significant word frequency and stroke number effects confirm our experimental manipulations were effective. We observed a parafoveal-on-foveal effect: fewer parafoveal strokes were associated with longer foveal fixation times (first fixation and total time). We also found a foveal frequency effect on parafoveal total time: higher foveal frequency yielded shorter parafoveal total fixation times.

4. Discussion

By simultaneously manipulating foveal word frequency and parafoveal stroke number, we examined whether foveal processing load influences saccade target selection by modulating parafoveal processing. We found significant effects of word frequency and stroke number on fixation times. Consistent with previous research (Li et al., 2014; Liu et al., 2015; Wei et al., 2013; Yan et al., 2006; Ma & Li, 2015), forward saccade length from foveal words was longer for high-frequency words and for parafoveal words with fewer strokes. Crucially, however, no significant interaction emerged between these factors.

The dynamic adjustment hypothesis of saccade target selection in Chinese reading proposes that the amount of parafoveal information acquired modulates subsequent saccade length—more parafoveal information yields longer saccades —rather than targeting specific word locations (Liu et al., 2015; Liu et al., 2016; Liu et al., 2017). Our results showing longer saccades to parafoveal words with fewer strokes align with this hypothesis (Ma & Li, 2015; Meng et al., 2014).

However, the hypothesis also posits that foveal processing load influences saccade target selection by modulating parafoveal information acquisition: lower foveal load yields more parafoveal information and longer saccades. This prediction was not supported—we found no significant interaction between foveal word frequency and parafoveal stroke number, and Bayesian analyses confirmed the reliability of this null effect. Two possible explanations exist.

First, although foveal load modulates parafoveal processing in alphabetic reading (e.g., English; Henderson & Ferreira, 1990), Chinese reading studies suggest parallel foveal and parafoveal processing (Yan, Richter, Shu, & Kliegl, 2009; Yan, Kliegl, Shu, Pan, & Zhou, 2010; Cui, Wang, Yan, & Bai, 2010), with foveal load not modulating parafoveal processing (Yan, 2015; Wang, 2016; Zhang, 2015). Although higher foveal load reduces attentional resources allocated to parafoveal processing, it simultaneously increases fixation duration, providing longer parafoveal preview time. These opposing mechanisms may cancel out, resulting in equivalent parafoveal information acquisition across foveal load conditions. Consequently, saccade programming using parafoveal information may be unaffected by foveal load. To test this, we included foveal gaze duration (parafoveal preview time) as a covariate. While preview time affected saccade length ($b = -0.076$, $SE = 0.014$, $t = 5.42$, $p < 0.001$), with longer preview yielding longer saccades, the preview time × parafoveal stroke number interaction was not significant ($b = -0.014$, $SE = 0.027$, $t = 0.52$, $p = 0.61$). This suggests foveal load does not influence saccade target selection by modulating preview time. We propose that both foveal and parafoveal processing influence saccade programming, but their effects are additive rather than interactive.

Second, although both foveal and parafoveal processing significantly affect saccade target selection, their mechanisms may differ: foveal processing may modulate saccade length, while parafoveal processing may directly determine landing position (Li, Huang, Hua, & Li, 2017). A processing-based saccade target selection strategy suggests readers estimate how many characters can be processed in one fixation and target the next position yielding new information (Wei et al., 2013). Although lower foveal load allocates more attentional resources, these may be distributed across more characters. Future research should examine whether perceptual span to the right differs across foveal load conditions and how parafoveal information characteristics (e.g., word segmentation, word length) affect saccade target selection under varying foveal loads to clarify potential mechanistic differences.

Additionally, when including foveal character frequencies as covariates, we found that character frequency also affected saccade length: for low-frequency foveal words, higher first-character frequency yielded longer saccades. Previous research shows that lower first-character frequency in low-frequency words increases fixation time (Yan et al., 2006), suggesting character frequency information may influence processing load and modulate subsequent saccade length. This may explain why Liu (2013) found no word frequency effect on saccade length when manipulating word frequency and contrast while controlling character frequency. Liu et al. (2015), Wei et al. (2013), and Wang (2016) reported word frequency effects on saccade length but did not report character frequency differences, whereas Liu (2013) controlled character frequency and found no word frequency effect. Our study did not strictly manipulate character frequency, so future research should simultaneously manipulate word and character frequencies to examine their respective contributions to saccade target selection.

Furthermore, when including foveal second-character frequency as a covariate, we found a significant interaction between second-character frequency and parafoveal stroke number on saccade length: lower second-character frequency produced a larger stroke number effect. This suggests both word- and character-level foveal information affect saccade target selection, with different relationships to parafoveal processing. This may explain the absence of a word-level frequency × stroke number interaction, highlighting the need for future research to simultaneously manipulate foveal word frequency, character frequency, and parafoveal processing to examine whether foveal-parafoveal relationships differ across processing levels.

5. Conclusion

Both foveal processing load and parafoveal word stroke number affect subsequent saccade target selection: higher foveal word frequency (lower load) yields longer saccades, and fewer parafoveal strokes yield longer saccades with landing positions closer to word centers. However, foveal processing load does not influence saccade target selection by modulating parafoveal information acquisition. Future theoretical models of Chinese reading must fully consider the role of foveal processing load in saccade target selection.

Key findings: In Chinese reading, foveal word frequency modulates subsequent saccade length; parafoveal word stroke number modulates subsequent saccade length; and foveal processing load influences saccade target selection independently of parafoveal information acquisition.

References

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*(4), 390–412.

Bai, X. J., Yan, G. L., Liversedge, S. P., Zang, C. L., & Rayner, K. (2008). Reading spaced and unspaced Chinese text: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 34*(5), 1277–1287.

Cui, L., Wang, S. P., Yan, G. L., & Bai, X. J. (2010). Parafoveal-on-foveal interactions in normal Chinese reading. *Acta Psychologica Sinica, 42*(5), 547–558.

Bates, D., Mäechler, M., & Bolker, B. (2012). lme4: Linear mixed-effects models using S4 classes. R package version 0.999375-42.

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*(3), 417−429.

Hoosain, R. (1992). Psychological reality of the word in Chinese. In H. C. Chen & O. J. L. Tzeng (Eds.), *Language processing in Chinese* (pp. 111−130). Elsevier.

Juhasz, B. J., Inhoff, A. W., & Rayner, K. (2005). The role of interword spaces in the processing of English compound words. *Language and Cognitive Processes, 20*(1-2), 291−316.

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology, 16*(1-2), 262-284.

Li, X. S., Bicknell, K., Liu, P. 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*(2), 895−913.

Li, X. S., Liu, P. P., & Rayner, K. (2011). Eye movement guidance in Chinese reading: Is there a preferred viewing location? *Vision Research, 51*(10), 1146−1156.

Li, Y. G., Huang, R., Hua, H. M., & Li, X. S. (2017). How do readers select the saccade targets? *Advances in Psychological Science, 25*(3), 404−412.

Liu, P. P. (2013). *Eye movement control during Chinese reading: How to select the saccade target* (Unpublished doctoral dissertation). University of Chinese Academy of Science.

Liu, Y. P., Guo, S. Y., Yu, L., & Reichle, E. D. (2017). Word predictability affects saccade length in Chinese reading: An evaluation of the dynamic-adjustment model. *Psychonomic Bulletin & Review, 1−9.*

Liu, Y. P., Huang, R., Gao, D. G., & Reichle, E. D. (2017). Further tests of a dynamic-adjustment account of saccade targeting during the reading of Chinese. *Cognitive Science, 41*(S6), 1264−1287.

Liu, P. P., & Li, X. S. (2014). Inserting spaces before and after words affects word processing differently in Chinese: Evidence from eye movements. *British Journal of Psychology, 105*(1), 57−68.

Liu, Y. P., Reichle, E. D., & Li, X. S. (2015). Parafoveal processing affects outgoing saccade length during the reading of Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(4), 1229−1236.

Liu, Y. P., Reichle, E. D., & Li, X. S. (2016). The effect of word frequency and parafoveal preview on saccade length during the reading of Chinese. *Journal of Experimental Psychology: Human Perception and Performance, 42*(7), 1008–1025.

Liversedge, S. P., Gilchrist, I. D., & Everling, S. (Eds.). (2011). *The Oxford handbook of eye movements.* Oxford University Press.

Ma, G. J., & Li, X. S. (2015). How character complexity modulates eye movement control in Chinese reading. *Reading and Writing, 28*(6), 747–761.

Ma, G. J., Li, X. S., & Pollatsek, A. (2015). There is no relationship between preferred viewing location and word segmentation in Chinese reading. *Visual Cognition, 23*(3), 399–414.

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research, 28*(10), 1107–1118.

Meng, H. X., Bai, X. J., Yan, G. L., & Yao, H. J. (2014). The number of strokes influences initial landing positions during Chinese reading. *Journal of Psychological Science, 37*(4), 809–815.

Morris, R. K., Rayner, K., & Pollatsek, A. (1990). Eye movement guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance, 16*(2), 268–281.

O’ Regan, J. K. (1992). Optimal viewing position in words and the strategy-tactics theory of eye movements in reading. In K. Rayner (Ed.), *Eye movements and visual cognition* (pp. 333–354). Springer.

O’Regan, J. K., & Jacobs, A. M. (1992). Optimal viewing position effect in word recognition: A challenge to current theory. *Journal of Experimental Psychology: Human Perception and Performance, 18*(1), 185–197.

Perea, M., & Acha, J. (2009). Space information is important for reading. *Vision Research, 49*(15), 1994–2000.

Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 8*(6), 817–833.

R Development Core Team (2014). *R: A language and environment for statistical computing.* Vienna, Austria: The R Foundation for Statistical Computing. URL: http://www.R-project.org/

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception, 8*(1), 21–30.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*(3), 372-422.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *The Quarterly Journal of Experimental Psychology, 62*(8), 1457—1506.

Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E. D. (2004). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z Reader model. *Journal of Experimental Psychology: Human Perception and Performance, 30*(4), 720-732.

Rayner, K., & Raney, G. E. (1996). Eye movement control in reading and visual search: Effects of word frequency. *Psychonomic Bulletin & Review, 3*(2), 245-248.

Reichle, E. D., Rayner, K., & Pollatsek, A. (2012). Eye movements in reading versus nonreading tasks: Using E-Z Reader to understand the role of word/stimulus familiarity. *Visual Cognition, 20*(4-5), 360—390.

Peng, R. Y., & Chen, J. Y. (2004). Even words are right, odd ones are odd: Explaining word segmentation inconsistency among Chinese readers. *Chinese Journal of Psychology, 46*(1), 49—55.

Schad, D. J., & Engbert, R. (2012). The zoom lens of attention: Simulating shuffled versus normal text reading using the SWIFT model. *Visual Cognition, 20*(4-5), 391—421.

Vitu, F., O'Regan, J. K., & Mittau, M. (1990). Optimal landing position in reading isolated words and continuous text. *Attention, Perception, & Psychophysics, 47*(6), 583—600.

Wang, Y. S. (2016). *The parafoveal processing influence on selection of target during Chinese reading* (Unpublished doctoral dissertation). Tianjin Normal University.

Wei, W., Li, X. S., & Pollatsek, A. (2013). Word properties of a fixated region affect outgoing saccade length in Chinese reading. *Vision Research, 80*, 1—6.

Yan, G. L., Xiong, J. P., Zang, C. L., Xu, L. L., Cui, L., & Bai, X. J. (2013). Review of eye-movement measures in reading research. *Advances in Psychological Science, 21*(4), 589—605.

Yan, G. L., Tian, H. G., Bai, X. J., & Rayner, K. (2006). The effect of word and character frequency on the eye movements of Chinese readers. *British Journal of Psychology, 97*(2), 259—268.

Yan, G. L., Zhang, Q. M., Zhang, L. L., & Bai, X. J. (2013). The effect of masking materials on perceptual span in Chinese reading. *Journal of Psychological Science, 36*(6), 1317—1322.

Yan, M. (2015). Visually complex foveal words increase the amount of parafoveal information acquired. *Vision Research, 111*, 91—96.

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*(4), 705–725.

Yan, M., Kliegl, R., Shu, H., Pan, J., & Zhou, X. L. (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*(6), 1669–1676.

Yan, M., Richter, E. M., Shu, H., & Kliegl, R. (2009). Readers of Chinese extract semantic information from parafoveal words. *Psychonomic Bulletin & Review, 16*(3), 561–566.

Zang, C. L., Liang, F. F., Bai, X. J., Yan, G. L., & 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*(3), 720–734.

Zhang, M. M. (2015). *The mechanism of word skipping in Chinese reading: An eye movement study* (Unpublished doctoral dissertation). Tianjin Normal University.

Note: Figure translations are in progress. See original paper for figures.