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Early parafoveal processing in reading Chinese sentences

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1. Introduction

Reading, the process of extracting meaning from written text, relies on the active sampling of visual information during eye fixations. The range within which useful information can be extracted during a fixation, commonly referred to as the perceptual span, is quite limited and asymmetric corresponding to the reading direction (see Rayner, 1998, for a review). For example, in English, the span for letter discrimination extends about eight letter spaces to the right and four letter spaces to the left of the fixation point (Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985). The perceptual span reflects the constraints of both visual acuity and processing resources (Rayner, 1986). In addition, successive perceptual spans overlap during reading, suggesting that readers usually fixate an area that has already been partially processed during the previous fixation. Information extracted parafoveally facilitates processing on the subsequent fixation, which is referred to as the parafoveal preview benefit (Rayner, 1998). At the same time, parafoveal information is used to guide eye movements. As words are segmented by inter-word spaces in most alphabetic scripts, the locations and lengths of the upcoming words can be obtained

ABSTRACT

The possibility that during Chinese reading information is extracted at the beginning of the current fixation was examined in this study. Twenty-four participants read for comprehension while their eye movements were being recorded. A pretarget-target two-character word pair was embedded in each sentence and target word visibility was manipulated in two time intervals (initial 140 ms or after 140 ms) during pretarget viewing. Substantial beginning- and end-of-fixation preview effects were observed together with beginning-of-fixation effects on the pretarget. Apparently parafoveal information at least at the character level can be extracted relatively early during ongoing fixations. Results are highly relevant for ongoing debates on spatially distributed linguistic processing and address fundamental questions about how the human mind solves the task of reading within the constraints of different writing systems.

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parafoveally and used for saccade targeting (see Vitu, 2003; Yang & McConkie, 2004, for different views). Previous studies further showed that information (e.g., word length, word frequency, and contextual predictability) obtained from the perceptual span influences *when* to move the eyes and *where* to direct the gaze (see Calvo & Meseguer, 2002; Kliegl, Grabner, Rolfs, & Engbert, 2004, for recent discussions).

A number of computational models have been proposed to elucidate the underlying mechanism, namely the coordination among visual, linguistic, and oculomotor systems, of eye movement control in reading (Engbert, Nuthmann, Richter, & Kliegl, 2005; Pollatsek, Reichle, & Rayner, 2006b; Reilly & Radach, 2006; see Reichle, Rayner, & Pollatsek, 2003, for comparisons among models). These models differ in their assumptions about (a) whether linguistic processing is the driving force that triggers eye movements and (b) whether words within the perceptual span are processed in a serial word-by-word fashion or in parallel as a function of a distributed processing gradient. The E-Z Reader model, which is the representative of sequential attention shift (SAS) models, proposes that an attentional beam shifts to the next word after the attended word (which corresponds to the fixated word most of the time) has been fully identified. Subsequently, linguistic processing of the next word starts. Therefore, parafoveal processing is usually confined to the end of the current fixation. In contrast, processing



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gradient (PG) models, such as the Glenmore and SWIFT models, propose that temporal overlap in the processing of words within the perceptual span is possible and frequently occurs in normal reading. In these latter models, the processing gradient is a function of eccentricity of words within the span and its profile changes dynamically with lexical activity of each word. One specific prediction associated with the idea of concurrent word processing is that properties of the parafoveal word may have an influence on the duration of the current fixation (i.e., the parafoveal-on-foveal effect).

The boundary paradigm (Rayner, 1975) is typically adopted in studies examining the nature of parafoveal processing. An invisible boundary is set prior to the target stimulus (a word or a character) embedded in a sentence. At the beginning of each trial, the target stimulus is replaced by a preview stimulus. After the participants move their eyes across the boundary, the preview stimulus immediately changes into the target stimulus. A significant reduction in target viewing durations (preview benefit) in comparison to an uninformative preview condition is assumed to indicate successful parafoveal processing.

There are many experimental demonstrations of parafoveal preview effect with regard to word n + 1 (i.e., the word to the right of the fixated word *n*; see Rayner, 1998, for a review), which can be accounted for within both SAS and PG models. Controversial is the case of preview benefit from a more distant word n + 2, which would be in line with the limited parallel processing idea of PG models. So far limited evidence for n + 2 preview was observed only when word n + 1 was a short high frequency word (Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Kliegl, Risse, & Laubrock, 2007; Radach & Glover, 2007; Rayner, Juhasz, & Brown, 2007). In addition, although previewing an orthographically illegal stimulus (e.g., a random letter string) in the parafovea increases the current fixation duration (e.g., Starr & Inhoff, 2004), it is still controversial whether such parafoveal-on-foveal effects also exist on the lexical level (Kennedy & Pynte, 2005; Kliegl et al., 2007; Rayner & Juhasz, 2004)

Taken together, the question of whether words within the perceptual span are processed in parallel is still a hotly debated issue. Nevertheless, so far these existing computational models focus on reading in alphabetic scripts and it is not clear whether and how they can be extended to alternative writing systems (see Rayner, Li, & Pollatsek, 2007, for a first attempt in this direction). Cross-language studies help to address the broader question of how the human processing system solves similar problems in the context of radically different orthographies.

Chinese has some characteristics that make it a unique experimental platform suitable for investigating the intricate operation of visual sampling in a radically different visual and linguistic environment. Chinese is a morphosyllabic script, with a character being a square-like unit that corresponds to one syllable and usually has its own meaning(s). A character can be a word by itself. Also, it can be combined with other characters to form different words. According to the Chinese word corpus of Academia Sinica Taiwan (1998), which has 54,393 unique word type entries, the proportion of one-, two-, three-, and four-character words are 9.5%, 65.6%, 12.4%, and 11.6%, respectively. The occurrence of words that contain one, two and more than two characters are 53.8%, 42.2% and 4% of 10 million word tokens, respectively. However, regardless of word length, Chinese sentences are written character by character without physical cues signaling word boundaries. In addition, most of the time, separately processing each character within the perceptual span cannot provide enough constraint to determine whether this character forms a single-character word or needs to be combined with character(s) to its left or right to form a multicharacter word. Among 5915 unique characters, only 2.1% of characters are used merely as single-character words (e.g., 塈, 'and'; 晦,

吨, 吨, exclamation words), but are never combined with other character(s) to form multi-character words. About 8.2% of characters are used solely as the beginning of multi-character words, but are never used as the end of multi-character words or as single-character words (e.g., 諮 in 諮詢, 'to consult'; 侷 in 侷限, 'to confine'). Another 7.5% of characters are used only as the end of words (e.g., 裳 in 衣裳, 'clothing'; 墉 in 廢墟, 'ruins'). The token frequency of these characters is very low (M = 1.1 per million, M = 1.1 per million, MSD = 2.4, range: 0.1–47.0 per million). Together, the total frequency of their occurrence is 1146.9 per million. However, about 49.1% of characters can be single-character words by themselves (e.g., 溒, 'distant, far'), as well as the beginning character (e.g., 溒 in 溒處, 'a distant place'), end character (e.g., 遠 in 遙遠, 'distant'), or internal character (e.g., 遠 in 望遠鏡, 'telescope') in other multi-character words. The total frequency of their occurrence is 960976.9 per million (M = 330.7 per million, SD = 1087.6, range: 0.5– 38622.2 per million). Occasionally, such character position uncertainty can result in lexical ambiguity.¹ To summarize, it is not easy to delineate word boundaries due to the lack of immediate segmentation cues on the basis of either visual spacing or statistical diagnosticity of unique word beginning or ending characters. This leads to the fundamental question of how words are extracted from a series of characters and what guides Chinese readers' eye movements during reading. Presumably, processing of characters within the perceptual span needs to overlap (i.e., occur concurrently) to some extent for word recognition and segmentation (see Yang, Wang, Xu, & Rayner, in press, for a similar view).

During the past decade, several basic eye movement characteristics in reading Chinese have been investigated. First, properties of words and their constituent characters were found to influence eye movement behavior. As an important example, fixation durations on high frequency words or words composed of high frequency characters were found to be shorter compared to those on low frequency counterparts (Yan, Tian, Bai, & Rayner, 2006; Yang & McConkie, 1999). Moreover, words with more orthographic neighbors (i.e., other words sharing the same constituent character) are fixated more briefly than words with fewer orthographic neighbors (Tsai, Lee, Lin, Tzeng, & Hung, 2006), Second, when reading from left to right, the perceptual span extends one character to the left and three characters to the right of the fixation point (Inhoff & Liu, 1998). So, the perceptual span may cover the currently fixated word and one or two words to the right. Within the perceptual span, parafoveal orthographic and phonological processing at the character level were observed (Liu, Inhoff, Ye, & Wu, 2002; Tsai, Lee, Tzeng, Hung, & Yen, 2004). In addition, a recent study from our group reported evidence pointing to the possibility of parafoveal processing at the word level (Yen, Tsai, Tzeng, & Hung, 2008). Yang et al. (in press) also found preview effects for word n+1 and for word n+2 when word n+1 was a high frequency one-character word.

Despite observing some eye movement patterns in Chinese reading that appear similar to those found during the reading of

¹ For example, in the character string (C123), the second character can be combined with characters on either side (the first or the third character) to form possible words (i.e., C12, , 'a form, a table'; and C23, , 'extraordinarily'). Such an ambiguity has to be solved by context. Inhoff and Wu (2005) have demonstrated that the contextually incompatible word in an ambiguous character string is activated and interferes with reading. In their study, a critical four-character string (C1234) was embedded in each sentence. In the control condition, the critical character string could be segmented into two non-overlapping words C12 and C34. That is, the combination of C2 and C3 was not a word. However, in the ambiguous condition, in addition to the two contextually consistent words C12 and C34, the combination of C2 and C3 was unrelated to the meaning of the whole character string – similar to 'design' in 'predesignation' in English. Inhoff and Wu found that fixation durations on the critical character string were longer in the ambiguous condition than in the control condition, suggesting that reading was hampered by the ambiguity of word segmentation.

alphabetic scripts, the underlying mechanisms for word recognition and parafoveal processing might be quite different. For example, in spatially segmented alphabetic scripts, the landing positions of incoming saccades tend to cluster at a 'preferred viewing location' (PVL) between the beginning and the center of target words (Rayner, 1979), suggesting that readers adopt a word-based saccade targeting strategy. However, perhaps due to the lack of apparent visual or linguistic word segmentation cues in Chinese, an equivalent PVL was not observed in most studies (Tsai & McConkie, 2003; Yang & McConkie, 1999; see Yan, Richter, Shu, & Kliegl, 2007, for a recent detailed examination). It should be noted that the relationship between word processing and eye movement control (regarding both the *when* and *where* decisions) in Chinese reading is not yet fully understood. Recently, Bai, Yan, Liversedge, Zang, and Rayner (2008) proposed that words may be the primary units in Chinese reading. However, more research is required to determine to what extent and how word processing guides eye movements and to account for the effects associated with word properties (e.g., frequency and orthographic neighborhood size) during reading.

As discussed above, character-to-word assignment in Chinese is not straightforward because of (1) the characteristics of the mixedword-length presentation of words in the absence of physical word boundaries and (2) the uncertainty in assigning a character to a certain position in a word. In order to recognize a word from a series of characters, processing of adjacent characters is necessary. Consequently, it is conceivable that the span of effective character recognition often extends beyond the currently fixated 'word', and that determining a word boundary may be a product rather than a precondition of lexical processing. In other words, the difficulty in word segmentation may promote immediate and simultaneous processing of characters within the perceptual span. Hence, it appears possible that parafoveal information is routinely extracted from neighboring characters starting at the very beginning of the fixation. The present study attempted to reveal the time course of this parafoveal information acquisition. Also, more generally, studying eye movements during Chinese reading can provide constraints on extending current computational models to non-western languages.

As noted above, in the ongoing debate on reading models it is controversial whether extraction of linguistic information from successive words within the perceptual span overlaps in time (Inhoff, Eiter, & Radach, 2005; Inhoff, Radach, & Eiter, 2006; Pollatsek, Reichle, & Rayner, 2006a; Pollatsek, Reichle, & Rayner, 2006c). The SAS models propose that words are processed one after another. According to the E-Z Reader model, processing of the parafoveal word is usually confined to the end of the current fixation. In contrast, the PG models suggest that words are processed in a limited parallel fashion. Therefore, processing of the parafoveal word overlaps with that of the foveal word and may start at the beginning of the current fixation. Inhoff et al. (2005) conducted a study to directly test this hypothesis. In their second experiment, visibility of the parafoveal word (the target) was manipulated in two time intervals during fixation on the pretarget. That is, the parafoveal word was either fully visible or masked by a pseudoword during the initial 140 ms on the pretarget (beginning-of-fixation 'BoF' visibility). After 140 ms, the target was either visible or masked until the end of pretarget viewing (end-of-fixation 'EoF' visibility). These manipulations resulted in four critical conditions, namely full preview (visible-visible), beginning-of-fixation visible (visible-masked), end-of-fixation visible (masked-visible) and full mask (masked-masked) conditions. During the experiment, the entire sentence was written in aLtErNaTiNg cases so that the configuration of the uninformative preview (pseudoword) was similar to that of the target. Furthermore, transitions between the uninformative previews and the targets during pretarget viewing were concealed by concurrent case changes. If parafoveal information can be extracted during a certain period of pretarget viewing, masking the target would prolong target viewing durations. Both the SAS and PG models predict the EoF preview effect. However, only the PG models predict the BoF preview effect. Critically, the results showed both significant BoF and EoF preview effects, indicating that extraction of parafoveal linguistic information was not confined to the end of the current fixation.

In the present study, an experimental design similar to the second experiment of Inhoff et al. (2005) was adopted. A pair of twocharacter words was chosen to be the pretarget and the target words. In four conditions, the visibility of the target was manipulated in two time intervals during fixation on the pretarget. Parafoveal information was masked by using rare characters that were matched to each character in the critical character string by number of strokes. These characters are orthographically legal but are very rarely seen in natural text. To reduce awareness of the critical display changes (i.e., masking or revealing the target), each display change was accompanied by concurrent change in font type (alternating between Ming and Kai fonts). Changing fonts also created equivalent physical changes in all conditions (note that in the full preview and full mask conditions, the same preview stimulus replaced itself after 140 ms during pretarget viewing; so, there were no physical changes if the fonts did not change). Switching the font type of the characters changed the visual features but preserved the symbolic content of the characters. To keep the experimental design simple, only the four critical conditions (namely beginning-of-fixation visible, end-of-fixation visible, full preview, and full mask conditions) in the second experiment of Inhoff et al. were adopted in the present study because the effect of case changes on preview benefit was shown to be negligible in their study (note that there were two additional conditions in which, throughout pretarget viewing, the targets were either visible or masked without case changes. However, the contrasts between the full preview and full mask conditions were the same regardless of the manipulation of concurrent case changes). Due to the characteristics of Chinese writing system, we expected that parafoveal information. at least at the character level, was obtained during the early phase of the on-going fixation to determine where the currently fixated word ends. Consequently, both BoF and EoF preview effects were expected. In other words, providing informative preview during the entire fixation was predicted to shorten target and/or pretarget viewing durations.

2. Method

2.1. Participants

Twenty-four college students at National Yang-Ming University were paid to participate in this experiment. All of them are native speakers of Chinese with normal or corrected-to-normal vision.

2.2. Materials and design

Participants read 144 sentences for comprehension. A pair of two-character words (pretarget and target) were embedded in each sentence. According to the Chinese word corpus of Academia Sinica Taiwan (1998), both of them have mid/high word frequency, i.e., 11-415 times per million (pretarget: M = 110, SD = 106, range: 11-415; target: M = 92, SD = 83, range: 11-324). The pretargets and targets were either nouns or verbs. The pretarget was either a modifier or an action so that readers would expect that the current clause would continue with at least one more word. The sentences contained 22–27 characters and the pretarget-target word pairs were embedded within the 11th to 20th character positions.

Punctuation marks (if any) were at least two characters to the left of the pretarget words or to the right of the target words. There was always a minimum of five characters succeeding the target. With a word segmentation norming procedure, 10 native speakers who did not participate in the main experiment were asked to segment the experimental sentences into words. Over 95% of participants agreed that the pretarget (96.4%) and target (95.1%) are indeed separate word entries. Extremely low frequency characters, which appear less than 0.7 times per million, were selected as masks. The number of strokes of each mask was matched to each constituent character of the pretarget or the target (M = 12, range: 8-17).

Using the eye-contingent display change technique, the visibility of the target was manipulated in two time intervals during fixation on the pretarget in a 2 by 2 factorial design. During the initial 140 ms after fixation onset on the pretarget, the target was either fully visible or masked by two rare characters. After 140 ms, the target was either visible or masked until the end of pretarget viewing. Therefore, there were four viewing conditions: (a) the beginning-of-fixation visible condition (visible-masked), in which the target was visible during the initial 140 ms on the pretarget and was masked afterwards; (b) the end-of-fixation visible condition (masked-visible), in which the target was masked during the initial 140 ms on the pretarget and was revealed afterwards; (c) the full

Before fixating on the pretarget

高醫師在受訪時,不斷<u>脘澔遒釟疋仨</u>預防及解決文明病的產生。 ۲ ۲

(a) full preview Begin visible	高醫師在受訪時,不斷 強調<i>運動<u></u>天仁</i> 預防及解決文明病的產生。 ④ (0-140 ms)					
End visible	高醫師在受訪時,不斷 強調<i>運動</i>正仁預防及解決文明病的產生。 (141 ms - end) 					
(b) beginning-of-fixation visible						
Begin visible	高醫師在受訪時,不斷 強調<i>運動<u></u>王仁</i> 預防及解決文明病的產生。 ④ (0-140 ms)					
End masked	高醫師在受訪時,不斷強調 <u>遒約定住</u> 預防及解決文明病的產生。 (141 ms - end) 					
(c) end-of-fixation	visible					
(c) end-of-fixation Begin masked	visible 高醫師在受訪時,不斷 強調<u>道</u> 叙 疋仁預防及解決文明病的產生。 ④ (0-140 ms)					
(c) end-of-fixation Begin masked End visible	visible 高醫師在受訪時,不斷 強調<u>道</u>貌 疋仁預防及解決文明病的產生。					
 (c) end-of-fixation Begin masked End visible (d) full mask 	visible 高醫師在受訪時,不斷強調 <u>道叙疋仁</u> 預防及解決文明病的產生。					
 (c) end-of-fixation Begin masked End visible (d) full mask Begin masked 	 visible 高醫師在受訪時,不斷強調<u>道紙定任</u>預防及解決文明病的產生。 (0 - 140 ms) 高醫師在受訪時,不斷強調<i>運動</i>定任預防及解決文明病的產生。 (141 ms - end) 高醫師在受訪時,不斷強調<u>道紙定任</u>預防及解決文明病的產生。 (0 - 140 ms) 					

During fixation on the pretarget, the visibility of the *target* was manipulated

After leaving the **pretarget**

高醫師在受訪時,不斷強調運動可以預防及解決文明病的產生。 ۲

preview condition (visible–visible), in which the target word was visible continuously while fixating on the pretarget; and (d) the full mask condition (masked–masked), in which the target word was masked while fixating on the pretarget. After participants moved their eyes out of the pretarget word, the target word was visible until they finished reading the sentence. Each of the 144 sentences was assigned to only one condition for each participant. That is, participants read each sentence only once. There were 36 sentences in each of the four conditions. The assignment of sentences to conditions was counterbalanced for every four participants. The sentences were presented in a random order during the experiment.

2.3. Apparatus

Eve movements were recorded using a head-mounted SR Eve-Link system running at 250 Hz. Reading materials were displayed on a ViewSonic PT795 monitor at a resolution of 800×600 with the extent of each character set to 24×24 pixels. The viewing distance was 60 cm, at which each character subtended about 0.95°. In custom built software controlling the experiment, a set of VGA routines from the PCTSCOPE library (Tsai, 2001) was used. These routines increased the vertical refresh rate of the display to 167 Hz and preloaded all images into VGA memory before each trial. Eye-contingent display changes were then implemented by combining the EYELINK software for detecting eye positions on line and the PCTSCOPE library for fast display change. In general, the movement of the eye across the boundary was detected within 10 ms. After this, the experiment control program switched images in 40.5 µs and the display change was completed within one refresh cycle (range: 0–6 ms).

2.4. Procedure

Participants were instructed to read sentences for comprehension at their normal pace. They were told that there would be a ves/no comprehension question after some of the sentences. After setting up the eye tracking system, a horizontal three-point calibration was conducted, followed by a validation routine that verified accuracy. Then, 12 practice trials were presented to ensure that participants understood the task. During the experiment, each trial started with a fixation point presented at the location of the first character of the sentence (the location was fixed regardless of sentence length). Participants read each sentence at their own pace and pressed a button to indicate that they finished reading and understood the sentence. During one-third of the trials, a comprehension question was presented on the screen following the disappearance of the sentence. Participants were asked to decide whether the sentence in the comprehension test paraphrased the one they just read by pressing buttons. Participants were allowed to take a break after 48 trials. Calibration was conducted every 12 trials, after breaks, and when there was a drift from the fixation point presented prior to the experimental sentence. The experiment lasted about 1 h.

The procedure for each trial is illustrated in Fig. 1. An invisible boundary was set at the first pixel of the space (4 pixels in width) preceding the pretarget word. At first, the pretarget word, the target word, and two characters following the target (post-target character string) were masked by rare characters matched for number of strokes. The pretarget had to be masked to prevent its parafoveal preprocessing so that pretarget viewing would be equivalent among all conditions. The post-target character string was also masked to obscure the word boundary after the target word. It was masked until participants moved their eyes out of the pretarget, which triggered the last display change. In total, there were three display changes. (1) After participants moved their eyes across the boundary, the first display change was implemented so that the pretarget was presented. Depending on the condition, the target either remained masked or became visible. (2) The second display change was initiated 140 ms after the following two criteria were met: (a) the boundary had been crossed and (b) start of fixation had been detected online by the PCTSCOPE program. Due to the monitor refresh rate, the actual implementation of this change took place after between 140 and 146 ms. After the second display change, the target was masked or visible according to the condition. (3) After participants moved their eyes out of the pretarget, the third display change was implemented so that the original normal sentence became visible. During the experiment, half of the sentences were initially presented in Ming font, while the other half were initially presented in Kai font. Concurrently with each display change, the font type of all characters in the whole sentence was switched (between *Ming* and *Kai* fonts) in all conditions. Thus, the potential disturbance of display change should be the same among all viewing conditions. Participants were told that the font type was alternated on purpose, and were instructed to ignore any disturbance while they were reading the experimental sentences.

3. Results

For data analysis, measures of eye movement behavior in the pretarget, target and post-target areas were calculated. Gaze duration (GD) was used as the primary measure (see Inhoff & Radach, 1998; Rayner 1998, for a discussion of oculomotor measures). It is the sum of the durations of all first-pass fixations in a region of interest (ROI; e.g., pretarget and target) before leaving it. Two other temporal measures were also calculated, namely first fixation duration (FFD, the duration of the first first-pass fixation in the ROI independent of number of fixations in that region) and single fixation duration (SFD, the fixation duration in the ROI receiving only one fixation). Similar patterns of results were predicted for all temporal measures. Other supplementary measures in the analysis include (1) number of first-pass fixations on the pretarget and target; (2) probability of fixating the target; (3) saccade length into the target (measured in characters); and (4) initial landing position on the target (measured in characters).

To examine the time course of processing over consecutive words within the perceptual span, analyses were restricted to trials in which the pretarget, target and post-target areas were fixated in sequence. That is, saccades into and leaving the pretargets and the targets were progressive. Less than six percent of trials were excluded because there were no first-pass fixations on the pretargets or the participants blinked while fixating the pretargets. An additional 15% of trials were excluded because the targets were not fixated immediately after pretarget viewing or the participants blinked while fixating the targets; and 7% of trials were eliminated because the eyes moved leftwards after target viewing (these two criteria were not applied to the calculation of the probability of fixating the targets). Then, another set of criteria was applied to ensure that the experimental manipulations could be implemented properly. To this end, 12% of trials were excluded because first fixation durations on the pretarget were shorter than 140 ms, gaze durations on the pretarget were longer than 1200 ms, or display changes were not triggered appropriately (e.g., due to drifts during fixations). This effectively addressed the issue that in a few cases participants might have become aware of display changes (White, Rayner, & Liversedge, 2005). Finally, separately for each viewing duration measure (i.e., GD, FFD, and SFD), cases with viewing durations shorter than 80 ms or longer than 1200 ms were also excluded from analysis of that measure. Overall, our data exclusion criteria were relatively strict, leading to 61% of all observations that are available for analysis (see Inhoff et al., 2005; Reichle, Pollatsek, Fisher, & Rayner, 1998 for similar procedures). Since 36 items were presented for each particular cell of the design, sufficient numbers of observations remained available for all analyses.

The linear mixed effects modeling approach (LME; Baayen, 2008; Baayen, Davidson, & Bates, 2008) was used to examine the BoF and EoF preview effects. By adding random effects from participants and items in the model, the LME approach is more powerful than the traditional ANOVA approach with separate participant (F1) and item (F2) analyses. In addition, the LME approach does not require prior averaging across participants and items; instead, it works with trial-based data set directly. It can handle missing data due to target skipping or tracking errors. The statistical procedure was conducted by using the lmer program (lme4 package; Bates, Maechler, & Dai, 2008) in the R system (R Development Core Team, 2008). Effect coding was used for the BoF and EoF visibility manipulation (-0.5 for the visible and 0.5 for the masked conditions). The estimated effect size (b), standard error, and t value for each effect were reported. The *p* values were obtained through Markov Chain Monte Carlo (MCMC) sampling.

3.1. Pretarget viewing

Distributions of single fixation durations on the pretarget for each condition are shown in Fig. 2. As could be expected as a result of transient stimulation associated with a visual change during fixation, there is a dip around 250 ms after fixation onset, indicating a delay in saccade programming due to display changes (Reingold & Stampe, 2000). Critically, the shape of the distribution is very similar across all viewing conditions.



Fig. 2. Distribution of single fixation durations on the pretarget for each condition.

The means and standard deviations of viewing duration measures and number of fixations on the pretarget for each condition are shown in Table 1.

3.1.1. Temporal parameters

Beginning-of-fixation preview significantly shortened gaze durations on the pretarget: gaze durations were on average 14 ms shorter in the BoF visible conditions than in the corresponding masked conditions (b = 17.96, SE = 5.99, t = 3.00, and p < 0.01). End-of-fixation preview did not influence gaze durations on the pretarget significantly (5 ms; b = 6.44, SE = 5.99, t = 1.08, and p > 0.28). The interaction between BoF and EoF visibility was not significant (p > 0.92). BoF preview significantly shortened SFD (12 ms; b = 14.91, SE = 5.20, t = 2.87, and p < 0.01) and slightly shortened FFD (6 ms; b = 6.45, SE = 4.57, t = 1.41, and p > 0.15). Neither the EoF preview effect nor the interaction was significant for SFD and FFD (all p > 0.13).

3.1.2. Number of fixations

There were on average 1.3 fixations on the pretarget. BoF preview significantly decreased number of fixations on the pretarget (b = 0.05, SE = 0.02, t = 2.41, and p < 0.05). However, EoF preview did not significantly decrease number of fixations on the pretarget (b = 0.03, SE = 0.02, t = 1.42, and p > 0.15). The interaction was not significant (p > 0.54).

3.2. Target viewing

The means and standard deviations of all dependent variables on the target for each condition are shown in Table 2.

3.2.1. Temporal parameters

Beginning-of-fixation preview significantly shortened gaze durations on the target by 19 ms (b = 21.83, SE = 6.33, t = 3.45, and p < 0.001). End-of-fixation preview also significantly decreased target gaze durations by 66 ms (b = 69.70, SE = 6.33, t = 11.01, and p < 0.001). The interaction was not significant (p > 0.29). Similar patterns were observed for FFD and SFD. The BoF preview effect was marginally significant for FFD (8 ms; b = 8.69, SE = 4.44, t = 1.96, and p = .051) and significant for SFD (14 ms; b = 14.91, SE = 5.22, t = 2.86, and p < 0.01). The EoF preview effect was significant for both FFD (36 ms; b = 37.13, SE = 4.44, t = 8.36, and p < 0.001) and SFD (53 ms; b = 56.45, SE = 5.23, t = 10.79, and p < 0.001). The interaction was not significant for both measures (p > 0.15).

3.2.2. Number of fixations

There were on average 1.3 fixations on the target. BoF preview significantly decreased number of fixations on the target (b = 0.04, SE = 0.02, t = 1.98, and p < 0.05). EoF preview also significantly decreased number of fixations on the target (b = 0.13, SE = 0.02, t = 6.45, and p < 0.001). The interaction was not significant (p > 0.82).

Table 1

Means and standard deviations (in parentheses) of first fixation duration, gaze duration, single fixation duration, and number of fixations on the pretarget for each condition. Note that prior to entering the pretarget word, both the pretarget and the target words were masked for all conditions.

Measure	Beginning-of-fixation visible		Beginning-of-fixation masked	
	End-of-fixation visible (full preview)	End-of-fixation masked (beginning-of-fixation visible)	End-of-fixation visible	End-of-fixation masked (full mask)
FFD (ms)	414 (108)	406 (116)	416 (111)	415 (119)
GD (ms)	489 (151)	490 (169)	499 (149)	508 (169)
SFD (ms)	427 (105)	412 (109)	435 (110)	429 (121)
Number of fixations	1.31 (0.50)	1.34 (0.53)	1.35 (0.54)	1.37 (0.54)

Table 2

Means and standard deviations (in parentheses) of first fixation duration, gaze duration, single fixation duration, number of fixations, probability of fixation, landing position on the target, and incoming saccade length to the target for each condition.

Measure	Beginning-of-fixation visible		Beginning-of-fixation masked	
	End-of-fixation visible (full preview)	End-of-fixation masked (beginning-of-fixation visible)	End-of-fixation visible	End-of-fixation masked (full mask)
FFD (ms)	311 (118)	342 (102)	314 (105)	355 (118)
GD (ms)	364 (167)	423 (152)	375 (164)	447 (169)
SFD (ms)	309 (122)	356 (104)	317 (110)	376 (121)
Number of fixations	1.22 (0.44)	1.34 (0.52)	1.25 (0.47)	1.37 (0.53)
Fixation probability	0.88 (0.33)	0.94 (0.24)	0.93 (0.26)	0.95 (0.22)
Landing position (characters)	0.91 (0.51)	0.86 (0.48)	0.92 (0.51)	0.85 (0.46)
Saccade length (characters)	1.88 (0.51)	1.81 (0.52)	1.86 (0.49)	1.75 (0.51)

3.2.3. Fixation probability

Probability of fixating the targets was the proportion of trials in which the eyes moved on progressively after pretarget viewing and immediately landed on the target in each condition. Similar to other measures, trials in which the pretarget was not fixated or display changes could not be implemented properly were excluded from analysis. In addition, trials in which the eyes moved leftwards after pretarget viewing were also excluded from analysis. Fixation probability was calculated with the remaining trials (73% of trials). Because the response for each trial was either 1 (fixated) or 0 (skipped), the generalized linear mixed model with binomial distribution and logistic link function was used. In general, the target was fixated 92% of time. BoF preview significantly reduced the probability of fixating the target word (3%; b = 0.58,² SE = 0.17, z = 3.36, and p < 0.001). EoF preview also significantly reduced the fixation probability (4%; b = 0.73, SE = 0.17, z = 4.17, and p < 0.001). The interaction was not significant (p > 0.23).

3.2.4. Saccade length

Providing useful BoF preview significantly increased the saccade length into the target word (0.04 characters; b = -0.06, SE = 0.02, t = -3.17, and p < 0.01). EoF preview also significantly increased the saccade length (0.09 characters; b = -0.10, SE = 0.02, t = -5.43, and p < 0.001). The interaction was not significant (p > 0.51).

3.2.5. Initial landing position

The average initial landing position on the target was slightly to the left of the center of the target word (0.88 character position on the two-character target word). Providing useful BoF preview did not influence the initial landing position on the target (p > 0.63). However, the initial landing position was further into the target when it was visible than when it was masked during the end of pretarget viewing (0.06 characters; b = -0.07, SE = 0.02, t = -3.24, and p < 0.01). The interaction was not significant (p > 0.94).

3.3. Post-target viewing

Neither BoF nor EoF visibility of the target influenced the duration of the first fixation out of the target (about 267 ms in all conditions), both ps > 0.72. Thus, no spillover effect was observed.

4. Discussion

Both beginning- and end-of-fixation preview effects on the target word were observed in this experiment. Viewing durations were lengthened if the target word was masked parafoveally either during the initial 140 ms or after 140 ms until the end of pretarget viewing. It is important to note that overall values for gaze durations and saccade amplitudes in the critical area as well as the large baseline preview benefit of 83 ms (the difference in gaze duration between the full preview and full mask conditions) are quite similar to results of prior research in Chinese using the eye-contingent display change technique (Inhoff & Liu, 1998; Liu et al., 2002). As a central result, we found substantial BoF and EoF preview effects (18 and 66 ms), indicating that a significant amount of parafoveal information was acquired under conditions of restricted visibility. These benefits of partial parafoveal preview are similar to those obtained in prior work in English (Inhoff et al., 2005). Visibility of the parafoveal characters also influenced spatial eye movement parameters. The target was more likely to be fixated, saccade length into the target was shorter and initial landing position was closer to the beginning of the target word if it was masked parafoveally than if it was visible. This is consistent with the suggestion of Morris, Rayner, and Pollatsek (1990) that information available during the entire fixation could influence the where decision. Lack of low level visual information (e.g., spatial segmentation via word spacing) and linguistic markers signaling how characters need to be combined to form a word may promote Chinese readers to simultaneously process characters within the perceptual span. Such early parafoveal processing may be obligatory within the constraints of the Chinese writing system.

The results also showed that the BoF preview effect was slightly weaker than the EoF preview effect. There are three possible explanations for this pattern, which are not mutually exclusive and may all contribute to the observed data. First, the BoF preview effect may have been smaller because it takes about 50–60 ms after fixation onset to acquire useful visual information (McConkie, Underwood, Zola, & Wolverton, 1985; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). This would have shortened the effective duration of an early preview. Second, given the average gaze durations (496 ms) on the pretarget, the BoF preview stimulus was generally presented for a shorter time interval than the EoF preview stimulus, which in itself may account for the observed asymmetry between the BoF and EoF preview effects. Third,

² The estimate can be transformed to odds ratio. For example, the corresponding odds ratio of the BoF preview effect is the exponential of 0.58, which equals to 1.79. The odds of fixation (i.e., the ratio of the probability of fixation to the probability of skip) are 1.79 times higher when the target was masked than that when it was visible during the beginning of pretarget viewing. Large odds of fixation correspond to high fixation probability. Thus, masking the target during the beginning of pretarget viewing increased the probability of fixating the target. The corresponding odds ratio of the EoF preview effect is 2.06, suggesting that blocking information from the target. Overall, fixation probabilities in the masked conditions were higher than those in the visible conditions.

according to SAS models, parafoveal processing should be confined to the end of the current fixation except that, in a few cases, attention might shift to the parafovea relatively early when initial lexical processing is exceptionally fast. Thus, the BoF preview effect, if it exists at all, should in any case be smaller than the EoF preview effect.

Two further predictions can be derived from the SAS models. First, the preview benefit of BoF visibility (the difference between the BoF visible and full mask conditions) should be evident when the pretarget viewing duration is short, because in this situation, it is highly likely that attention has shifted to the parafovea during the beginning of the fixation on the pretarget. Second, viewing durations on the target in the EoF visible condition should be similar to those in the full preview condition when the pretarget viewing duration is long. These predictions for gaze durations on the target were tested in a supplementary analysis analogous to that of Inhoff et al. (2005). Two sets of predictors and their interactions were specified in a linear mixed effects model. The first set included two contrasts, which were (1) paired comparison between the full mask and BoF visible conditions and (2) paired comparison between the EoF visible and full preview conditions. The second predictor was the fixation durations on the pretargets receiving exactly one fixation (SFD). This predictor was centered at the median (416 ms). Note that SFD shorter than 140 ms had been excluded from analysis to ensure the implementation of the critical display change. The difference between the full mask and BoF visible conditions was significant (*b* = 27.38, *SE* = 10.58, *t* = 2.59, and *p* < 0.01), but the difference between the EoF visible and full preview conditions was not (*b* = 17.60, *SE* = 10.64, *t* = 1.65, and *p* > 0.09). While increase in SFD on the pretarget significantly increased GD on the target (b = 0.14, SE = 0.04, t = 3.82, and p < 0.001), it did not interact with either of the contrasts (ps > 0.15). Thus, no supporting evidence was found for these additional predictions derived from SAS models

As mentioned above, our results are similar to the findings of Inhoff et al. (2005) in that both the BoF and EoF preview effects were observed, which suggest that parafoveal processing is not confined to the end of pretarget viewing. However, there are two critical differences between the two studies. First, methodologically, the pretarget word was masked before it was fixated in the present work. This may result in more processing resources being allocated to the pretarget word at the beginning of pretarget viewing; consequently, the BoF preview effect was smaller. However, the small but significant BoF preview effect suggests that early parafoveal processing was observed even in a situation strongly favoring foveal processing.

Second, the time course and the level of parafoveal processing may be different between writing systems. Early visual processing provides Chinese readers with distinctive units that correspond to 'characters' rather than 'words' (i.e., there are no clusters of characters delineated by inter-word spaces as in most alphabetic scripts). Thus, linguistic processing is necessary to segment Chinese text into words. In order to accomplish word segmentation, temporal overlap between the processing of the 'foveal' word and 'parafoveal' characters may be obligatory and part of a routine processing sequence. In other words, at the beginning of fixation, one major purpose of parafoveal processing is always to determine the right-side boundary of the fixated word. Then, lexical processing of the parafoveal word (Yen et al., 2008) becomes gradually more important later during the time course of processing. This account is supported by the complementary pattern of results: BoF visibility mainly influenced pretarget viewing while EoF visibility solely affected target viewing. The pretarget was fixated longer when characters in the parafovea were masked than when they were visible at the beginning of pretarget viewing. The second character (C2) of the pretarget word can be (1) the end character of the foveal word (C12), (2) the beginning character of the parafoveal word (C23 or longer), or (3) the internal character of a longer foveal word (C123 or longer). During the early phase of pretarget viewing, blocking parafoveal information (i.e., C3 or more) made the right-side boundary of the foveal word undetermined. This interruption in foveal word recognition increased the probability of refixation and lengthened fixation durations. On the other hand, EoF manipulation did not affect pretarget viewing but mainly influenced target viewing (i.e., lengthening target viewing durations, increasing probabilities of fixation and refixation, and shortening the incoming saccade lengths), suggesting that preview benefit on the parafoveal stimuli gradually emerged later during pretarget viewing.³

Due to the significant differences between the writing systems involved, the results of the present study may not directly contribute to the ongoing debate on whether consecutive words in reading are processed in a strictly serial or a limited parallel fashion. This is a critical issue in the context of existing computational models of reading in alphabetic scripts (see Inhoff et al., 2005; Inhoff et al., 2006; Pollatsek et al., 2006a; Pollatsek et al., 2006c). However, the problem of sequential vs. parallel word processing takes on a different angle under the conditions of reading in Chinese. The current study suggests that characters within the perceptual span are likely to be processed in parallel (also see Yang et al., in press), while it does not provide a direct test for the view that processing of consecutive 'words' overlap in time. In any case the fact that there is early extraction of parafoveal information from the region to the right of the fixated word could be taken as solid evidence that an early and fast allocation of attention into this subsequent word takes place. However, the existing sequential attention models of eye movement control in reading assume that the extent of the attentional beam corresponds to the length of the to-be-processed parafoveal word (Reichle et al., 1998). This is quite unlikely in Chinese, because, as discussed above, in the absence of pre-attentional visual cues, the length of the next word⁴ is not yet known when the attention shift is triggered. So, the aperture of the attentional beam would have to be of a predetermined extent and possibly adjusted later to fit the size of the target word. It is doubtful. however, that a complex mechanism like this is in a good position to pass the test of Ockham's razor (see Jacobs, 2000; Radach, Reilly, & Inhoff, 2007; Reichle et al., 2003, for discussions of criteria for the appropriateness of reading models).

Recently, Rayner, Li, et al. (2007) have extended their sequential, attention-based E-Z Reader model to Chinese reading. In this work, they are maintaining processing assumptions originally suggested for English reading, especially the mechanisms of wordbased attention shifts and saccade targeting. The extended model was able to approximate human reading behavior quite well, but this success came at the expense of not addressing the theoretical issues discussed above. We doubt that a comprehensive account within a sequential processing framework can be based on the assumption that Chinese readers utilize the same type and se-

³ Preview effects might be influenced by the frequency of the pretarget word (Henderson & Ferreira, 1990; Henderson & Ferreira, 1993). More processing resource was allocated to the pretarget if it was a low frequency word than a high frequency word, and this may lead to a smaller preview benefit for the parafoveal word. The natural logarithm of pretarget word frequency was added in a linear mixed effects model as an additional predictor (centered at 4.2, which corresponded to the frequency of 65.7 per million words). While increase in pretarget word frequency slightly increased gaze durations on the target (b = 8.17, SE = 4.35, t = 1.88, and p = 0.061), there was no interaction between pretarget frequency and either the BoF or EoF preview effect (ps > 0.34). In addition, pretarget frequency did not interact with either preview effect on pretarget viewing durations (ps > 0.48).

⁴ To reiterate, while most Chinese word type entries are composed of two characters, it is almost equally often to encounter one- and two-character word tokens. In addition, only 28.2% of one-character words are of high frequency (higher than 10 per million words) and most of these characters can be part of multi-character words as well.

quence of processing operations as suggested for English. An explicit cognitive mechanism is needed to explain how Chinese readers utilize early parafoveal processing for word recognition within the constraints of their morphosyllabic writing system.

Processing gradient models can account for the present findings by suggesting that characters within the perceptual span are processed simultaneously with efficiency scaled by eccentricity relative to the current fixation position. However, current models in this tradition are also not yet equipped with an explicit mechanism that accomplishes the necessary transition from unconstrained character processing to focused lexical access (Engbert et al., 2005; Reilly & Radach, 2006). In this context, it may be interesting to note that, for reading in English, it is widely assumed that letter processing within words occurs in parallel (see Pollatsek & Rayner, 1989, for a seminal discussion). If visual word boundaries are removed as in Chinese script, it appears feasible to take limited parallel character processing within the perceptual span as a reasonable starting point unless a more complex modeling approach is shown to be necessary.

Because of the characteristics of the Chinese writing system, such as lack of cues for word boundaries, and the relationship between words and their constituent characters, it is an appropriate platform to examine to what extent assumptions developed on the basis of research in alphabetic writing systems can be generalized to other languages. Thus, although the general goal of reading, which is forming a mental representation of text, remains the same, the nature and order of processing operations necessary to attain this goal may be substantially different. Therefore, studying eye movements in extremely different orthographies sheds light on the universal aspects of how humans actively sample information for comprehension as well as on the unique skills developed after being immersed in a particular visual and linguistic environment.

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References

- Academia Sinica Taiwan (1998). Academia sinica balanced corpus (Version 3) [CD-ROM]. Taipei, Taiwan: Academia Sinica, Chinese Knowledge and Information Processing Group.
- Angele, B., Slattery, T. J., Yang, J., Kliegl, R., & Rayner, K. (2008). Parafoveal processing in reading: Manipulating n+1 and n+2 previews simultaneously. *Visual Cognition*, 16, 697–707.
- Baayen, R. H. (2008). Analyzing linguistic data: A practical introduction to statistics using R. Cambridge, UK: Cambridge University Press.
- 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, 390–412.
- Bai, X., Yan, G., Liversedge, S. P., Zang, C., & Rayner, K. (2008). Reading spaced and unspaced Chinese text: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, 34, 1277–1287.
- Bates, D., Maechler, M., & Dai, B. (2008). Ime4: Linear mixed-effects models using S4 classes R package (Version 0.999375-27) [Computer software]. Vienna, Austria: R Foundation for Statistical Computing.
- Calvo, M. G., & Meseguer, E. (2002). Eye movements and processing stages in reading: Relative contribution of visual, lexical, and contextual factors. *The Spanish Journal of Psychology*, 5, 66–77.

- Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review*, 112, 777–813.
- 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.
- Henderson, J. M., & Ferreira, F. (1993). Eye movement control during reading: Fixation measures reflect foveal but not parafoveal processing difficulty. *Canadian Journal of Experimental Psychology*, 47, 201–221.
- Inhoff, A. W., Eiter, B. M., & Radach, R. (2005). Time course of linguistic information extraction from consecutive words during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance*, 31, 979–995.
- 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.
- Inhoff, A. W., & Radach, R. (1998). Definition and computation of oculomotor measures in the study of cognitive processes. In G. Underwood (Ed.), Eye guidance in reading and scene perception (pp. 29–53). Amsterdam: Elsevier.
- Inhoff, A. W., Radach, R., & Eiter, B. (2006). Temporal overlap in the linguistic processing of successive words in reading: Reply to Pollatsek, Reichle, and Rayner (2006a). Journal of Experimental Psychology: Human Perception and Performance, 32, 1490–1495.
- Inhoff, A. W., & Wu, C. (2005). Eye movements and the identification of spatially ambiguous words during Chinese sentence reading. *Memory and Cognition*, 33, 1345–1356.
- Jacobs, A. M. (2000). Five questions about cognitive models and some answers from three models of reading. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 721–732). Oxford: Elsevier.
- Kennedy, A., & Pynte, J. (2005). Parafoveal-on-foveal effects in normal reading. Vision Research, 45, 153–168.
- 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, 262–284.
- Kliegl, R., Risse, S., & Laubrock, J. (2007). Preview benefit and parafoveal-on-foveal effects from word n + 2. Journal of Experimental Psychology: Human Perception and Performance, 33, 1250–1255.
- Liu, W., Inhoff, A. W., Ye, Y., & Wu, C. (2002). Use of parafoveally visible characters during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance*, 28, 1213–1227.
- McConkie, G. W., Underwood, N. R., Zola, D., & Wolverton, G. S. (1985). Some temporal characteristics of processing during reading. *Journal of Experimental Psychology: Human Perception and Performance*, 11, 168–186.
- 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, 268–281.
- Pollatsek, A., & Rayner, K. (1989). Reading. In M. I. Posner (Ed.), Foundations of cognitive science. Cambridge, MA: MIT Press.
- Pollatšek, A., Reichle, E. D., & Rayner, K. (2006a). Serial processing is consistent with the time course of linguistic information extraction from consecutive words during eye fixations in reading: A response to Inhoff, Eiter, and Radach (2005). *Journal of Experimental Psychology: Human Perception and Performance*, 32, 1485–1489.
- Pollatsek, A., Reichle, E. D., & Rayner, K. (2006b). Tests of the E-Z Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology*, 52, 1–56.
- Pollatsek, A., Reichle, E. D., & Rayner, K. (2006c). Attention to one word at a time in reading is still a viable hypothesis: Rejoinder to Inhoff, Radach, and Eiter (2006). Journal of Experimental Psychology: Human Perception and Performance, 32, 1496–1500.
- R Development Core Team (2008). R: A language and environment for statistical computing (Version 2.7.2) [Computer software]. Vienna, Austria: R Foundation for Statistical Computing.
- Radach, R., & Glover, L. (2007, August). Exploring the limits of spatially distributed word processing in normal reading: A new look at N-2 preview effects. Paper presented at the 14th European Conference on Eye Movements, Potsdam, Germany.
- Radach, R., Reilly, R., & Inhoff, A. W. (2007). Models of oculomotor control in reading: Toward a theoretical foundation of current debates. In R. P. G. van Gompel, M. H. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye movements: A window* on mind and brain (pp. 237–269). Amsterdam: Elsevier.
- Rayner, K. (1975). The perceptual span and peripheral cues in reading. Cognitive Psychology, 7, 65–81.
- Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. Perception, 8, 21–30.
- Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology*, 41, 211–236.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. Psychological Bulletin, 124, 372–422.
- Rayner, K., Inhoff, A. W., Morrison, R. E., Slowiaczek, M. L., & Bertera, J. H. (1981). Masking of foveal and parafoveal vision during eye fixations in reading. *Journal* of Experimental Psychology: Human Perception and Performance, 7, 167–179.
- Rayner, K., & Juhasz, B. J. (2004). Eye movements in reading: Old questions and new directions. European Journal of Cognitive Psychology, 16, 340–352.
- Rayner, K., Juhasz, B. J., & Brown, S. J. (2007). Do readers obtain preview benefit from word n + 2? A test of serial attention shift versus distributed lexical processing

models of eye movement control in reading. Journal of Experimental Psychology: Human Perception and Performance, 33, 230–245.

- Rayner, K., Li, X., & Pollatsek, A. (2007). Extending the E-Z Reader model of eye movement control to Chinese readers. *Cognitive Science*, *31*, 1021–1033.
- Rayner, K., Well, A. D., & Pollatsek, A. (1980). Asymmetry of the effective visual field in reading. Perception and Psychophysics, 27, 537–544.
- 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.
- Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eyemovement control in reading: Comparisons to other models. *Behavioral and Brain Sciences*, 26, 445–526.
- Reilly, R. G., & Radach, R. (2006). Some empirical tests of an interactive activation model of eye movement control in reading. *Cognitive Systems Research*, 7, 34–55.
- Reingold, E. M., & Stampe, D. M. (2000). Saccadic inhibition and gaze contingent research paradigms. In A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), *Reading as a perceptual process* (pp. 119–145). Amsterdam: Elsevier.
- Starr, M. S., & Inhoff, A. W. (2004). Attention allocation to the right and left of a fixated word: Use of orthographic information from multiple words during reading. European Journal of Cognitive Psychology, 16, 203–225.
- Tsai, J.-L. (2001). A multichannel PC tachistoscope with high resolution and fast display change capability. Behavior Research Methods, Instruments and Computers, 33, 524–531.
- Tsai, J.-L., Lee, C.-Y., Lin, Y.-C., Tzeng, O. J.-L., & Hung, D. L. (2006). Neighborhood size effects of Chinese words in lexical decision and reading. *Language and Linguistics*, 7, 659–675.
- Tsai, J.-L., Lee, C.-Y., Tzeng, O. J.-L., Hung, D. L., & Yen, N.-S. (2004). Use of phonological codes for Chinese characters: Evidence from processing of parafoveal preview when reading sentences. Brain and Language, 91, 235–244.

- 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). Amsterdam: Elsevier.
- Underwood, N. R., & McConkie, G. W. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly*, 20, 153–162.
- Vitu, F. (2003). The basic assumptions of E-Z Reader are not well-founded. Behavioral and Brain Sciences, 26, 506–507.
- 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 and Review*, 12, 891–896.
- Yan, G., Tian, H., Bai, X., & Rayner, K. (2006). The effect of word and character frequency on the eye movements of Chinese readers. *British Journal of Psychology*, 97, 259–268.
- Yan, M., Richter, E. M., Shu, H., & Kliegl, R. (2007, August). Reading Chinese script The Beijing Sentence Corpus. Paper presented at the 14th European Conference on Eye Movements, Potsdam, Germany.
- Yang, H.-M., & McConkie, G. W. (1999). Reading Chinese: Some basic eye-movement characteristics. In J. Wang, A. W. Inhoff, & H.-C. Chen (Eds.), *Reading Chinese script: A cognitive analysis* (pp. 207–222). Mahwah, NJ: Lawrence Erlbaum Associates.
- Yang, J., Wang, S., Xu, Y., & Rayner, K. (in press). Do Chinese readers obtain preview benefit from word n + 2? Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance.*
- Yang, S.-N., & McConkie, G. W. (2004). Saccade generation during reading: Are words necessary? European Journal of Cognitive Psychology, 16, 226–261.
- Yen, M.-H., Tsai, J.-L., Tzeng, O. J.-L., & Hung, D. L. (2008). Eye movements and parafoveal word processing in reading Chinese. *Memory and Cognition*, 36, 1033–1045.