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Parafoveal grouping of characters facilitates encoding of morphological hierarchical structure during sentence reading

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Abstract

The types and priority of parafoveal information processing is relevant to theoretical debates on reading. Whether readers make use of high-level linguistic features such as semantics and morphology in the parafoveal vision during reading has been debated. Some recent studies on agglutinative languages such as Uighur and Finnish have demonstrated that saccades can be affected by morphological structure. However, the underlying mechanism of such morphological influences has not been determined completely. In the current study, participants read three-character Chinese compound words embedded in sentences. The target words differed in their morphological hierarchical structure and were preceded by parafoveally presented pseudo-word primes whose grouping patterns were either consistent or inconsistent with the morphological hierarchical structure of the target word. Our results showed an influence of preview on first-fixation location, indicating that Chinese readers use the grouping information for saccade generation. More importantly, the readers processed the target words more briefly following consistent than inconsistent previews. The results suggest that parafoveal information influences subsequent foveal lexical processing, providing support to the notion that the processing of morphological hierarchical structure during Chinese sentence reading may occur early.

Keywords Eye-tracking · Saccade · Morphological hierarchical structure · Chinese

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Introduction

During natural sentence reading, lexical processing begins when a word appears in the parafoveal vision before it is fixated on. The foveal vision covers a region about 1° of visual angle in diameter in the visual field, where readers obtain precise visual information. Words beyond the foveal vision and within 5° of visual angle are processed in a reader's parafoveal vision (Engbert et al., 2002). So far, researchers have not yet reached a complete agreement on the types and priority of parafoveal information processing within the perceptual span. Different computational models of eye movement in reading have been developed (e.g., Engbert et al., 2005; Reichle et al., 1998; Reilly & Radach, 2006). Although these models can account for many phenomena such as word skipping, they differ with respect to whether parafoveal high-level linguistic features can influence fixation location and duration. Specific to Chinese reading, the current study is theoretically relevant to debates on word segmentation. The lack of inter-word spaces in Chinese prevents readers from obtaining word boundary information through low-level visual processing, and therefore raises a fundamental challenge to current models of eye movements. Indeed, different theoretical perspectives about eye movements during Chinese reading focus on whether readers can segment words from an unspaced string of characters during an early, parafoveal processing stage (Yan et al., 2010), or only during a late, foveal processing stage (e.g., Liu et al., 2015). Utilizing the gaze-contingent boundary paradigm (Rayner, 1975), the present study presents evidence that parafoveal grouping information can influence subsequent foveal lexical processing, suggesting that Chinese readers are highly sensitive to these cues for constructing morphological hierarchical structure.

According to the eye-mind assumption (Just & Carpenter, 1980), all possible psycholinguistic processes are completed within a fixation. Fixation location corresponds to a decision in saccade generation on where to attend to next, whereas fixation duration reflects the amount of cognitive processing undertaken. One specific topic that has received much attention is whether parafoveal information beyond low-level visual features can influence eye movements in reading (see Kliegl, et al., 2006 and Rayner, 2009, for reviews). In this area, the gaze-contingent boundary paradigm (Rayner, 1975) has been widely used. In this paradigm, during fixations on and prior to a pre-target word, a preview word occupies the position of a target word. A saccade crossing an invisible boundary located between these words triggers an immediate display change in which the correct target word replaces the preview. Following a priming logic, the preview is manipulated experimentally to determine the types of information that can be encoded parafoveally. A preview benefit (PB) is defined by the time saved in target-word fixation duration when primed by an identical or a related preview over an unrelated preview. In the past decades, a view that parafoveal processing is limited to low-level features has been overwhelmingly dominant, supported by evidence for orthographic and phonological PBs (Inhoff, 1990; Inhoff & Tousman, 1990; Pollatsek et al., 1992), with a lack of semantic PB (Hyönä & Häikiö, 2005; Inhoff, 1982; Inhoff & Rayner, 1980; Rayner et al., 1986). However, the conclusion, based primarily on English, an alphabetic script with a deep orthography, has been challenged recently (see Yan & Kliegl, 2023). Yan et al. (2009) documented semantic PB in Chinese, taking advantage of a close association between words' graphic forms and their meanings in this logographic script. Later studies have not only replicated the effect in Chinese (Pan et al., 2016; Pan et al., 2022; Yan et al., 2012; Yang et al., 2012), but also extended it to other writing systems, especially those with transparent letter-to-phoneme correspondences, such as German (Hohenstein & Kliegl, 2014; Hohenstein et al., 2010) and Korean (Kim et al., 2012; Yan et al., 2019). Presumably, fast phonological decoding in transparent orthographies like German and Korean promotes access to high-level semantic and syntactic aspects of words (Hohenstein et al., 2010). These is also evidence of morphological parafoveal processing in English. Dann et al. (2021) reported PBs from parafoveal previews that shared with the target words the same stem but with a different suffix (e.g., stressary–stressful), but not from those with a nonaffix (e.g., stressard–stressful), suggesting parafoveal extraction of stem. Overall, these studies jointly suggest that high-level information can be obtained from parafoveal words.

Another branch of research on eye movement in reading investigates where readers fixate next. Since saccades toward target words are programmed during fixations on previous words, effects of target-word properties on target-word fixation location are parafoveal influences. Likewise, existing evidence generally favors a low-level guidance of saccade. First-fixation location (FL; where eye gaze initially lands within a word) distribution typically forms a Gaussian distribution with a peak around the word center, suggesting word length plays a primary role in eye guidance, as word length can be easily determined on the basis of inter-word spaces (Rayner, 1979). Effects of low-level visual properties other than word length have also been documented. For instance, irregular combinations in the beginning of a word, rather than regular ones, shifted FLs closer to the word beginning (Hyönä, 1995; Radach et al., 2004). In the same vein, there were several failed attempts in establishing morphological effects on FL (Beauvillain, 1996; Deutsch & Rayner, 1999; Hyönä & Pollatsek, 1998; Inhoff, et al., 1996). Inspired by recent evidence for semantic PB, parafoveal morphological effects on FL have been reexamined and established in some agglutinative languages, where many words are formed through concatenating a root morpheme with several affixes and thereby bear a high level of morphologically complexity in a single word. Focusing on Uighur, an Arabic-derived alphabetic language in the Turkic language family, Yan et al. (2014) conducted a corpus analysis in their Experiment 1 and illustrated that FL shifted closer to the beginning of the word with an increase in number of suffixes during natural sentence reading comprehension. Their Experiment 2 reported that FL was closer to the beginning of the word for suffixed target words than for monomorphemic target words matched on word length. Hyönä et al. (2018) replicated the critical effect in Finnish (see also Hyönä et al., 2021, for further evidence). To sum up, results from these experiments jointly suggest that FL shifts further into the word (i.e., closer to the end of the word) for morphologically simpler words.

In another study, Luo et al. (2023) investigated the influence of morphological hierarchical structure, as a type of high-level information, on eye guidance in

Chinese. They employed a natural sentence reading comprehension task and manipulated the internal hierarchical structure of 3-character compound target words—the grouping of characters that is not determined by low-level perceptual cues. Specifically, their target words shared an identical beginning character and formed either a [2+1] structure, where the first two characters were more firmly combined, or otherwise a [1+2] structure. Take "内陆河 (inland river)" and "内蒙古 (Inner Mongolia)" for example: while both words can be decomposed into smaller, meaningful constituents that exhibit a modifier-head relationship in terms of their morphological structure, 内陆河 consists of 内陆 (inland, 2 characters) and 河 (river, 1 character), and 内蒙古 consists of 内 (inner, 1 character) and 蒙古 (Mongolia, 2 characters). Notably, like typical compound words, they are utilized as cohesive units with fixed meanings and do not permit the insertion of internal grammatical markers, as this would either render the structure ungrammatical or alter the intended word meaning. Luo et al. observed that FL shifted further into the target word in the [1+2] condition than in the [2+1] condition, suggesting that Chinese readers decompose the 3-character words parafoveally and target the larger unit.

The theoretical debates on the role of parafoveal morphological processing is especially important in the context of Chinese reading. Most modern writing systems use spaces to indicate where a word begins and ends. Although inter-word space became widely used only in the tenth century among the European scripts (Manguel, 1996; Saenger, 1997), it serves an important visual cue in oculomotor guidance for readers to generate saccades towards the word center for effective lexical processing (e.g., Epelboim et al., 1994; McConkie et al., 1989; Pollatsek & Rayner, 1982; Rayner et al., 1998). In unspaced scripts such as Chinese, Japanese and Thai, characters must be grouped into larger units for correct understanding (Hoosain, 1992; Reilly & Radach, 2012). Despite the importance of word/morphological segmentation for comprehension, different saccade models of Chinese reading, however, do not agree on where the segmentation process takes place. On the one hand, Yan et al. (2010) hypothesized a dynamic saccade generation that follows an early and *parafoveal* segmentation process. Chinese readers target to the word center only when they have segmented the upcoming word during prior fixations. Otherwise, they typically generate character-based saccades towards the first character beyond the current word. In a similar vein, Fan and Reilly (2022) proposed character-based eye guidance for distant saccadic launch sites, at which word boundary information is more difficult to access, otherwise word-based saccades for close launch sites. An alternative processing-based model proposed a simpler mechanism: Chinese readers program their saccades to the next unprocessed character during each fixation and perform a relatively late and *foveal* word segmentation (Liu et al., 2015). Although both accounts can explain many empirical findings, they differ fundamentally with respect to the use of parafoveal word/morphological segmentation information.

Readers of unspaced scripts, such as Thai and Chinese, can achieve word segmentation based on statistical information (Kasisopa et al., 2013; Reilly et al., 2005; Yen et al., 2012). For instance, Yen et al. (2012) proposed that skilled Chinese readers use simple statistical knowledge, such as the probability that a character appears at different ordinal positions within a word, to compensate for the lack of inter-word spaces in Chinese for word segmentation. Meanwhile, they also benefit from artificially introduced low-level visual cues to facilitate reading. When using alternating text colors to indicate word boundaries based on perceptual grouping (e.g., Treisman & Gelade, 1980), Chinese readers demonstrated facilitation in reading speed and in oculomotor indices (Perea & Wang, 2017; Zhou et al., 2018), especially among unskillful readers (Pan et al., 2021; Zhou et al., 2020). These studies indicate that Chinese readers can flexibly make use of visual cues, albeit unfamiliar, to ease the segmentation process, which in turn facilitates their lexical process and saccade generation. It is reasonable to expect that Chinese readers can also rely on text color for perceptual grouping of morphological hierarchical structure within words.

To summarize, the present study has been inspired by theoretical debates and recent research reviewed above. Our research question focused on the role of parafoveal character-grouping information and explored its effect on subsequent foveal lexical processing of the target word, utilizing the gaze-contingent paradigm. We orthogonally manipulated parafoveal structure and target word morphological hierarchical structure. Our predictions are straightforward and as follows. If Chinese readers acquire parafoveal grouping information and integrate it across saccades, we expect an influence of preview structure on FL. Although such an effect by itself is likely induced by perceptual grouping, the preview critically leads to a structure that is either consistent or inconsistent with the morphological hierarchical structure of the target word. According to the character-based saccade model which advocates late, foveal word segmentation (e.g., Liu et al., 2015), any structure information that has been perceived parafoveally should not influence foveal processing of the target word. On the other hand, according to saccade models which assume an influence of parafoveal word/morphological segmentation (e.g., Fan & Reilly, 2022; Yan et al., 2010), faster target word processing should be expected, when the preview and the target had the same structure than when they did not.

Method

Participants

Sixty-eight university students (mean age = 22.6 years old, *SD* = 2.7 years, 41 females) participated in the eye-tracking experiment. A separate group of 15 readers from the same population as the eye-tracking participants, who did not participate in the eye-tracking experiment, were recruited for target word predictability assessment. All participants were native to Chinese with normal or corrected-to-normal vision. Experimental procedures were approved by the Human Research Ethics Committee of the Department of Psychology, University of Macau. The participants were recruited through advertisement and provided their written informed consent prior to the experiment. They received credits or a small financial reward for their participation.

Material

We used a 2 (target word morphological hierarchical structure type) by 2 (preview type) within-subject and within-item experimental design. For the manipulation of target word morphological hierarchical structure, 88 pairs of three-character compound words were adopted from Luo et al. (2023). All of the compound words were legal words as defined by entries in the Modern Chinese Word Frequency Dictionary (Institute of Linguistics Studies, 1986) and differed with respect to their relative closeness between each two neighboring characters. In the [2 + 1] structure condition, the first two characters bounded tightly and formed into a meaningful unit, whereas in the [1 + 2] structure condition the last two characters did. The target words shared an identical initial character within each pair and were closely matched for word frequency, word predictability, the second and the third characters' character frequencies and visual complexities (all p–values > 0.1; Table 1). The preview contained three of the same character, 鏕, a legal traditional Chinese character of extreme low frequency. The character is the name of an ancient county and is not used in modern simplified Chinese. The two preview conditions consisted of the same string, but were presented with a [2 + 1] or [1 + 2] structure afforded by alternating text colors (Fig. 1). Using alternating text colors is necessary to delineate a pure low-level grouping without providing lexical information. The experiment focused on within-participant comparisons (consistent vs. inconsistent coloring) and not across individuals. Therefore, results are irrelevant to individual reading levels. The present study aimed at exploring whether parafoveal grouping could influence subsequent foveal processing of target words, instead of determining a facilitation or an inhibition over a baseline. In this sense, an identical preview condition would not be meaningful. Additionally, an identical preview condition, where characters are printed in black, is visually distinct from the preview conditions, where characters are printed in blue and red, making it difficult to serve as a baseline condition.

Words in each pair were embedded into an identical sentence frame, which was equally non-predictive for the two types of target words. For target word

Table 1 Target word properties

	Condition	
	2 + 1	1 + 2
Example	内陆河	内蒙古
Word meaning	Inland river	Inner Mongolia
Word frequency	0.57 (0.43)	0.57 (0.46)
Word predictability	0.0 (0.0)	0.0 (0.0)
2nd char. log frequency	2.72 (0.66)	2.70 (0.78)
2nd char. stroke	7.28 (3.11)	7.18 (3.37)
3rd char. log frequency	2.70 (0.68)	2.55 (0.73)
3rd char. stroke	7.76 (3.03)	8.08 (3.15)

Means and standard deviations in parentheses. Character and word frequency information was obtained from Institute of Linguistics Studies (1986)

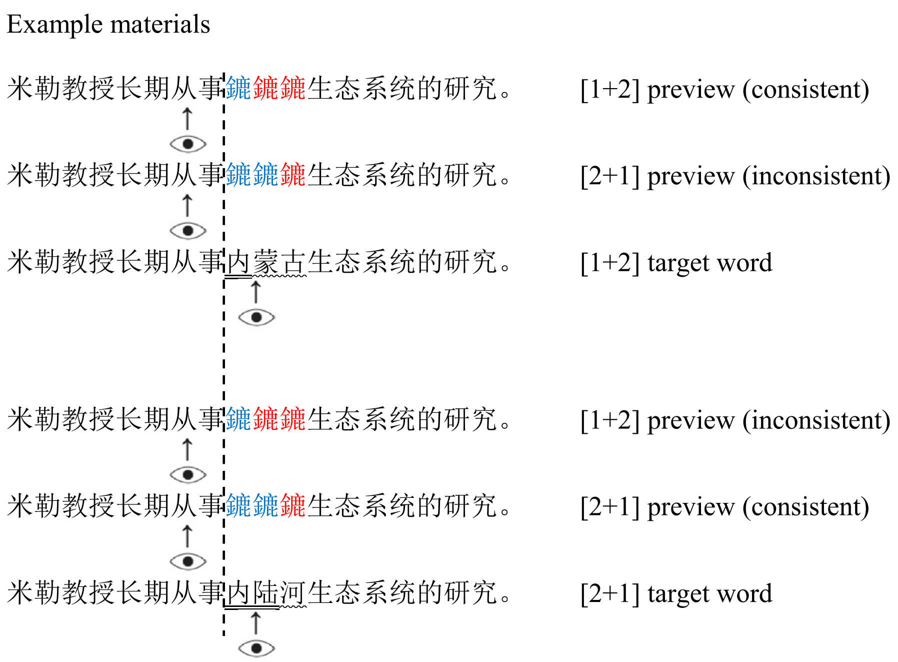

Fig. 1 Prior to a reader's gaze on the target word, one of the previews is presented at the location of the target word. The previews are immediately replaced by the target word once a reader's gaze crosses an invisible vertical boundary located between the pre-target and target words (as indexed by the vertical dashed line). The first constituents of the target words are double-underlined and the second ones are wave-underlined only for the purposed of illustration but not during the experiment. The sentence translates as: *Professor Miller has long been engaged in research on the ecosystem of inland river / Inner Mongolia*

predictability assessment, we presented to the norming participants all of the words prior to the target word in each sentence and asked them to predict the next word. Thus, any experimental effects were unlikely confounded by differences in predictability from prior context. The pre-target words, which were always two characters in length, and target words, were never among the first or the last three words in the sentences. Various sentence structures were employed across different items for natural reading. A different randomized order of sentence presentation was created for each participant.

Apparatus

The experiment was conducted in a dimly lit and quiet room. Data were collected using the Experiment Builder software (Version 2.3.38). The participants' eye movements were recorded with an EyeLink Desktop system running at a sampling rate of 1000 Hz. Each sentence was presented in a single horizontal line on a 24-inch BenQ ZOWIE XL2546K (resolution: 1,920 × 1,080 pixels; frame rate: 240 Hz) using the Song font. The participants were seated 70 cm from the monitor and were tested individually in a small chamber, with their heads positioned on a forehead-and-chin rest. Each character occupied a 48-by-48 pixel grid and subtended 1.1° of visual angle. Sentences were left-aligned and were printed in black on a grey background. All recordings and calibrations were done monocularly, based on the right eye, and viewing was binocular.

Procedure

Before the experiment started, the participants' gaze positions were calibrated with a 5-point grid (maximum errors < 0.5°). The tracking accuracy was checked prior to each sentence. The participant's gaze on the initial fixation-point initiated the presentation of the next sentence, with its first character occupying the fixation point. Otherwise, if the eye tracker did not detect the gaze around the fixation point, an additional calibration was performed. The participants were instructed to read the sentences silently for comprehension, then to fixate on a point in the lower-right corner of the monitor, and finally to press a keyboard button to signal completion of a trial. The gaze-contingent display-change technique was adopted to manipulate the parafoveal preview (see Fig. 1). The participants received 12 practice trials before reading the experimental sentences. We randomly selected 24 experimental sentences, each to be followed by an easy yes–no comprehension question, to encourage the participants' engagement with the reading task. The participants, on average, correctly answered 90.5% (SD = 6.0%) of the questions.

Data Analysis

Fixations were determined with an algorithm for saccade-detection (Engbert & Kliegl, 2003). The data were screened in the following steps. First, 230 (3.8%) trials were removed either due to tracker errors or participants' blinks, coughing or body movements during reading. Following trail exclusion standards from previous eye-tracking studies (e.g., Pan et al., 2016), trials with the target words' first-fixation durations (FFDs; duration of the first fixation on a word irrespective of the number of fixations) shorter than 60 ms or longer than 600 ms, or gaze durations (GDs; the cumulative duration of all fixations during the first-pass reading of the word) longer than 800 ms were removed (n = 300, 5.4%), because these very short or long fixations may reflect atypical viewing behaviors. Additionally, trials with regressions from the pre-target words were excluded because they may have reflected incomplete lexical processing (Briihl & Inhoff, 1995; n = 235, 4.2%). Additionally, 41 target words (0.7%) with extremely far launch sites over 6 characters were discarded because they may have reflected eye-tracker errors or untypical saccadic behaviors. Finally, trials in which display changes were triggered during fixations were excluded (n = 500, 8.2%). These data-screening procedures are standard and the data exclusion rate was comparable to previous studies. The general pattern of results did not depend on the choice of any particular criterion mentioned above. The remaining 4,576 observations (82% of all fixated words) were largely distributed evenly across the conditions and the participants.

It has been established that different fixation duration measures are associated with different temporal stages during processing. Reporting experimental effects in different fixation measures depicts the time course of the underlying cognitive processes. In particular, experimental effects that appear in FFD are considered to arise in an earlier temporal stage than those that show up only in GD when the target word is refixated on. In contrast, total reading time (TRT; sum of all fixations on a word including regressive fixations) is considered typically as a second-pass reading measure to indicate a late processing stage (Inhoff, 1984; Inhoff & Radach, 1998).

Estimates were based on linear mixed models (LMMs) using the *lme4* package (Version 1.1–35.5; Bates et al., 2015) and p-values were obtained using the *lmerTest* package (Version 3.1–3; Kuznetsova et al., 2017) in the R environment (Version 4.4.1). We specified sum contrasts for the fixed effects of target word morphological hierarchical structure and preview type. For the random-effects, we included subject- and item-related variance components for intercepts and random-slopes for the fixed-effects and started with full random-effects, and reported parsimonious LMMs for successful convergence (Matuschek et al., 2017). Dependent variables of viewing duration measures were log-transformed in the LMMs (Kliegl et al., 2010).

Results

Table 2 shows the fixation properties and Table 3 illustrates the model outputs. FL was measured in number of character spaces from the word beginning. There was a significant main effect of the preview on FL (Fig. 2A). Fixations landed further into the word when the preview provided a [2 + 1] grouping structure than a [1 + 2] structure, indicating that the preview structure information, afforded by color-based perceptual grouping, affected eye guidance. Moreover, fixation duration analyses indicated significant interactions in GD (Fig. 2B) and TRT (Fig. 2C). Processing time significantly decreased when the structures of the preview and the target were consistent than when they were inconsistent, showing a clear structural priming effect. Other effects were not statistically significant.

Table 2 Eye-movement measurements

	Condition			
	Preview [1 + 2] Target [1 + 2]	Preview [2 + 1] Target [1 + 2]	Preview [2 + 1] Target [2 + 1]	Preview [1 + 2] Target [2 + 1]
FL	0.94 (0.22)	0.97 (0.24)	0.96 (0.23)	0.89 (0.21)
FFD	283 (40)	287 (33)	287 (35)	283 (32)
GD	390 (69)	404 (72)	405 (80)	406 (75)
TRT	432 (85)	456 (93)	445 (94)	455 (108)

Means (and standard deviations in parentheses) for first-fixation location (FL) in character, first-fixation duration (FFD), gaze duration (GD) and total reading time (TRT) in millisecond. Values were computed across participant means

Table 3 Linear mixed model estimates

Fixed effect	First-fixation location				Gaze duration				Total reading time			
	Est	SE	t	p	Est	SE	t	p	Est	SE	t	p
(Intercept)	0.941	0.023	41.439	< 0.001	5.925	0.023	260.376	< 0.001	6.024	0.026	234.528	< 0.001
Target structure	−0.024	0.018	−1.374	0.173	0.020	0.016	1.193	0.237	−0.010	0.018	0.615	0.540
Preview structure	0.048	0.018	2.608	0.011	0.018	0.011	1.665	0.101	0.024	0.011	2.240	0.028
TS × PS	0.041	0.035	1.179	0.238	−0.050	0.020	−2.509	0.012	−0.074	0.020	−3.706	< 0.001

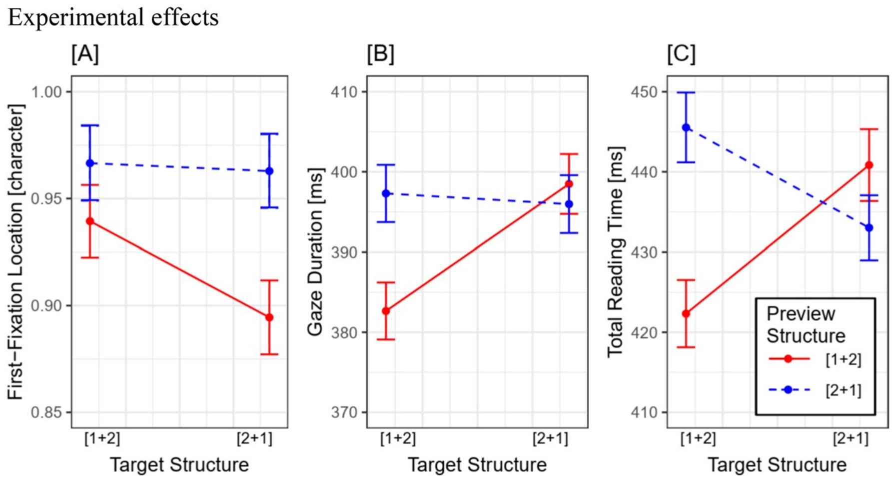

Fig. 2 Experimental effects of first-fixation location (left panel), gaze duration (middle panel) and total reading time (right panel). Error bars indicate one standard error. Plots were generated with the remef package (Version 0.6.10; Hohenstein & Kliegl, 2015) and the ggplot2 package (Version 2.1.0; Wickham, 2016)

Discussion

In the present study, we aimed to understand how parafoveal grouping information influences subsequent foveal lexical processing during Chinese sentence reading. The research topic is theoretically relevant to two interrelated issues, including the debates on the types and priority of parafoveal information processing and on early versus late views on Chinese word segmentation. Morphological processing and word segmentation are strongly connected because word segmentation in Chinese involves deciding to which word each morpheme (i.e., a character) belongs. We found that FL was influenced by the preview type, indicating that Chinese readers incorporate visual information for saccade generation. The effect of perceptual grouping on FL is not of our primary interest because it is by nature a perceptual effect and may not be able to tease apart different models of eye movements. Instead, it is our foremost objective to test whether target word processing differs when the prime is consistent/inconsistent with the target in structure. Any consistency effect should support the view that Chinese readers make use of parafoveal information for morphological hierarchical structure encoding. Interestingly, shorter target-word processing was observed when having previewed a consistent over an inconsistent structure. Below we discuss implications of the study on saccade generation and word segmentation in Chinese.

Although early studies have found no evidence for processing parafoveal morphological structure (Kambe, 2004; Lima, 1987), positive evidence has been obtained recently (Hyönä et al., 2018; Yan et al., 2014). Two language-specific possibilities have been proposed to explain the failures to find evidence for parafoveal morphological processing in some classical studies in English. Typically, affixes can be much shorter than root morphemes in Indo-European languages such as English, which may reduce the effect size of parafoveal morphological processing (Yan et al., 2014). In addition, phonological decoding in English may lag behind due to poor letter-to-phoneme correspondence, which possibly delays activation of high-level information. In the present study, we used pseudo-words as mask previews. Therefore, lexical information was unavailable until the target words were fixated on. In this case, the FL effect should be attributed to an influence of perceptual grouping. FL shifted further away from the word beginning for the [2 + 1] preview structure than the [1 + 2] preview structure, possibly suggesting that the readers always attended to the first constituent. The results are likely in favor of the dynamic saccade model over the character-based saccade model of Chinese reading. The character-based saccade model assumes that FL is only influenced by character-level properties, according to which no difference in FL is expected, because different previews had the same character.

Researchers attempted to improve reading by inserting artificial inter-word spaces in Chinese (Hsu & Huang, 2000a, 2000b; Liu et al., 1974), Japanese (Kajii et al., 2001; Sainio et al., 2007) and Thai (Kasisopa et al., 2013), but found little or null benefits. Insertion of spaces not only interferes with the reading of a highly familiar unspaced format (Kohsom & Gobet, 1997), but also pushes upcoming words more eccentric and decreases parafoveal processing efficiency (Perea et al., 2015). Indeed, a novel approach of presenting Chinese words with alternating text colors has been introduced, providing "a less intrusive visual cue than inserting interword spaces" (Perea & Wang, 2017, p. 1165). Studies have reported oculomotor benefits when words were presented with alternating text colors, in addition to processing costs in an alternating-color non-word condition, where characters from different words were printed in the same color (Pan et al., 2021, 2024; Zhou et al., 2018, 2020). Applying text color to legal words may have mixed lexical and perceptual processes for word segmentation. Using meaningless previews, we ruled out parafoveal lexical processing in the present study and illustrated a pure perceptual effect. Interestingly, the preview structure effect on FL in the present study appeared in an opposite direction to that observed by Luo et al. (2023), who found that FL shifted further away from the word beginning for [1 + 2] than [2 + 1] target words. Luo et al. (2023) did not use parafoveal masks and therefore, their readers were more likely to complete lexical access of the single-character first stem in the [1 + 2] condition than the double-character first stem in the [2 + 1] condition, leading to a longer saccade in the former condition. In the current study, however, target words were always masked and deprived of parafoveal access, causing the readers unlikely to target the second stem in the [1 + 2] condition. Instead, they may have incorporated preview structure and stem length, resulting in a right-shifted FL in the [2 + 1] preview condition.

Having previewed a consistent grouping structure over an inconsistent one resulted in more speeded target-word processing. Interestingly, we observed an earlier preview effect in GD for the [1 + 2] target-word structure condition than for the [2 + 1] condition. The preview effects were similar for both [1 + 2] and [2 + 1] target words in a late eye movement measure, TRT. The readers may detect the hierarchical structure earlier for the [1 + 2] than for the [2 + 1] target words, since the morphological boundary of the [1 + 2] target words is just after the first character. There are two possible explanations to account for the preview effect. The effect could be attributable to morphological priming. The underlying logic is that, a preview grouping structure is activated for subsequent foveal morphological decomposition of the target word and reduces its processing time. This explanation is supported by foveal morphological priming effects. For instance, Nagy et al. (1989) reported inflectional and derivational family frequency effects on word stem identification. McCutchen et al. (2009) demonstrated that children made faster responses to target words preceded by prime words shared the same morphemes with the targets. Liu and McBride-Chang (2014) demonstrated that reaction time to Chinese target words was reduced by preceding primes of the same type of morphological structure (a subordinate or a coordinative structure). Results from these studies, besides the present work, jointly support a view that morphological relations of words are represented in readers' mental lexicon (Zhou & Marslen-Wilson, 1995).

Alternatively, previewing a correct grouping structure may have guided readers' gaze to a preferred viewing location. During sentence reading, readers select the word center, where word identification is known optimized (e.g., O'Regan et al., 1984), as their intended FL. If readers initially land their fixations further away from this preferred viewing location, they are more likely to perform "corrective" saccades, which are costly in terms of reading efficiency, leading to a longer processing time on the word (Nuthmann, et al., 2005, 2007; Sainio et al., 2007; Vitu et al., 2001). Considering these basic patterns of eye movements, when our readers fixated initially at an unintended location as misguided by the inconsistent previews, their processing time increased. Importantly, the two possible explanations are not contradictory and both indicate an influence of parafoveal structure. Overall, our results suggest that parafoveal grouping structure influences subsequent foveal lexical access. The fixation duration results are at odds with the processing-based saccade generation model in Chinese, which advocates foveal word segmentation and predicts no influence of preview structure on target word processing. In contrast, the present results are more compatible with the parafoveal segmentation view (e.g., Yan et al., 2010).

Suggestions for future research

First, bigram frequency can be naturally low at the morphological boundary in different orthographies. Previous eye tracking studies have ruled out the confound of bigram frequency in morphological effects (e.g., Bertram et al., 2004; Yan et al., 2014). Considering that Chinese word boundary segmentation can be achieved via frequency information (e.g., Yen et al., 2012), the influence of bigram frequency deserves further investigation. Second, prefixed words can potentially provide valuable evidence for morphological processing. However, parafoveal morphological effects have been shown weaker for prefixed words than for suffixed words (Dann et al., 2021). Unfortunately, there is only a very small number of prefixed words in Chinese. Future studies can explore the influence of prefixes in other orthographies.

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Data availability The datasets generated during and/or analyzed during the current study are available in the OSF repository. https://doi.org/10.17605/OSF.IO/3Q8C5

Declarations

Conflict of interest The authors have no conflict of interests related to this study.

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