Morphological structure influences saccade generation in Chinese reading

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Abstract
Recent studies have demonstrated that saccadic programming in reading is not only determined by low-level visual factors. High-level morphological effects on saccade have been shown in two morphologically rich languages. In the present study, we examined the underlying mechanism of such morphological influences by comparing the processes of reading three-character Chinese compound words that differ in their structures in terms of morphological decomposition. Consistent with earlier reports, our results showed an effect of morphological structure on saccade. The readers' first-fixation location shifted further away from the beginning of the word, when the last two characters were more morphologically bounded and thus formed a [1 + 2] structure, than when the first two characters were more bounded (i.e., a [2 + 1] structure). The results are not accountable by a processing difficulty hypothesis, which proposes that saccade amplitude is determined by morphological complexity; rather, they suggest that Chinese readers parafoveally decompose a word and spontaneously target its longer stem, thus reflecting parafoveal access to words' stems.

Keywords Eye tracking · Saccade generation · Morphological decomposition · Chinese

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Introduction

Reading involves processing of different types of words, including not only monomorphemic simple words, but also morphologically complex words (inflected, derived, and compound). These morphologically complex words can be decomposed into smaller meaningful units, morphemes. The mental representation and cognitive process of morphologically complex words have been investigated extensively over the past few decades. Studies of morphological processing so far have focused almost exclusively on foveal processing when a word is fixated upon. However, in any writing system, words seldom appear in isolation. Instead, they usually appear in a flow of continuously written text, that is, sentences. In addition, lexical processing starts even before a word is fixated on; this is known as parafoveal processing. For instance, studies of perceptual span in English reading have shown that useful information can be extracted from an area of 20 letters around a skilled reader's current fixation (McConkie & Rayner, 1975). The perceptual span, in contrast, covers up to six characters in Chinese reading (Inhoff & Liu, 1998; Yan et al., 2015). One topic that has received much attention in psycholinguistic research is whether high-level information in the parafovea can influence eye-movement control in reading. In general, researchers have come to a conclusion that saccade generation is driven primarily by low-level visual factors in the parafovea. However, in the present study, we documented an early, parafoveal analysis of morphological structure to influence saccade generation during natural reading of Chinese sentences.

Oculomotor control, which dominates fixational and saccadic eye movements to ensure efficient extraction of visual and linguistic information from printed text, includes two largely independent decisions: when to move the eyes and where to send them (e.g., Brysbaert et al., 2005; Vainio et al., 2009). There has been considerable debate on the depth of parafoveal processing, that is, the types of information that can be obtained from words before they are fixated on, to influence the aforementioned "where" and "when" decisions. Most classic experimental evidence favors a purely low-level view of parafoveal processing, whereas this notion has been challenged by a growing body of evidence indicating that some high-level information can jointly influence the two decisions of oculomotor control in reading. Below we review evidence for and against the purely low-level view. Rayner (1979) reported that fixation location peaked close to the word center and formed a Gaussian distribution, suggesting that low-level visual information, such as word length, primarily determines the where-decision as reflected by the first-fixation location (FL; where eye gaze initially lands within a word). Arguably, saccades aim at the center of the next word which is going to be fixated on, because word processing is known to be optimal at this location (McConkie et al., 1989; O'Regan & Lévy-Schoen, 1987). Critically, readers can plan for word-based saccades towards this intended landing position because low spatial-frequency information (i.e., inter-word spaces) in the parafoveal or peripheral vision provides an explicit and distinct cue to determine where the next word is located. In addition, some studies have shown that visual properties other than inter-word spaces can also influence saccade targeting. For example, words with irregular beginnings were found to receive fixations closer to the word beginning than those with regular beginnings (Hyönä, 1995; Radach et al., 2004). Although there was a small effect of word predictability on FL, this effect could have been due to mislocated fixations (Rayner et al., 2001; see Rayner et al., 2006 and Vainio et al., 2009, for null effects of predictability on FL). Finally, earlier research endeavoring to establish an influence of morphological structure on saccade generation in French (Beauvillain, 1996), Finnish (Hyönä & Pollatsek, 1998), Hebrew (Deutsch & Rayner, 1999) and English (Inhoff et al., 1996) ended in failure, with FL not found to be influenced by morphological structure in any of these languages. As a consequence, the low-level eye guidance view has been commonly accepted. Such a mechanism of eye-movement guidance by visual factors has been among the core principles of the serial attention shift models of reading, such as the E-Z Reader (Reichle et al., 1998).

Relatedly, concerning the when-decision of oculomotor control, research on parafoveal lexical processing traditionally reported no evidence for high-level influences on fixation duration, suggesting that high-level information such as semantic knowledge may not be involved from parafoveal words. For instance, parafoveal phonological effects have been reported consistently (e.g., Pollatsek et al., 1992; Miellet, & Sparrow, 2004). However, there has been no evidence for parafoveal semantic effects for decades (e.g., Inhoff, 1982; Inhoff & Rayner, 1980; Rayner et al., 1986). Experimental results from studies reviewed above seemingly suggest that parafoveal processing is restricted to low-level features.

However, this notion has been challenged. As a proof of principle, Yan et al. (2009) documented a parafoveal semantic effect on fixation duration using simple (i.e., pictographical and indicative) Chinese characters with orthographic forms strongly associated with the concepts that they represent. Later studies have extended the effect to more representative cases of compound (phonogram) characters in Chinese (e.g., Yan et al., 2012; Yang et al., 2012), and to other writing systems such as German (Hohenstein & Kliegl, 2014) and Korean (Kim et al., 2012; Yan et al., 2019). Arguably, certain language-specific properties of these writing systems, such as fast and direct semantic activation in Chinese (Hoosain, 1991; Reilly & Radach, 2012), and the highly regular letter-to-phoneme correspondences in German and Korean, may have promoted early access to high-level knowledge. Inspired by positive evidence for parafoveal semantic effects in the when-decision, the effect of morphological structure on saccade generation has been re-explored recently, also taking advantage of language-specific features in some morphologically rich writing systems. Both Uighur and Finnish are scripts of this type. Across two experiments respectively employing a statistical control approach and an experimental control approach, Yan et al. (2014) reported that FL shifted towards the word beginning for words with more suffixes (Exp.1), and for double-suffixed words over monomorphemic words (Exp.2). These critical findings were replicated and extended to another agglutinative language, Finnish (Hyönä et al., 2018). Results across the two studies consistently showed effects of pre-lexical parafoveal morphological decomposition on saccadic generation during the where-decision of eye-movement control.

However, the underlying nature of such parafoveal morphological analysis cannot be determined based on existing results. Yan et al. (2014) hypothesized two possible mechanisms. It is possible that readers' eyes are attracted to the root morphemes, where more useful semantic information can be obtained, in contrast to the suffixes, which are mainly for grammatical purposes. Such an influence of relative informativeness within a word was hypothesized initially by Underwood et al. (1990), who observed that fixations landed further into complex words when their second halves provided decisive information (e.g., superstore), in contrast to words with redundant endings (e.g., engagement). The critical finding reported by Underwood et al. (1990) was not replicated in later studies (e.g., Hyönä, 1995; Rayner & Morris, 1992). An alternative explanation of the morphological complexity effect on FL rests on saccade amplitude serving as an index of processing difficulty (Hohenstein et al., 2017; Pan et al., 2021); readers send their eye gazes closer to the word beginning when parafoveal processing load increases. When readers encounter suffixed words in contrast to mono-morphemic words in the parafovea, they are assumed to go through a more complex processing of morphological decomposition in which the morphological boundaries are determined. These two possible mechanisms discussed above are similar in the sense that both involve parafoveal morphological decomposition and they have the same prediction when comparing mono-morphemic and suffixed words. They differ, however, when comparing double-stemmed compound words with their morphological boundaries located in different positions. No difference in FL should be expected according to the processing load mechanism. A similar manipulation was first used by Hyönä and Pollatsek (1998). Using two-morpheme Finnish compound words as targets, they varied the lengths of each component while keeping the word length constant and found no effect of morpheme length on FL. We consider that two possible factors may have blurred the effect. First, words are typically long in Finnish. It is therefore possible that the target words were too eccentric, weakening parafoveal morphological processing. We argue that Chinese offers a better chance to observe the difference because words are typically shorter. Second, the difference in morphological boundaries in the two conditions may not have been large enough for the difference in FL to appear reliably.

In addition to resolving the uncertainty about the mechanism underlying a morphological structure effect on saccade generation, the present study also sheds some light on saccade generation in Chinese. Readers of alphabetic scripts with spaces between words are generally assumed to generate word-based saccades towards the word center (McConkie et al., 1989). Saccade generation in Chinese is theoretically important, because the lack of inter-word spaces raises a fundamental challenge to current computational models of eye movements in reading, which have been developed based on spaced alphabetic scripts. Indeed, there has been a considerable debate on the saccade generation mechanism in Chinese. On the one hand, Yan et al. (2010) hypothesized that Chinese readers dynamically switch between two possible saccade targets. Readers target the center of the upcoming word if they have segmented it successfully from a string of characters during prior fixations. Otherwise, the first character of the upcoming word is chosen as the saccade-target instead. As an alternative model, Liu et al. (2015) proposed that Chinese readers process as many characters as possible during each fixation and program their saccades to the next unprocessed character. Both theories can explain foveal influences on saccade generation. However, due to its purely character-based saccade mechanism and its denial of any influence from word-boundary knowledge, the processing-based saccade theory is unlikely to account for any effects of morphological structure on FL.

In the present study, we tested native Chinese readers' morphological processing. Chinese is fundamentally different from alphabetic scripts such as English and Finnish. The basic writing units, Chinese characters, are disconnected square-shaped objects. They occupy the same extent of space but vary in their visual complexity. Although a single character by itself often represents more than one morpheme, it usually conveys one specific morphemic meaning when combined with other characters to form a word/phrase. Therefore, it is essentially critical for Chinese readers to decompose words and access appropriate morphemic meanings quickly and accurately. Pan et al. (2022) reported reduced fixation duration on target words, when they were primed by parafoveal preview words containing the same morpho-semantic knowledge, over different-morpheme prime words. These results are evidence for early, parafoveal morphological decomposition and disambiguation processes on the when-decision indexed by fixation duration. However, there is still a need to establish whether there is a morphological effect on the when-decision in Chinese sentence reading.

Incorporating the research reviewed above, the present study aimed at testing the influence of the morphological structure of Chinese words on the saccade generation of eye movement in reading reflected by FL. Previous studies of morphological decomposition have almost non-exclusively focused on foveal processing, which may not hint at the earliest processing stage as long as natural sentence reading is concerned. The only two existing demonstrations of the morphological structure effect on saccade generation, however, are rather specific to morphologically rich languages and the underlying mechanism of the effect is not exclusive. Therefore, it is theoretically important to extend the effect to a different language with a new experimental manipulation. In the present study, we used two groups of three-character Chinese words with identical initial characters while varying their structures in terms of morphological decomposition. The three-character form is a productive structure type in Chinese. According to the Modern Chinese Dictionary (5th edition, Institute of Linguistics, Chinese Academy of Social Sciences, 2005), about 8.7% of the collected items are identified as having the three-character form. Nearly 80% of them have a nominal use to denote entities or name events. Except for some rare exceptions of mono-morphemic multi-character words in Chinese, such as loan words, most three-character words are decomposable. There are two main types of decomposable three-character words, [2 + 1] and [1 + 2], which differ in the relative closeness of each two neighboring characters (Wang, 2008). While the first and the second characters are bounded more tightly than the second and the third in the [2 + 1] structure (e.g., "北极圈" (*Arctic Circle*) = "北极" (*Arctic*) + "圈" (*Circle*)), it is the opposite in the [1 + 2] structure (e.g., "北半球" (*the Northern Hemisphere*) = "北" (*north*) + "半球" (*hemisphere*)). Our prediction was clear: Any difference in FL should be considered supportive of the morpheme-attraction hypothesis. Specifically, because previous studies have shown that single-character (and single-morpheme) words are likely to be recognized parafoveally and thus skipped, we expected our readers should have further FLs when the structure was

[1+2]. In contrast, the processing load hypothesis would not predict any difference in FL between the two conditions when relevant linguistic properties are matched.

Method

Participants

Sixty university students (mean age = 21.0 years old, *SD* = 2.2 years, 40 females) participated in the eye-tracking experiment (excluding four participants who had reading comprehension rates lower than 75%). An independent group of 15 readers, who did not participate in the eye tracking experiment, rated the target word predictability. All participants were native to Chinese with normal or corrected-to-normal vision. The experimental procedures were approved by the Human Research Ethics Committee of the Department of Psychology, University of Macau. The participants gave their written informed consent prior to the experiment, which conformed to the tenets of the Declaration of Helsinki.

Material

We selected 88 pairs of three-character compounds, with an identical initial character for each pair, for the experimental manipulation of structure in terms of morphological decomposition. We carefully matched the target words for word frequency (Beijing Language Institute Publisher, 1986), second character frequency and visual complexity (as indexed by number of strokes) and third character frequency and visual complexity (all *p*-values > 0.1; Table 1). For each of the pairs, we constructed a sentence frame identical to the pre-target words (see Fig. 1). These

Table 1 Target word properties

	Condition	
	2+1	1+2
Example	北极圈	北半球
Word meaning	Arctic Circle	Northern Hemisphere
Word frequency	0.57 (0.43)	0.57 (0.46)
Word predictability	0.0 (0.0)	0.0 (0.0)
1st Char. frequency	2.92 (0.53)	2.92 (0.53)
1st Char. stroke	6.85 (3.10)	6.85 (3.10)
2nd Char. frequency	2.72 (0.66)	2.70 (0.78)
2nd Char. stroke	7.28 (3.11)	7.18 (3.37)
3rd Char. frequency	2.70 (0.68)	2.55 (0.73)
3rd Char. stroke	7.76 (3.03)	8.08 (3.15)

Means values and standard deviations in parentheses. Frequency values are in log-transformed occurrence per million and predictability values are correct guesses in percent

总统在会上表示支持北极圈石油开采计划。 (2+1 condition)
总统在会上表示支持北半球石油开采计划。 (1+2 condition)

Fig. 1 An example of experimental materials. The first constituents of the compound target words are double-underlined and the second ones are single-underlined only for the purposed of illustration but not during the experiment. The target sentence translates as: *At the meeting, the president expressed support for the* ***Arctic Circle / Northern Hemisphere*** *oil exploration plan.*

pre-target words were always two characters long, and the target preceding contexts were non-predictive for different types of previews in order to minimize top-down processing. As confirmed by a cloze test, the target words were equally unpredictable (p-value > 0.1). The post-target sentence endings were allowed to vary between the conditions for fluent continuation. The pre-target and target words were never among the first or the last three words in the sentences. We adopted a within-subject and within-item design with the experimental conditions counterbalanced across participants. We used a different randomized order of sentence presentation for each participant.

Apparatus

The participants' eye-movements were recorded with an Eyelink Desktop system running at 1000 Hz. Each sentence was presented in a single line on a 24-inch Dell E2416H monitor (resolution: 1920 × 1080 pixels; frame rate: 60 Hz) using the Song font. The subjects were seated comfortably with their heads placed on a chin-and-forehead rest at a distance of 70 cm from the monitor. Each character subtended 0.8 degrees of visual angle. All recordings and calibrations were performed monocularly based on the subjects' right eyes and viewing was binocular.

Procedure

Before the experiment, the participants' gaze-positions were calibrated with a standard 5-point grid (error < 0.5°). After validation of the calibration accuracy, a fixation-target appeared on the left side of the monitor for a drift check. If the eye tracker identified a participant's gaze on the fixation-target, the fixation-target disappeared and a sentence appeared, with the center of the first character in the sentence at the fixation-target position. Otherwise, failure to detect a participant's gaze on the initial fixation-target initiated a re-calibration.

The participants were instructed to read the sentences silently for comprehension, then fixate on a dot in the lower-right corner of the monitor, and finally press a keyboard button to signal trial completion. Twenty-four sentences were followed by an easy yes–no comprehension question to ensure the participants' engagement with the reading task. On average they answered 88% of the questions correctly ($SD = 5\%$).

Data analysis

Fixations were determined with an algorithm for saccade-detection (Engbert & Kliegl, 2003). Trials containing missing samples or participants' blinks or coughs during sentence reading were excluded from the analyses (n = 171, 3.2% of all sentences). Target words with first-fixation durations (FFDs; duration of the first fixation on a word, irrespective of total number of fixations) shorter than 60 ms or longer than 600 ms and gaze durations (GDs; the sum of all fixation durations during the first-pass reading of a word) longer than 1000 ms were removed (n = 77, 1.7%). Additionally, 204 target words (4.4%) with extremely far launch sites over 6 characters were discarded because they may have reflected eye-tracker errors or untypical saccadic behaviors. Together we kept 4349 observations for the data analyses reported below.

Estimates are based on linear mixed models (LMMs) using the lme4 package (Version 1.1–23; Bates et al., 2015) and the *lmerTest* package (Version 3.1–2; Kuznetsova et al., 2017) in the R environment. There were four fixed-effects: the manipulated factor of the morphological structure, and three covariates of launch site, visual complexity and log-transformed word frequency. Generally, launch site, the distance between the location of the last fixation and the left border of the currently fixated word, cannot be controlled prior to the experiment and in previous studies has shown robust influences on eye-movement parameters. Although word frequency and visual complexity were matched between the conditions, there were variabilities across items. The covariates were centered before entering the LMM. It has been well documented that these additional variables influence eye movements in reading and thus were included in this study for statistical control, although their significance was not a focus of the study. For the random-effects, we included subject- and item-related variance components for the intercepts and random-slopes for the fixed-effects and started with full random-effects. Following a standard parsimonious LMMs selection procedure (Matuschek et al., 2017), we dropped correlation parameters and small variance parameters for successful model convergence.

Results

FL was measured as the number of characters from the word beginning. The final model is reported in Table 2. Figure 2 shows the four significant main effects. FLs decreased with increasing launch site ($b = -0.495$, $SE = 0.020$, $t = -24.206$, $p < 0.001$) and with target word visual complexity ($b = -0.006$, $SE = 0.002$, $t = -2.641$, $p = 0.009$). The launch effect on FL is a canonical oculomotor effect and

Table 2 Linear mixed model estimates

Fixed effect	First-fixation location				Gaze duration			
	Est	SE	t	*p*	Est	SE	t	*p*
(Intercept)	1.201	0.063	18.954	< 0.001	5.748	0.035	164.959	< 0.001
Cond	− 0.050	0.020	− 2.571	0.012	0.002	0.013	0.189	0.850
LS	− 0.495	0.020	− 24.206	< 0.001	0.093	0.013	7.004	< 0.001
LF	− 0.007	0.028	− 0.263	0.793	-0.049	0.020	-2.463	0.014
NS	− 0.006	0.002	− 2.641	0.009	0.005	0.002	2.625	0.009
Cond × LS	− 0.001	0.016	− 0.060	0.952	0.005	0.012	0.437	0.662
Cond × LF	0.068	0.052	1.313	0.191	-0.016	0.036	-0.457	0.648
LS × LF	− 0.036	0.021	− 1.732	0.084	0.028	0.015	1.875	0.062
Cond × NS	0.003	0.004	0.866	0.389	-0.005	0.002	-2.115	0.035
LS × NS	0.003	0.002	1.690	0.093	0.001	0.001	0.661	0.510
LF × NS	− 0.001	0.005	− 0.239	0.812	0.003	0.004	0.841	0.400
Cond × LS × LF	0.061	0.040	1.499	0.135	− 0.023	0.029	− 0.792	0.429
Cond × LS × NS	− 0.003	0.003	− 1.016	0.310	0.002	0.002	0.749	0.454
Cond × LF × NS	− 0.018	0.010	− 1.834	0.069	0.010	0.007	1.431	0.153
LS × LF × NS	0.005	0.004	1.338	0.182	0.000	0.003	0.157	0.875
Cond × LS × LF × NS	0.010	0.008	1.359	0.175	− 0.002	0.005	− 0.377	0.707

Cond = condition, LS = launch site, LF = log frequency, NS = number of strokes

has been reported consistently in previous research across different writing systems. The visual complexity effect on FL in Chinese has also been reported (e.g., Pan et al., 2021). More relevant to the theoretical interest of the present study, FL differed as a function of morphological structure ($b = -0.050$, $SE = 0.020$, $t = -2.571$, $p = 0.012$) (Fig. 2).

Fixation duration analyses indicated that GD increased significantly with increasing launch site ($b = 0.093$, $SE = 0.013$, $t = 7.004$, $p < 0.001$) and visual complexity ($b = 0.005$, $SE = 0.002$, $t = 2.625$, $p = 0.009$), and with decreasing word frequency ($b = -0.005$, $SE = 0.002$, $t = -2.463$, $p = 0.014$). These effects have been commonly reported in previous studies, reflecting visual, oculomotor and lexical influences. Their existence indicates that the data are reliable. Although the main effect of morphological structure was not significant, there was an interaction with visual complexity, indicating a weaker morphological structure effect for more complex words ($b = -0.005$, $SE = 0.002$, $t = -2.115$, $p = 0.035$). Obviously, readers are less likely to obtain high-level morphological information when more visual decoding is required.

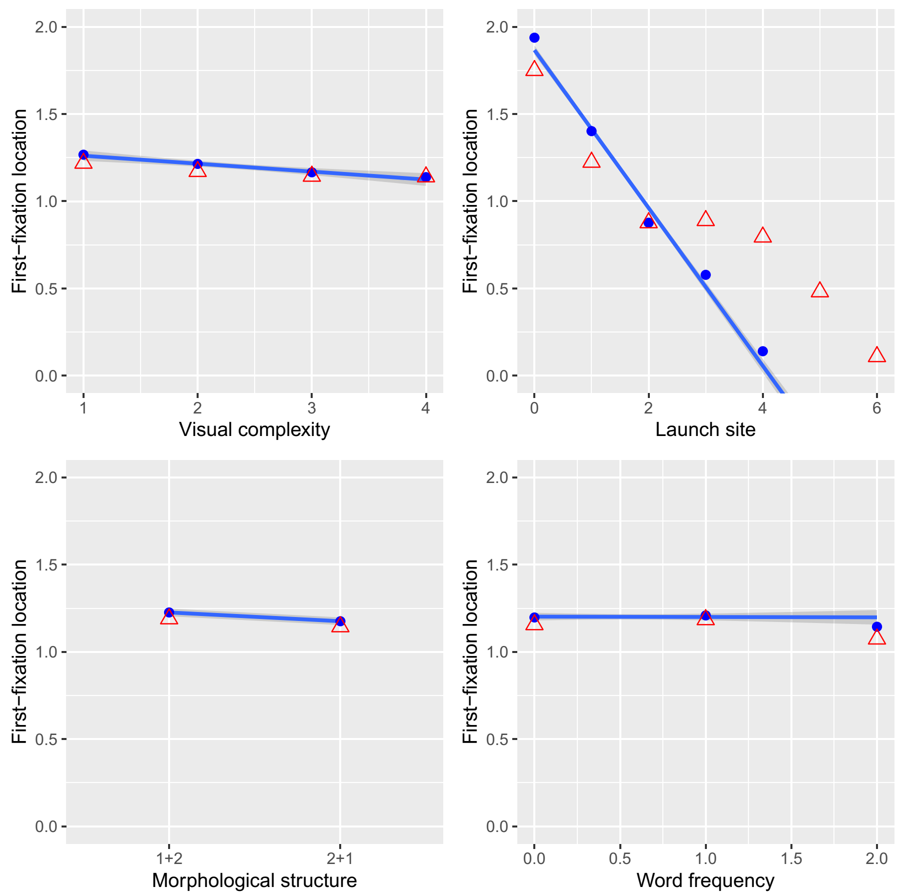

Fig. 2 Main effects of visual complexity (top left), launch site (top right), morphological structure (bottom left) and word frequency (bottom right) on first-fixation location. Lines, points, and shaded 95% confidence intervals are partial effects based on linear mixed model (estimates after statistical control of other variables in the model and removal of between-participant and between-sentence random effects), using the remef package (Version 0.6.10; Hohenstein & Kliegl, 2015). Triangles are observed means (rounded to the next integer on *x*-axis). Graphics were generated using the ggplot2 package (Version 2.0.0; Wickham, 2009)

Discussion

The main purpose of the present study was to understand the role that morphological decomposition plays in the where-decision of eye-movement control. Previous research on morphological processing has mostly utilized a foveal priming paradigm during isolated word recognition and was not able to tap early, parafoveal processing during online sentence reading. Our results are the first to show that FL can be influenced by morphological structure during Chinese reading: FL shifted further away from the beginning of a three-character double-stemmed compound when its structure was [1 + 2] than when it was [2 + 1]. As such, the results echo a growing body of experimental evidence for parafoveal morphological processing and clearly suggest that early cognitive processes of high-level information, morphological structure, can influence saccade generation. The non-significant effect of word frequency on FL mirrors a recent report by Pan et al. (2021), showing no evidence of an influence of word frequency on saccade generation in Chinese. Since the experimental conditions were controlled for lexical difficulty, the morphological structure effect on FL is unlikely caused by processing difficulty but rather by a spontaneous decision of eye guidance at a very early stage of processing.

Eye-tracking investigations of morphological processing have focused mostly on how morphological decomposition influences the when-decision of eye-movement control in reading. For instance, comparing compound words and monomorphemic words, Drieghe et al. (2010) reported a greater disruption for the monomorphemic word than for the compound word when a reader has an incorrect parafoveal preview of the second part of the word. Arguably, due to morphological decomposition of compound words, readers prioritized the first constituents and thus the second constituents were processed in a shallower manner. In a later study focusing on Korean, Kim et al. (2012) found that previewing correct case markers facilitated lexical processing, reducing fixation durations on target words. Hyönä et al. (2021) demonstrated that previewing Finnish target words' stems facilitated their subsequent foveal processing. In two experiments, Pan et al. (2022) investigated morphological decomposition in Chinese and Korean by manipulating the morpho-semantic relationship between preview and target words. They found a larger priming effect when the homographic previews contained the same morphemic meaning than when they did not. Their results suggest that preview words need to be morphologically decomposed in an early, parafoveal processing stage for semantic access. These findings above jointly suggest that morphological decomposition can occur before lexical identification (Taft, 1994).

In contrast, less is known about the morphological effect on the where-decision of eye-movement control in reading. The morphological effect is theoretically relevant to one fundamental debate on whether or not variables beyond low-level visual information can influence where the eyes initially fixate on within a word (see Rayner, 2009; for a review). In general, evidence for processing of high-level linguistic information from parafoveal words that are not yet fixated on speaks against serial models and favors parallel models of reading. Classic research on eye-movement control has reached a widely accepted conclusion that, based on word length which can be calculated from spatial frequency information in the parafoveal and peripheral vision, readers select the center of the next word as the intended landing position and execute a saccade towards it for optimal lexical processing (McConkie et al., 1989). In addition, early studies have failed to find evidence for processing of morphological structure of parafoveal words (Kambe, 2004; Lima, 1987). Recently, challenging the view of eye-movement guidance by purely visual factors in reading, positive evidence in support of parallel models has been reported in Uighur (Yan et al., 2014) and Finnish (Hyönä et al., 2018). However, the underlying mechanism of the morphological effect on saccade generation was unclear: Readers could either aim at the informative root morphemes, or reduce their saccade amplitude due to an increase of parafoveal processing load. The motivation for the present study was, therefore, to tease apart the two possible explanations: Under our current manipulation of morphological boundary location, the two experimental conditions were matched for processing load. As such, the observed difference in FL ruled out the parafoveal processing load account.

Comparing the present study to earlier works in Uighur (Yan et al., 2014) and Finnish (Hyönä et al., 2018), it is important to notice that we did not adopt their experimental manipulation of morphological complexity. Rather, we manipulated the target word's structure in terms of morphological decomposition. This is because a manipulation of morphological complexity would not have enabled us to tease apart the two possible mechanisms discussed above. In addition, practically, the Chinese language has a very limited number of suffixes, making a manipulation of morphological complexity unfeasible. As expected, the results showed that readers sent their fixations further into the target word when encountering target words with a [1+2] morphological structure than those with a [2+1] structure, as if the readers' gazes were attracted to the longer constituent. In Chinese, single-characters are often highly frequent and are likely parafoveally accessed and thus skipped (e.g., Yan et al., 2010). In this case, the remaining two-character constituent provides more novel information during the foveal processing of the target word. As such, the present result agrees in principle with previous findings from Uighur and Finnish, jointly implying that informativeness within a word may influence the where-decision of eye-movement control.

Additionally, the present results have an implication for saccade target selection in Chinese reading. Different models of saccade generation in Chinese have been proposed. On the one hand, the dynamical saccade-target model hypothesized that contingent on the successfulness of parafoveal word segmentation, Chinese readers target either the center of the upcoming word, or the first character of it (Yan et al., 2010). In contrast, the processing-based model assumes only character-level influences on saccade generation (Liu et al., 2015). Although some common predictions can be made from the two models, such as dynamic adjustment of saccade amplitude by foveal processing load, the latter is unlikely to account for any parafoveal effects of morphological structure on saccade generation, because of its purely character-based saccade mechanism. As such, the present results are more compatible with the dynamical saccade theory.

The present study is also related to research regarding morphological awareness, an ability to understand and manipulate morphemes. Studies of English children's morphological awareness typically tested inflectional and derivational morphemes. However, due to uncommon uses of these affixes and a high degree of morpho-semantic ambiguity in Chinese, studies of morphological awareness in Chinese have focused mainly on morphological disambiguation using a lexical compounding task (Ku & Anderson, 2003; McBride-Chang et al., 2003). Indeed, the quick development of an ability to discriminate among multiple morpho-semantic candidates and to select the appropriate one can promote children's acquisition of new words, leading to a rapid growth in reading comprehension (e.g., McBride-Chang et al., 2008). More recently, there have been some studies testing morphological awareness in the form of decomposition. For instance, Zhang et al. (2021) demonstrated that morphological decomposition, along with other morphological awareness tasks, had a significant direct contribution to second-language Chinese learners' Chinese reading comprehension. Using a morphological judgment task in which children were to judge whether the first morphemes of two orally presented words had the same meaning, Li et al. (2017) reported they were able to do this more effectively when the morphemes were identical than when they were synonymous. They concluded that shared phonological and orthographic forms facilitate morphological decomposition when the two morphemes share the same meaning.

The eye-movement results when the participants read three-character compounds also advance our understanding of the processing nature of Chinese, a language system of "one character as one morpheme". The linguistic hierarchy of Chinese is controversial, particularly regarding the distinction between a word and a phrase if both can be decomposed further into smaller units with meanings. As for the three-character compounds focused on in this study, although their constituent characters are used stably as a whole and do not allow grammatical markers inserted in between like typical "words", some linguists suggest that the [2+1] structure is internally connected more compactly than the [1+2] structure from the prosody-syntax perspective (see Wang, 2008 for a review). But such a proposal could not explain our saccadic findings. In fact, a further first-fixation location on the [1+2] target compounds due to the skipping of the first character is in accordance with earlier results of phrasal-level processing in Chinese (e.g., Luo et al., 2013).

Conclusion

In sum, the present study tested early, parafoveal processing of morphology in Chinese. Together with earlier findings, there is consistent evidence across different writing systems (Roman alphabets: Finnish; Arabic alphabets: Uighur; and logography: Chinese) that saccade target selection in eye-movement control can be influenced by morphological structure. We conclude that morphological decomposition is a basic stage for saccade-target selection. It is of great theoretical importance for future studies to explore developmental changes in Chinese readers' awareness of morphological structure.

Appendix

All the target items used in the experiment.

	2+1	1+2		2+1	1+2		2+1	1+2
1	白血病	白细胞	31	国务卿	国宾馆	61	手术室	手风琴
2	北极星	北美洲	32	海岸线	海平面	62	书生气	书呆子
3	北极圈	北半球	33	黑手党	黑社会	63	双氧水	双眼皮
4	变速箱	变戏法	34	红外线	红十字	64	私生子	私生活
5	菜籽油	菜篮子	35	红眼病	红卫兵	65	死亡率	死心眼
6	超短裙	超负荷	36	灰白色	灰姑娘	66	糖尿病	糖葫芦

	2+1	1+2		2+1	1+2		2+1	1+2
7	成员国	成问题	37	急诊室	急行军	67	铁甲舰	铁蚕豆
8	打字机	打下手	38	集中营	集大成	68	铁道部	铁饭碗
9	打谷场	打头阵	39	金钱豹	金钥匙	69	团体操	团中央
10	大气层	大动脉	40	聚光灯	聚乙烯	70	拖拉机	拖后腿
11	大头针	大拇指	41	军功章	军大衣	71	外交官	外祖母
12	大奖赛	大提琴	42	开阔地	开眼界	72	外国人	外祖父
13	单人床	单方面	43	开幕式	开玩笑	73	无产者	无党派
14	单身汉	单相思	44	看守所	看热闹	74	无线电	无意识
15	得益于	得人心	45	拉丁文	拉关系	75	心脏病	心血管
16	电影院	电冰箱	46	老龄化	老丈人	76	亚麻布	亚热带
17	电线杆	电风扇	47	脑膜炎	脑血栓	77	眼镜蛇	眼睫毛
18	动力学	动真格	48	内陆河	内蒙古	78	英雄榜	英联邦
19	多元化	多一半	49	农业局	农作物	79	有心人	有意思
20	多样化	多方位	50	偏执狂	偏心眼	80	有效期	有时候
21	发烧友	发脾气	51	曲棍球	曲别针	81	原子能	原材料
22	翻译家	翻白眼	52	全球性	全方位	82	中学生	中世纪
23	反应堆	反作用	53	热水瓶	热处理	83	中山装	中美洲
24	反动派	反革命	54	热水袋	热心肠	84	重头戏	重工业
25	负责人	负离子	55	山水画	山旮旯	85	重要性	重武器
26	感染力	感兴趣	56	山地车	山大王	86	主力军	主旋律
27	干果店	干儿子	57	伤病员	伤脑筋	87	主席团	主考官
28	高中生	高血压	58	少壮派	少东家	88	总统府	总领事
29	公安部	公积金	59	市场化	市辖区			
30	共同体	共存亡	60	手术台	手榴弹			

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