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Character Order Processing in Chinese Reading

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We explored how character order information is encoded in isolated word processing or Chinese sentence reading in 2 experiments using a masked priming paradigm and a gaze-contingent display-change paradigm. The results showed that response latencies in the lexical decision task and reading times on the target word region were longer in the unrelated condition (the prime or the preview was unrelated with the target word) than the transposed-character condition (the prime or the preview was a transposition of the 2 characters of the target word), which were respectively longer than in the identity condition (the prime or preview was identical to the target word). These results show that character order is encoded at an early stage of processing in Chinese reading, but character position encoding was not strict. We also found that character order encoding was similar for single-morpheme and multiple-morpheme words, suggesting that morphemic status does not affect character order encoding. The current results represent an early contribution to our understanding of character order encoding during Chinese reading.

Keywords: character order encoding, parafoveal processing, Chinese reading

The order in which letters appear is important for word recognition in alphabetic writing systems, and English readers use this information during reading (Rayner, White, Johnson, & Liversedge, 2006; White, Johnson, Liversedge, & Rayner, 2008; Johnson & Eisler, 2012). Without this information, readers would not be able to distinguish between anagrams such as *stop*, *post*, and *spot*, which contain the same constituent letters. In the past several decades, many researchers have investigated how the human brain encodes letter position information in alphabetic printed words, and several models have been proposed offering different letter order encoding mechanisms. In Chinese, a completely different writing system from English, character order information is also important for successful reading comprehension. Analogous to English, some words (3.3%) consist of the same set of characters that only differ from each other by character order.[1] For example, 蜜蜂 (bee) and 蜂蜜 (honey) are two words with different meanings, although they are made of the same characters. However, how character order is encoded in Chinese reading has been rarely studied and is relatively poorly understood.

Studies using a lexical decision paradigm (including standard lexical decision tasks for isolated words and masked priming lexical decision tasks) have shown that a transposed letter (TL) nonword prime, created by transposing two adjacent letters of a word, activates the representation of its base word to a greater degree than a substituted letter (SL) nonword prime, in which two corresponding letters, or even one letter, are replaced (i.e., the TL effect). However, TL nonword primes activate the representation of their base word to a lesser degree than do identity primes (Andrews, 1996; Bruner & O'Dowd, 1958; Chambers, 1979; Forster, Davis, Schoknecht, & Carter, 1987; Holmes & Ng, 1993; Kinoshita & Norris, 2009; O'Connor & Forster, 1981; Perea & Fraga, 2006; Perea & Lupker, 2003a, 2003b, 2004; Perea, Rosa, & Gomez, 2005; Perea, Winskel, & Ratitamkul, 2012; Schoonbaert & Grainger, 2004). Moreover, letter order information is processed in natural reading (Rayner et al., 2006; White et al., 2008; Johnson & Eisler, 2012). The finding that TL nonwords facilitate the processing of the target word less than the identity condition suggests that letter identity and letter order information is encoded at some level when the prime is presented briefly. However, the finding of a benefit in the TL condition over the SL condition suggests that the letter order encoding is not absolutely strict. If letter position encoding was very strict, the level of activation of the base word should have been equally activated by both TL nonwords and SL nonwords. For both of these types of nonwords, there are two letters in inaccurate positions. This finding is in conflict with the predictions of some visual word recognition models that assume slot-based encoding. Examples of such models include the multiple read-out model (Grainger & Jacobs, 1996), the dual-route cascaded model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), the interactive activation model (McClelland & Rumelhart, 1981), and the activation-verification model (Paap, Newsome, McDonald, & Schvaneveldt, 1982). These models assume that letter position is coded early in lexical processing and

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[1] The information is from the Research of Modern Chinese Corpus System in Beijing Language and Culture University.

letters are immediately tagged to their specified position within the string of letters. Each letter of a word is processed within its own specific position independent of the other letters in that word. Given the predictions of these models, the TL nonword *dsek* and the SL nonword *dnok* are both equally similar to the word *desk*, because both nonwords contain two letters in their correct positions. Thus, these models cannot account for the flexibility of letter position coding found in alphabetic writing systems.

Letter order encoding in parafoveal vision has also been studied using the eye-contingent display-change technique known as the *boundary paradigm* (Rayner, 1975; Johnson, 2007; Johnson, Perea, & Rayner, 2007; Johnson & Dunne, 2012). Before readers' eyes cross an invisible boundary to the left of the target word, a preview appears in that position. When the readers' eyes cross the boundary, the preview changes to the target word. The preview could be identical to the target word (the identity condition), be a transposed nonword (TL condition; with two letters of target words being transposed), or be a substituted nonword (SL condition; with two letters of target words being substituted with other letters). These studies showed that fixation durations on the target word were longer in the SL condition than in the TL condition, which were respectively longer than the identity condition (Johnson, 2007; Johnson et al., 2007; Johnson & Dunne, 2012; Masserang & Pollatsek, 2012; Winskel & Perea, 2013). These results are important because they indicate that letter order information can be processed in parafoveal vision and that parafoveal letter order encoding is not strict.

Although visual word recognition models that assume slot-based encoding cannot explain the flexibility of letter position encoding, some current letter position encoding models can account for the TL effects in alphabetic writing systems. The self-organizing lexical acquisition and recognition (SOLAR) model uses a spatial coding scheme in which letter codes are indexed independent of position context. The relative order of the letters in a letter string is encoded by the relative activities across letter nodes. Different letter orderings result in different spatial patterns of activity. For example, the words *salt* and *slat* share the same set of letter nodes, but they produce different activation patterns (e.g., in the word *salt*, the letter code corresponding to *S* is the one associated with the highest activation value, then the letter code corresponding to the letter *A* is associated with a slightly smaller activation value, and so on). Because serial position is encoded by relative activation rather than being position-specific, *salt* and *slat* are more similar than, say, *slat* and *scat*. Thus, the SOLAR model can readily explain TL effects (Davis, 1999; Davis, 2010; Davis & Bowers, 2006).

The overlap model assumes that a string that is presented unmasked and for an unlimited viewing time can produce accurate location coding, while strings that are presented briefly have distributions over letter position (Gomez, Ratcliff, & Perea, 2008). For any string of letters, each letter is assumed, at least initially, to be associated with more than one position. That is, the identities of the letters in any string of letters are assumed to be normally distributed over the positions. For instance, if the string of letters is the word *judge*, the letter *d* will be associated with Position 3, but also, to a lesser degree, with Positions 2 and 4, and, to an even lesser degree, with Positions 1 and 5. This model, therefore, also predicts that *judge* and *jugde* are, relatively, perceptually similar. Other models, such as the noisy channel model (Norris & Kinoshita, 2012), make similar assumptions, and they used similar mechanisms to implement it.

Although letter order encoding has been studied quite thoroughly in the alphabetic writing systems, how character order information is encoded in other writing systems, such as Chinese, is less clear. Unlike alphabetic writing systems, Chinese text is formed by strings of equally spaced symbols called characters and each character is a single syllable. There are no spaces or other explicit visual cues between successive words in Chinese texts except for punctuation marks. According to a formal model of Chinese word processing, word segmentation and word recognition are a unified processes (Li, Rayner, & Cave, 2009). The model assumed that Chinese word recognition is an interactive process involving many nodes at multiple levels (i.e., a feature level, a character level, and a word level). Characters are processed in parallel at the character level, but only a single word prevails at the word level. Distorting character order will result in failure to activate the related word at the word level, because this model assumes strict character order encoding.

However, some studies have found that character order encoding in Chinese is not strict. Taft, Zhu, and Peng (1999, Experiment 5) examined the character position coding of transposable two-character words and transposable two-character nonwords with a nonword interference paradigm. For transposable two-character words, a character transposition resulted in the formation of another different word (e.g., both 领带 [tie] and 带领 [lead] are words). For transposable nonwords, a character transposition could result in a word (e.g., 光 风 is a nonword, but the transposed characters 风光 form a word [scene]). In addition, nontransposable two-character words (e.g., 节目 [program]) and nontransposable two-character nonwords (e.g., 返构) were used as control stimuli. These four types of targets were presented for 500 ms, and then participants were asked to decide as quickly and as accurately as possible whether the target was a word or nonword. Results showed that reaction times (RTs) were slower for transposable words than nontransposable controls. Moreover, RTs for transposable two-character nonwords were also slower if these two characters created a real word through transposition than when they did not. The authors interpreted these results as evidence supporting the claim that the presentation of two characters activated both the original word and the transposed word, and thus suggested that characters have position-free representations in Chinese. Note that the paradigm used in this study was different from those used most often in traditional letter position encoding studies in English.

Yang (2013) explored semantic processing in parafoveal vision by manipulating character order of two-character preview words embedded in a sentence. For all of the target words, transposing the characters resulted in another real word. However, some of the transposed-character words had a meaning that was identical to the original target words, while others had a meaning that was quite different from the meaning of the original target words. Yang used the boundary paradigm to provide readers with a parafoveal preview word that then changed to a target word when the eyes fixated it (Rayner, 1975). In Yang's (2013) study, the preview word was identical to the target word in the identical condition, was a transposed-character word in the transposed condition, and was a different word to the target word in the control condition. Compared to the control condition, Yang found a benefit in the transposed condition in gaze duration. She also found a clear benefit of correct order preview for the target words in which the meaning changed as two characters were transposed, but no benefit for correct order preview for the words in which characters could be transposed without changing the meaning. Based on these data, she argued that it is more difficult to identify a word in the transposed-word preview condition when the transposition affects the meaning of the word in its sentence context. Because the purpose of Yang's study was not to explore character order encoding, per se, she did not explicitly discuss the results in terms of this issue. Indeed, while the stimuli that Yang employed were ideal for the theoretical question she chose to focus on, they are less ideal when considering issues of character order encoding. The words used by Yang have very special characteristics and only represent a very small number of words in Chinese reading. The vast majority (96.7%) of two-character words do not make up another word when the order of their constituent characters is transposed. Interference effects or the reading difficulty may be related to a later stage of processing associated with semantic integration, rather than early orthographic processing. Although the studies above provide some information regarding character order encoding in Chinese reading, whether character order information is encoded and how it is encoded is still not fully understood. For this reason, we undertook our investigation of character order encoding in visual word recognition, with stimuli that were more representative of two-character words that appear in the Chinese language.

In the present study, we explored whether character order information in two-character Chinese words is encoded at an early stage of lexical processing. Experiment 1 employed a masked priming paradigm (Meyer & Schvaneveldt, 1971). After a brief exposure to a stimulus (the prime), participants were presented with a target stimulus (either the same as or different from the prime). Participants were asked to make a lexical decision to the target stimulus. RTs on this task reflect how the exposure of the prime word in central foveal vision activates the target. Experiments 2 was an eye movement experiment in which we employed the boundary paradigm (Rayner, 1975) and the primes used in the lexical decision experiment were used as the preview items here. We compared fixation durations on the target word to investigate how character order information is processed in parafoveal vision under normal sentence reading conditions.

In our experiments, we used three types of stimuli as primes (Experiment 1) and as previews (Experiment 2): an identity condition, a transposed-character condition (TC nonword condition) and an unrelated condition (substituted-character nonword condition). Subjects were required to make a lexical decision, and we measured RTs in Experiment 1 and examined fixation durations on the target word in Experiment 2. We compared response latencies and eye movement measures between the identity condition and the TC condition. If character order information is encoded at an early stage of processing, the identity prime (or preview) should provide increased activation of the target word than the TC prime (or preview). Thus, RTs and fixation durations in the identity condition should be shorter than in the TC condition. Alternatively, if character-order information is not encoded early during lexical processing, we would expect no difference between the identity condition and the TC condition. We also considered the RTs and fixation durations for words in the TC condition compared to the unrelated condition. If character order was strictly encoded, TC nonwords should facilitate processing of the target word no more than the unrelated nonwords. For both of these types of nonwords, there are two characters in inaccurate positions in a string of characters. Thus, according to these accounts, there should be no difference between the unrelated condition and the TC condition in RTs and fixation durations. Alternatively, if the character order was not encoded strictly, we expect the TC nonwords were more similar to the target than the unrelated nonwords, and thus expect RTs or fixation durations were shorter in the TC condition than in the unrelated condition.

Furthermore, the current study was conducted to compare character order encoding in multiple-morpheme words and single-morpheme words in Chinese reading. A multiple-morpheme word is composed of at least two morphemes (a morpheme is the smallest meaningful unit in a language; Feng, 2001). Thus, when a multiple-morpheme word consists of two characters, each character is a free morpheme. The meaning of each character of a multiple-morpheme word usually contributes to the meaning of the whole word (e.g., 地震 [earthquake], 地 [ground], 震 [quake]). Over 70% of all words used in Chinese are multiple-morpheme words (Institute of Language Teaching and Research, 1986). In comparison, single-morpheme words are comprised of only one morpheme. A single-morpheme may be formed from one character (e.g., 水 [water]) or multiple characters. If a single-morpheme word is comprised of more than one character, each constituent character does not carry its own meaning (e.g., 哆嗦 [tremble]; 哆 and 嗦 do not carry meaning by themselves) or carries a different meaning to the whole word (e.g., 烂漫 [bright-colored], 烂 [bad], 漫 [overflow]). This situation is similar to single-morphemic words and multiple-morpheme words in English. Hence, character transposition in multiple-morpheme Chinese words involves a cross-morpheme transposition, whereas character transposition in single-morpheme Chinese words does not and is instead a within-morpheme transposition. A lexical decision study by Crepaldi, Rastle, Davis, and Lupker (2013) investigating morpheme position coding showed that the presentation of transposed-morpheme nonwords (e.g., *moonhoney*) as primes facilitated the identification of multiple-morpheme words (e.g., *honeymoon*). In contrast, monomorphemic words did not produce a similar pattern (e.g., *italhosp* did not prime *hospital*). These results indicated that the position of free morphemes is encoded flexibly. The current study provided us with an opportunity to explore whether character order encoding is modulated by the morphological structure of a two-character word in Chinese.

Some Chinese word recognition models that adopt the interactive activation framework assume a separate morpheme level (Zhang & Peng, 1992). According to this model, characters belonging to different morphemes are processed at different units at the morpheme level, while characters belonging to the same morpheme are processed at the same morpheme unit at the morpheme level. An interesting question, therefore, is whether character order encoding occurs earlier than morpheme processing. If the processing of morphemes occurs at an early stage of visual word processing, coinciding with character order encoding, morpheme structures of words should affect character order encoding. The position of characters in single-morpheme words is more constrained than that in multiple-morpheme words. That is to say, encoding of character positions in single-morpheme words may be more specific than is the case for multiple-morpheme words. Thus, for two-character words, it is possible that TC nonwords produced from single-morpheme words are no more similar to their base words than TC nonwords produced from multiple-morpheme words. Therefore, if character order encoding is different for within- and cross-morpheme transpositions, transposing two characters within a single-morpheme word (a within-morpheme transposition) should produce decreased preview benefit relative to transposing two characters within a multiple-morpheme word (a cross-morpheme transposition).

Not all of the Chinese word processing models assume a separate morpheme processing level. For example, in the model proposed by Taft and Zhu (1997), no specific mechanism was proposed to process morphemes. Thus, according to this kind of model, character order encoding should be independent of morpheme structure. If the morphological status of a two-character Chinese word does not modulate character order processing, then the preview effects between single-morpheme words and multiple-morpheme words should be similar.

Experiment 1

Experiment 1 was conducted to explore character order encoding for Chinese isolated words using a masked-priming paradigm.

Method

Participants. Twenty-four native Chinese speakers (average age of 21.7 years) who were undergraduates or postgraduates from universities near the Institute of Psychology, Chinese Academy of Sciences took part in this experiment. They were paid 20 Yuan (approximately USD $3) to participate in the experiment. All of the participants had normal or corrected-to-normal vision and all were naive to the purpose of the experiment.

Apparatus. Stimulus presentation and response registration were controlled by a desktop computer. Stimuli were presented on a 21-in. CRT monitor with a resolution of 1024 × 768 pixels and a refresh rate of 150 Hz. Participants viewed the stimuli approximately 58 cm from the monitor.

Materials and design. Experiment 1 utilized a masked-priming lexical decision task. The targets were 120 two-character words, half of them were single-morpheme words and half were multiple-morpheme words. The radicals of the two characters were always different in both types of words. Transliteration loanwords (e.g., 沙发 [sofa]) were excluded because their pronunciation is similar to that of the corresponding English word. Frequencies of all the target words ranged from 0.12 to 5.88 occurrence per million ($M = 1.58$) and represented a variety of word classes (e.g., noun, verb, adjective).[2] The frequency and number of strokes of single-morpheme words (frequency: $M = 1.59$ occurrence per million, $SD = 1.28$; number of strokes: $M = 10.32$, $SD = 1.77$) did not differ from those of multiple-morpheme words (frequency: $M = 1.57$ occurrence per million, $SD = 1.26$; number of strokes: $M = 11.07$, $SD = 1.98$; $ps > .1$). There were three priming conditions for each target word: (a) identity condition, the prime was identical to the target word, for example, a single-morpheme word, 吝啬—吝啬; (b) TC condition, the prime was a transposition of two characters of the target word, for example, 啬吝—吝啬; (c) unrelated condition, the prime differed from the target word by two characters, for example, 菠汞—吝啬. The frequency and number of strokes of the first character of TC nonwords (frequency: $M = 44.99$ occurrence per million, $SD = 92.26$; number of strokes: $M = 10.88$ occurrence per million, $SD = 3.09$) did not differ from those of unrelated nonwords (frequency: $M = 44.95$ occurrence per million, $SD = 92.65$; number of strokes: $M = 10.83$, $SD = 3.11$; $ps > .1$). The frequency and number of strokes of the second character of TC nonwords (frequency: $M = 56.45$ occurrence per million, $SD = 105.03$; number of strokes: $M = 10.51$, $SD = 2.79$) did not differ from those of unrelated nonwords (frequency: $M = 56.42$ occurrence per million, $SD = 104.74$; number of strokes: $M = 10.48$, $SD = 2.70$; $ps > .1$). The two characters in the TC condition and in the unrelated condition were matched in structure (top-down, left-right, etc.).

An additional set of 120 two-character nonwords was included for the purposes of the lexical decision task. The nonwords were comprised of two Chinese characters that did not form a word. The manipulation for the nonword targets was the same as that for the word targets (e.g., 牲缉—牲缉, 缉牲—牲缉, 搂浑—牲缉). The frequency and number of strokes of the first character of the word targets (frequency: $M = 56.45$ occurrence per million, $SD = 105.03$; number of strokes: $M = 10.51$, $SD = 2.79$) did not differ from those of nonword targets (frequency: $M = 56.50$ occurrence per million, $SD = 105.04$; number of strokes: $M = 10.53$, $SD = 2.72$; $ps > .1$). The frequency and number of strokes of the second character of the word targets (frequency: $M = 44.99$ occurrence per million, $SD = 92.26$; number of strokes: $M = 10.88$ occurrence per million, $SD = 3.09$) did not differ from those of nonword targets (frequency: $M = 45.04$ occurrence per million, $SD = 93.61$; number of strokes: $M = 10.87$, $SD = 3.09$; $ps > .1$).

Procedure. A black fixation point was presented at the center of the screen for 500 ms, and participants were asked to fixate on it. Then, a forward mask consisting of a row of two masks (※※) was presented for 500 ms. The mask was immediately followed by the prime for a duration of 60 ms, which was in turn immediately followed by a row of two masks (※※) for a duration of 40 ms. Then, the target replaced the mask and remained on the screen until the response. Finally, when participants pressed one of two response buttons, a blank screen was presented for 1,000 ms. Each stimulus was centered in the viewing screen and was superimposed on the preceding stimulus.

Stimuli were presented as black on a white background. Reaction times were measured from target onset until the participant's response. Participants were asked to judge whether the two characters formed a word or a nonword. Participants indicated their decisions by pressing one of two response buttons. When participants responded, the target disappeared from the screen. Each participant received a different random ordering of targets. Each participant received a total of 20 practice trials prior to the 240 experimental trials. For the experimental items, participants saw only one priming condition with each target and saw equal numbers of each type of target. The entire experimental procedure took approximately 25 min.

[2] The following corpus was used to assess the word frequency of items: Chinese Linguistic Data Consortium. (2003). 现代汉语通用词表 [*Chinese lexicon*] (CLDC-LAC-2003-001). Beijing, China: Tsinghua University, State Key Laboratory of Intelligent Technology and Systems, and Chinese Academy of Sciences, Institute of Automation.

Results

Mean accuracy and latencies for correct responses to words were calculated across subjects (F_1) and items (F_2). A 2 (Word Type: Single-Morpheme Word or Multiple-Morpheme Word) × 3 (Priming Condition: Identity Condition, TC Condition, or Unrelated Condition) ANOVA was conducted on participants' response latencies and percentage accuracy.

Accuracy. Accuracy was 91.7%, indicating that participants could do the task very well. As shown in Table 1, accuracy was higher in multiple-morpheme words than in single-morpheme words, $F_1(1, 23) = 16.32$, $p = .001$, $\eta_p^2 = .42$, $MSE = .003$, and $F_2(1, 118) = 2.29$, $p = .133$, $\eta_p^2 = .02$, $MSE = .015$. Accuracy was also affected by priming condition, $F_1(2, 46) = 11.28$, $p < .001$, $\eta_p^2 = .33$, $MSE = .007$, and $F_2(2, 236) = 24.79$, $p < .001$, $\eta_p^2 = .17$, $MSE = .008$. Accuracy in the unrelated condition was lower than in the TC condition, $F_1(1, 23) = 14.53$, $p = .001$, $\eta_p^2 = .39$, $MSE = .019$, and $F_2(1, 118) = 36.89$, $p < .001$, $\eta_p^2 = .24$, $MSE = .018$. There was no significant difference between the accuracy in the TC condition and the identity condition, Fs < 1. These results indicate that the nature of the prime, and in particular, whether it was a transposed character prime relative to an unrelated prime, influenced responses to target words presented centrally in the fovea in a lexical decision task. The interaction between word type and priming condition was not significant either by participants or by items (Fs < 1).

Reaction time. Trials with RTs that were shorter than 100 ms or longer than 1,500 ms, as well as those with RTs over three standard deviations from the mean RT (calculated separately for each condition for each participant) were excluded from the analyses. We also excluded those trials in which participants made an erroneous response. In total, 11.3% of the trials were excluded. Mean correct RTs are shown in Table 1. RTs were shorter for multiple-morpheme words than single-morpheme words, $F_1(1, 23) = 14.24$, $p = .001$, $\eta_p^2 = .38$, $MSE = 3{,}696$, and $F_2(1, 118) = 5.86$, $p = .017$, $\eta_p^2 = .05$, $MSE = 26{,}432$. RTs were affected by priming condition, $F_1(2, 46) = 73.49$, $p < .001$, $\eta_p^2 = .76$, $MSE = 4{,}415$, and $F_2(2, 236) = 71.98$, $p < .001$, $\eta_p^2 = .38$, $MSE = 13{,}571$. RTs for the unrelated condition were longer than for the TC condition, $F_1(1, 23) = 65.19$, $p < .001$, $\eta_p^2 = .74$, $MSE = 11{,}658$, and $F_2(1, 118) = 69.88$, $p < .001$, $\eta_p^2 = .37$, $MSE = 33{,}785$. RTs for the TC condition were longer than in the identity condition, $F_1(1, 23) = 7.29$, $p = .013$, $\eta_p^2 = .24$, $MSE = 5{,}445$, and $F_2(1, 118) = 7.25$, $p = .008$, $\eta_p^2 = .06$, $MSE = 13{,}134$. The TC condition was faster than the unrelated condition but slower than the identity condition. The pattern of effects in the RT analyses is similar to those obtained in the accuracy analyses. The interaction between word type and priming condition was not significant either by participants or by items (Fs < 1).

We further evaluated nonsignificant interactions by calculating the Bayes factors (Rouder, Morey, Speckman, & Province, 2012; Wetzels, Grasman, & Wagenmakers, 2012) to enable comparisons of models within an ANOVA design (see Table 4). We calculated the Bayes factor between the full model (i.e., M_{FWP}), which contains the main effects and their interaction, and the model with only main effects (i.e., M_{W+P}). Models excluding the interaction were preferred for both RTs and accuracy (RT: 61.25:1; Accuracy: 3.69:1).

Table 1
Reaction Times (Means) and Accuracy by Word Type and Prime Condition for Experiment 1

	Reaction times			Accuracy		
	SM	MM	Nonwords	SM	MM	Nonwords
Identical	619 (26)	597 (22)	753 (30)	.92 (.02)	.96 (.01)	.94 (.01)
TC	655 (30)	619 (25)	799 (28)	.92 (.01)	.96 (.01)	.93 (.01)
Unrelated	791 (41)	735 (26)	753 (27)	.86 (.02)	.88 (.02)	.95 (.01)

Note. The numbers in brackets are standard errors. SM = single-morpheme words; MM = multiple-morpheme words; TC = transposed character.

Discussion

Experiment 1 was conducted to examine whether character order information is encoded during the early stages of lexical processing for two-character words in Chinese reading using a masked-priming lexical decision task. RTs and accuracy in Experiment 1 showed that TC nonword primes activate the base word to a greater extent than unrelated nonword primes. These results suggest that character order is encoded for two-character Chinese words during the early stages of word recognition but that encoding is not strict in relation to position, and that such encoding occurs when Chinese words are presented centrally at fixation and in isolation. From the results, RTs for single-morpheme words were significantly longer than multiple-morpheme words. However, the differences between the three priming conditions were similar for single-morpheme words and multiple-morpheme words. The morphological status of the transposed/substituted characters of the word did not modulate the degree to which character position information was encoded.

Experiment 2

The results of Experiment 1 suggested that character order information was encoded when words were presented centrally in foveal vision, but that character order encoding was not strict. In Experiment 2, we tested whether the effects generalized to a normal sentence reading situation, in which the delivery of visual information about words is staggered over fixations made relative to parafoveal and then foveal stimuli. In this experiment, target words were embedded in sentence frames and the boundary paradigm was used to explore how character order was processed in parafoveal vision.

Method

Participants. Forty-eight native Chinese speakers (average age of 22.6 years) who were undergraduates or postgraduates from universities near the Institute of Psychology, Chinese Academy of Sciences. They were paid 25 Yuan (approximately USD $4) to participate in the experiment. All of the participants had normal or corrected-to-normal vision and all were naive to the purpose of the experiment. None of them participated in Experiment 1.

Apparatus. Eye movements were recorded using an SR Eye-Link 2000 tracker, which has a resolution of approximately 30′ of arc. Participants read the target sentences (which were printed horizontally from left to right) on a 21-inch CRT monitor (Sony Multiscan G520) connected to a Dell computer. The eye-tracking system sampled at 1,000 Hz and provided eye movement data for further analysis via another PC. Participants rested their chins on a chinrest to minimize head movements during the experimental trials. Viewing was binocular, but eye movement data were collected only from the right eye. The refresh rate of the CRT monitor was 150 Hz, and the resolution was 1024 × 768. Participants were seated 58 cm from the video monitor; at this distance, one character subtended 0.8° of visual angle.

Materials and design. Participants read 60 experimental sentences with six experimental conditions. Each experimental sentence frame contained two types of target words: 60 single-morpheme and 60 multiple-morpheme words. Because some of the words in Experiments 1 did not fit sentence frames readily, only 81% of the words in Experiment 1 were used in Experiment 2. Each participant read only one version of each sentence frame. Each target word was embedded into a single-line sentence no more than 31 characters long (ranging from 23 to 31 characters). In addition, the radicals of the two characters within a trial were always different in both types of words. Frequencies of target words ranged from 0.12 to 5.88 occurrences per million (M = 1.47) and represented a variety of word classes (e.g., noun, verb, adjective). The frequency and number of strokes of characters in single-morpheme words (frequency: M = 1.48 occurrences per million, SD = 1.26; number of strokes: M = 10.39 occurrences per million, SD = 2.03) did not differ from those of multiple-morpheme words (frequency: M = 1.46 occurrences per million, SD = 1.24, $t[59]$ = 1.21, p = .23; number of strokes: M = 10.80 occurrences per million, SD = 1.89; $t[59]$ = 1.04, p = .30). The target words were in the middle of the sentence so that they were at least eight characters away from the beginning and the end of the sentence.

There were three parafoveal preview conditions for each target word. In the identity condition, the preview was identical to the target word (e.g., 颈椎 as the preview of 颈椎). In the TC condition, the preview was a transposition of two characters (e.g., 椎颈 as the preview of 颈椎) of the target word. In the unrelated condition, the preview differed from the target word by two characters (e.g., 裸剔 as the preview of 颈椎).

The frequency and number of strokes of the first character of TC nonwords (frequency: M = 31.15 occurrences per million, SD = 41.16; number of strokes: M = 10.54, SD = 3.11) did not differ from those of unrelated nonwords (frequency: M = 31.06 occurrences per million, SD = 40.99, $t[119]$ = 1.03, p = .31; number of strokes: M = 10.52, SD = 3.11; $t[119]$ = .47, p = .64). The frequency and number of strokes of the second character of TC nonwords (frequency: M = 32.45 occurrences per million, SD = 33.90; number of strokes: M = 10.62, SD = 2.81) did not differ from those of unrelated nonwords (frequency: M = 32.48 occurrences per million, SD = 33.88, $t[119]$ = .32, p = .75; number of strokes: M = 10.62, SD = 2.67; t = 0). The two characters in the TC condition and in the unrelated condition were matched in structure (top-down, left-right, etc.). Word type and parafoveal preview condition were both within-subject and within-item variables. A sample sentence is shown in Table 2 with six different manipulations.

Procedure. When participants arrived at the laboratory, a brief description of the experimental procedure and the apparatus was given to them to read. They were then verbally instructed about the task. The eye tracker was calibrated at the beginning of the experiment and the calibration was validated as needed. For calibration and validation, participants looked at a dot that was presented at each of three locations horizontally arranged at the center of the display in a random order. The maximum error permitted for validation throughout the experiments was 0.5°. After validation, participants read nine practice sentences to familiarize themselves with the procedure.

Experimental sentences were presented in a random order and one at a time at the center row of the monitor. Each trial started with a drift check procedure, during which the participant had to fixate on a circle located at the center of the monitor. After the drift check, a white fixation box appeared on the monitor at the location corresponding to where the first character of the sentence would appear. Once the eye tracker detected that the participant was looking at the box, the sentence was shown (see Figure 1). Additional calibration and validation was conducted when drift was beyond 1° visual angle. Most of participants were recalibrated fewer than three times. When participants' eyes crossed an invisible boundary located just to the left of the preview word, the preview word changed into the target word. After the experiment, we asked participants whether they noticed anything unusual during the experiment. None of them reported that they noticed any display change when they read the sentences. The sentence remained on the screen until the participants finished reading the sentence. Participants were told to read silently and at a habitual pace. They pressed a button on the response box when he or she finished reading the sentence. There were 40 filler items intermixed with the 60 experimental items and the experimental procedure repeated until all sentences had been read. Once again, a

Table 2
Sample Experimental Sentence for Experiment 2

Word type	Display	Example
SM	Identity	帕西诺成功地塑造了一个生性乖戾却又不失纯朴的退休军官的形象.
	TC	帕西诺成功地塑造了一个生性戾乖却又不失纯朴的退休军官的形象.
	Unrelated	帕西诺成功地塑造了一个生性庖卓却又不失纯朴的退休军官的形象.
MM	Identity	帕西诺成功地塑造了一个生性愚钝却又不失温良的西部牛仔的形象.
	TC	帕西诺成功地塑造了一个生性钝愚却又不失温良的西部牛仔的形象.
	Unrelated	帕西诺成功地塑造了一个生性籽窝却又不失温良的西部牛仔的形象.

Note. SM = single-morpheme words; MM = multiple-morpheme words. English translation: (1) *Pacino plays a part of a retired officer who is* **surly** and honest successfully; (2) *Pacino plays a part of a west cowboy who is* **fatheaded** and kind successfully.

(1) 老师教育我们不能仅仅怀着寻找某种 | 径捷或治学秘诀的想法而读书。
*

(2) 老师教育我们不能仅仅怀着寻找某种 | 捷径或治学秘诀的想法而读书。
*

Figure 1. Example sentence using the boundary paradigm. In (1), the transposed-character nonword preview 径捷 (pathway quick) is initially displayed in the target location. When the reader's eyes crossed the invisible boundary location (|) located just to the left of the target word, the preview is replaced by the target word 捷径 (shortcut), see (2). The asterisks represent the fixation locations. The English translation of this sentence is, *The teacher told us that we can't read just for looking for some shortcuts or scholarship secrets.*

Latin square design was adopted. Presentation of the 100 items was in random order for each participant. Participants were required to answer comprehension questions after 30% sentences to ensure that they were reading the sentences carefully. They pressed a button on the response box to answer these multiple-choice questions. The entire experimental procedure took approximately 30 min.

Normative data. Experimental sentences were normed by another group of participants to make sure that the target words fit well within the context of that sentence. Ten participants were recruited to judge how well each target word fit into the given sentence frame on a scale from 1 (*not natural at all*) to 7 (*very natural*). All target words were rated as natural within their respective sentence frame (5.90). These participants did not take part in the eye tracking section of the experiment.

To ensure that the target words were equally predictable for all of the conditions, we structured the sentences in such a way that the target words were not predictable from their previous context. To do so, 10 participants were given the first part of the experimental sentence (up to the target word) and were then asked to provide the next word in the sentence (i.e., predict the target word). The predictability of the items was close to zero, indicating that the target words were not predictable from their preceding contexts.

Results

Comprehension scores ranged from 85% to 100%, with a mean of 93.4%. The accuracy is high, suggesting that participants could understand sentences well. We computed target word skipping, first fixation duration and gaze duration on the target word. Skipping, as the name suggests, is the percentage of trials in which the target word was not fixated during the first pass of the eyes through the sentence. First fixation duration is the amount of time spent on the initial fixation of the target word, regardless of whether there is more than one fixation on it. Gaze duration is the sum of fixation durations on the target word before the reader leaves that word. Trials were eliminated from data analysis if one or more blinks occurred when the eyes fixated on the pretarget character, target word, or posttarget character or when tracker loss occurred during a trial (Johnson, Perea, & Rayner, 2007). Consistent with most eye movement research (Rayner, 1998), extremely short (<80 ms) fixations and extremely long (>1,000 ms) fixations were excluded from the data set prior to analyses. In sum, 3% of the data were eliminated.

For each of the eye movement measures, a 2 (Word Type: Single-Morpheme Word or Multiple-Morpheme Word) × 3 (Parafoveal Preview Condition: Identity, TC Condition, or Unrelated Condition) ANOVA was conducted. Error variance was calculated over participants (F_1) and over items (F_2). In addition, planned comparisons were run to compare fixation durations between the TC condition and the identity condition and between the TC condition and the unrelated condition.

The target words were skipped on 10% of the trials. The skipping probability of single-morpheme words (M = .09, SE = .02) was lower than multiple-morpheme words (M = .12, SE = .02), $F_1(1, 47) = 7.64$, $p = .008$, $\eta_p^2 = .14$, $MSE = .005$, and $F_2(1, 59) = 4.53$, $p = .037$, $\eta_p^2 = .07$, $MSE = .011$. The skipping probability was affected by preview conditions, $F_1(2, 94) = 7.08$, $p = .001$, $\eta_p^2 = .13$, $MSE = .008$, and $F_2(2, 118) = 4.60$, $p = .012$, $\eta_p^2 = .07$, $MSE = .015$. The difference in skipping probability in the identity (M = .13, SE = .02) and TC condition (M = .11, SE = .02) was not significant, $F_1(1, 47) = 2.40$, $p = .128$, and $F_2(1, 59) = 1.79$, $p = .187$. Skipping probability was lower in the unrelated condition (M = .08, SE = .02) than the TC condition, $F_1(1, 47) = 6.86$, $p = .012$, $\eta_p^2 = .13$, $MSE = .01$, and $F_2(1, 59) = 2.51$, $p = .119$. This effect was significant in the subjects, but not items analysis. The interaction between word type and parafoveal preview condition was not significant, Fs < 1. Target words were fixated once on 66% of the trials, and more than once on 24% of the trials. Because target words were fixated more than once on only 24% of the trials, single fixation duration was highly correlated with the first fixation duration, and therefore, we do not report it. Mean first fixation durations and gaze durations for each of the three parafoveal preview conditions using the two types of words are shown in Table 3.

First fixation durations showed a significant main effect of parafoveal preview, $F_1(2, 94) = 26.01$, $p < .001$, $\eta_p^2 = .36$, $MSE = 1214$, and $F_2(2, 118) = 24.84$, $p < .001$, $\eta_p^2 = .30$, $MSE = 1695$. First fixation durations were significantly longer in the TC condition than in the identity condition by participants, $F_1(1, 47) = 5.32$, $p = .026$, $\eta_p^2 = .10$, $MSE = 1975$; but the effect was not significant in item analysis $F_2(1, 59) = 2.75$, $p = .103$. The numerical difference suggests that character order information was encoded from the parafovea during reading. First fixation duration in the unrelated condition was longer than that in the TC condition, $F_1(1, 47) = 23.53$, $p < .001$, $\eta_p^2 = .33$, $MSE = 2521$, and $F_2(1, 59) = 25.54$, $p < .001$, $\eta_p^2 = .30$, $MSE = 3396$. The longer first fixation durations in the unrelated condition suggests that character order information was not strictly encoded in Chinese reading, at least in early stages of lexical processing. The effect of word type

Table 3
Participants' Means (and Standard Errors) by Word Type and Preview Condition for Experiment 2

	First fixation		Gaze duration	
	SM	MM	SM	MM
Identity	287 (7)	292 (7)	360 (18)	355 (14)
TC	298 (7)	302 (7)	368 (15)	391 (16)
Unrelated	326 (8)	323 (8)	433 (17)	427 (14)

Note. All durations are in milliseconds. SM = single-morpheme words; MM = multiple-morpheme words; TC = transposed character.

Table 4
Ratio of Bayes Factors for the Two-Way ANOVA

Measures	Bayes factors				
	(M_{FWP}:M_N)	(M_{WP}:M_N)	(M_{W+P}:M_N)	(M_W:M_N)	(M_P:M_N)
Experiment 1					
RT	3.51×10^{92}	0.01	2.15×10^{94}	0.51	3.88×10^{94}
ACC	2.71×10^4	0.27	1.00×10^5	0.14	7.12×10^5
Experiment 2					
FFD	1.19×10^6	0.01	9.16×10^7	0.06	1.62×10^9
Gaze	1.14×10^9	0.09	1.35×10^{10}	0.05	2.42×10^{11}

Note. M_{FWP} = the full model that contains the main and interaction effects; M_{WP} = the model that contains only the interaction effects; M_{W+P} = the model that contains only the main effects; M_W = the model that contains only the effects of word type; M_P = the model that contains only the effects of parafoveal preview condition; M_N = the null model; RT = reaction time; ACC = accuracy; FFD = first fixation duration.

was not significant, Fs < 1. The interaction between word type and parafoveal preview condition was not significant, Fs < 1.

Gaze duration showed a similar pattern of effects. Gaze duration was affected by parafoveal preview condition, $F_1(2, 94) = 25.27$, $p < .001$, $\eta_p^2 = .35$, $MSE = 5212$, and $F_2(2, 118) = 28.62$, $p < .001$, $\eta_p^2 = .33$, $MSE = 5864$. Gaze duration in the unrelated condition was longer than that in the TC condition, $F_1(1, 47) = 25.82$, $p < .001$, $\eta_p^2 = .36$, $MSE = 9494$, and $F_2(1, 59) = 28.19$, $p < .001$, $\eta_p^2 = .32$, $MSE = 11517$, and gaze durations in the TC condition were significantly longer than in the identity condition, $F_1(1, 47) = 5.16$, $p = .028$, $\eta_p^2 = .10$, $MSE = 8719$, and $F_2(1, 59) = 4.38$, $p = .041$, $\eta_p^2 = .07$, $MSE = 11562$. The effect of word type was not significant, Fs < 1. The interaction between word type and parafoveal preview condition was not significant, $F_1(2, 94) = 1.61$, $p = .206$, and $F_2(2, 118) = 1.97$, $p = .144$.[3]

As in Experiment 1, we calculated the Bayes factor between the full model (i.e., M_{FWP}) and the model with only main effects (i.e., M_{W+P}). The models excluding the interaction were preferred for first fixation duration (76.97:1) and gaze duration (11.84:1). Thus, Bayesian analyses showed character order encoding was not different for single-morpheme words and multiple-morpheme words during Chinese reading.

Discussion

Experiment 2 was conducted to examine how character order information is encoded from the parafovea in Chinese reading. Fixation durations on the target word were longer in the unrelated condition than the TC condition, and respectively longer than in the identity condition. In other words, the identity condition was always a better preview than the TC condition or the unrelated condition. These results provide strong evidence that character order information can be activated from the parafovea before a word is directly fixated when the word was comprised of two characters. The pattern of (primed) character order encoding in foveal vision was similar to that for parafoveal processing during normal reading. Primes facilitate activation of the word when it is presented at fovea, and readers are able to activate character order information from the parafoveal word. In general, a robust TC effect was found in Experiment 2. However, the interaction between word type and parafoveal preview condition was not significant for either first fixation duration or gaze duration. Bayes analysis showed that a model without an interaction is preferred to a model with an interaction indicating that character order encoding was not different between single-morpheme and multiple-morpheme words in Chinese reading.

General Discussion

The present study explored whether character order information associated with two-character words is encoded at an early stage of lexical processing during Chinese reading. Our pattern of effects, namely, longer times for the unrelated than the TC stimuli, and in turn for the TC than for the identity stimuli, suggest that character order information is encoded, and also that character order is not strictly encoded during Chinese reading. In addition, these results also suggest that character identity information plays a dominant role in lexical identification relative to character position information during word identification. Similarly, Experiment 2 showed that fixation durations on the target word in natural reading were shorter in the identity condition than the TC condition, which was respectively shorter than that in the unrelated condition. Character order encoding in the masked priming experiment and the eye movement boundary paradigm experiment were similar, suggesting that character order encoding occurred similarly for centrally presented isolated Chinese words (preceded briefly by a prime word) and Chinese words read normally in a sentence. In short, we found TC effects in Chinese two-character word recognition. We also compared whether character order encoding is affected by morphemic status of a word. Results showed that the TC effects were similar for single-morpheme words and multiple-morpheme words, suggesting that character order encoding was not affected by morpheme boundaries.

[3] We have assessed the accuracy of the display-change time and found that there were a small proportion of trials in which the display change was late. To assess whether this affected the results of our study, we conducted the following analyses. We constructed linear mixed models using the lme4 package (Bates, Maechler, Bolker, & Walker, 2014). For the first fixation duration and gaze duration, a linear mixed-effects model was fit to the data with participants and items as random factors, and with display-change time (relative to the onset of next fixation after the saccade past the invisible boundary), word type, and parafoveal preview condition as fixed factors. When display-change time was included as a factor in the linear mixed model, for first fixation duration and gaze duration, neither the main effect of display-change time, nor any other interaction involving display-change time was significant. Moreover, including display-change time as a factor did not change the pattern of results.

To date, no formal models of character position encoding have been developed for Chinese reading. However, some of the models may be modified to account for the findings of the current study. Taft and Zhu (1997) proposed a multilevel activation framework for conceptualizing the lexical processing of Chinese words. The lexical processing system includes the feature, radical, character, and multicharacter levels. From the lowest level features, activation passes up to the radical units associated with the activated features, and in turn passes up to the character units associated with the activated radical units, and then to the multicharacter units associated with the activated character units. This model simply activates the whole-word representation via character-level representations, but the order of character activation is not defined precisely. Thus, this model cannot account for our results. However, this model could be modified to explain the results by introducing flexible character position encoding as per models such as Davis's (1999, 2010) SOLAR model. As mentioned previously, words are represented via activity in position-independent letter representations. The ordering of the letters is encoded by the pattern of activity across these position-independent letter units. The first letter is assigned the largest value 1, the second letter is assigned the next largest value 2, and so on. Thus, the spatial gradient representation is formed by a series of spatial codes in a word. For example, at the character level, in order to encode the word 偷窃 (steal), a temporary position code of 1 could be assigned to the character 偷, and a temporary position code of 2 could be assigned to the character 窃. The TC nonword (窃偷) and the word 偷窃 both share the same character nodes. While the transposition of two characters alters the corresponding spatial gradient representation a little (a code of 1 for 窃 and a code of 2 for 偷), the spatial pattern used to encode character positions of the base word is similar to that for the TC nonword. However, unrelated nonwords (垫炼) have totally different character nodes than the corresponding base words (偷窃), and the characters that are not present in the string therefore receive no activation in the spatial gradient representation. Thus, the spatial patterns of the base word and the unrelated nonword are not comparable. In general, for two-character Chinese words, if the spatial coding scheme is involved in the character level of lexical processing system of Taft and Zhu (1997), TC effects can be explained well.

As mentioned previously, free morphemes have explicit meanings by themselves in multiple-morpheme words. Each character of a multiple-morpheme word has its own meaning in a two-character word. Consequently, Chinese characters are similar to morphemes of compound words in English (Taft & Zhu, 1997). Therefore, character order encoding in Chinese may be analogous to morpheme order encoding in English. Some researchers have shown that the presentation of reversed compounds (e.g., *fishgold*) activates the lexical representation of its base word (e.g., *goldfish*), which indicates that English free stems are coded flexibly in relation to their position (Crepaldi, Rastle, Davis, & Lupker, 2013). It seems that the word identification system for English is sensitive to morpheme positional information. Additionally, Angele and Rayner (2013) found that transposed morpheme previews of compound words (e.g., *boycow*) resulted in processing disruption compared to the identity condition (e.g., *cowboy*) in normal sentence reading. This suggests that information about the morpheme order in a multiple-morpheme word is encoded during normal sentence reading. Furthermore, Yang (2013) found reading times on target words were longer in the reverse preview condition than the identical condition when the reverse preview word was implausible in the sentence. Thus, it appears that there is only disruption to the identification of a target word with its constituent characters in the wrong order when the character transposition affects its meaning, which is also consistent with the present results.

In the current study, we found that the character order encoding was similar for single-morpheme words and multiple-morpheme words. This indicated that character order encoding is independent of morphemic structure, and the morphological status of a two-character Chinese word does not modulate character order processing. Thus, we speculate that character order encoding occurs at a very early stage of word identification, before the processing of morphemes.

Even though morpheme structure did not affect character order encoding, the results of the current study showed that single-morpheme words and multiple-morpheme words may be processed differently. In Experiment 1, we found RTs were shorter for multiple-morpheme words than single-morpheme words, and accuracy was higher in multiple-morpheme words than in single-morpheme words. In Experiment 2, multiple-morpheme words were skipped more frequently than single-morpheme words. These results showed that single-morpheme words may be harder to process than multiple-morpheme words during Chinese reading. For single-morpheme words, each constituent character either does not carry its own meaning, or carries a different meaning to the meaning of the whole word. Thus, the meaning of the word can only be accessed when the whole word is fully processed. On the other hand, mostly, one of the characters of a multiple-morpheme word carries the same meaning as the whole word. Thus, accessing the meaning of one character of a multiple-morpheme word may help in accessing the meaning of the whole word. As a result, the processing of the multiple-morpheme word may be easier than the processing of a single-morpheme word.

In summary, we found TC effects for two-character words in Chinese reading, and character order encoding occurred at a very early stage of word recognition. Furthermore, the morphemic structure of a word had no effect on character order encoding in two-character words. Given the fact that little is currently known regarding character order encoding in Chinese reading, the current results represent an early contribution to our understanding of this aspect of cognitive processing.

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