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The Effect of Transposed-Character Distance in Chinese Reading

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Previous research in alphabetic languages has shown that both position (external, internal) and distance (adjacent, nonadjacent) modulate letter position encoding during reading. To examine the generality of this pattern for a comprehensive model of word recognition and reading, we examined these effects during Chinese reading (i.e., an unspaced logographic language). Participants in two experiments read intact sentences and sentences containing transposed-character nonwords while their eye movements were monitored. Experiment 1 manipulated the distance between the transposed characters (adjacent vs. nonadjacent) within three-character words. Reading times were longer when nonadjacent characters were transposed compared with adjacent characters. Also, for adjacent character transpositions, a word-beginning character transposition led to longer reading times than a word-ending character transposition. Experiment 2 manipulated orthogonally character transposition distance (adjacent vs. nonadjacent) and position within four-character words, including the beginning versus the last character. Reading times were longer when the transposition involves the first character than when involves the ending character. Fixation durations on the target regions in the nonadjacent character transposition condition were longer than those in the adjacent character transposition condition. Taken together, these results reveal robust effects of both the initial character position and transposed-character distance in Chinese reading. Thus, the privileged status of the initial character is intrinsically related to how we access lexical information.

Keywords: character transposition, Chinese reading, eye movements

In alphabetic writing systems, the encoding of letter order is a key component of the orthographic processes that underlie lexical access. Otherwise, readers would be unable to distinguish between words such as *stop*, *spot*, *post*, *pots*, or *tops* (Davis, 2010; Gomez et al., 2008; Grainger & van Heuven, 2003; Johnson et al., 2007; Logan, 2021; Whitney, 2001). Nonetheless, anagrams are relatively infrequent in most alphabetic languages, and letter position encoding is somewhat flexible. For instance, readers can read sentences that include jumbled words, such as "Mr. Smith was the jugde in yesterday's trial," with only a small reading cost compared with its corresponding intact sentence. Notably, the reading cost is greater when transposing the initial letter (e.g., *ujdge* instead of *judge*; Rayner et al., 2006; see also Perea et al., 2015; White et al., 2008; for converging evidence in English and Spanish). Character order encoding is also necessary when reading Chinese, a logographic writing system with many unique properties compared with the alphabetic writing system. In Chinese, there are many anagrams such as "蜜蜂" (bee) and "蜂蜜" (honey). However, how character order is encoded is much less well understood in Chinese than in alphabetic languages.

The primary goal of the present eye-movement study was to examine how readers encode character order when reading sentences in an unspaced logographic writing system, Chinese, during normal reading. In particular, we were interested in (a) the role of the initial versus final character of Chinese words, and (b) the degree of flexibility of character position coding by comparing adjacent versus nonadjacent transpositions. Chinese text has a unique structure formed by contiguous equal-width characters with no space to mark word boundaries. Previous research on another unspaced alphabetic language, Thai, has shown that the cost is similar for initial and internal transpositions during sentence reading (Winskel et al., 2012). This diverging pattern may suggest that the unique role of the initial letter position may be more salient in spaced writing systems. However, unlike alphabetic Thai, where

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the relative frequency of some letter combinations may act as a word-boundary cue (see Kasisopa et al., 2013), Chinese readers depend entirely on lexical knowledge to segment words. As we review below, there are still many gaps in the literature on how character order is encoded during sentence reading in Chinese. We first review the literature on letter position coding in alphabetic languages and then introduce the rationale for the experiments performed in this study.

In recent decades, a growing body of word recognition experiments have shown that a transposed-letter (TL) nonword created by transposing two adjacent letters within a word (e.g., *jugde* for the base word *judge*) can activate its base word across a variety of techniques: (a) via masked priming (e.g., faster response times to the word *JUDGE* when preceded by the prime *jugde* than by the replacement-letter control *jupte*; Andrews, 1996; Christianson et al., 2005; Forster et al., 1987; Kinoshita & Norris, 2009; Perea & Acha, 2009; Perea & Carreiras, 2006c; Perea et al., 2008; Perea & Lupker, 2003a, 2003b; Perea et al., 2012; Schoonbaert & Grainger, 2004); and (b) via single-presentation lexical decision, where response times are longer (and more error prone) to the transposed-letter nonword *jugde* than to its control *jupte* (Andrews, 1996; Chambers, 1979; Holmes & Ng, 1993; O'Connor & Forster, 1981; Perea et al., 2005). Furthermore, transposed-letter effects (i.e., the TL effect) have also been reported during sentence reading using (Rayner's, 1975) gaze-contingent boundary change paradigm. In this paradigm, fixation times to a target word embedded in a sentence (e.g., *judge*) are shorter when the parafoveal preview is jugde than when it is jupte (Johnson, 2007; Johnson et al., 2007; Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015; Winskel & Perea, 2013). Finally, other eye-movement studies have compared the reading times of intact sentences versus sentences containing transposed-letter stimuli (e.g., external vs. internal transpositions, as in *judeg* vs. *jugde*). In this latter setup, the more word-like the transposed-letter stimulus is, the lesser the reading cost (Blythe et al., 2014; see also Johnson & Eisler, 2012; Perea et al., 2015; Rayner et al., 2006; White et al., 2008).

While letter position encoding is somewhat flexible in alphabetic writing systems, not all letter positions are equally important. Previous research has consistently shown that external letters are more important than internal letters for letter order encoding (Bruner & O'Dowd, 1958; Johnson & Eisler, 2012; Milledge et al., 2021; Rayner et al., 2006; White et al., 2008). The first study on letter position coding (Bruner & O'Dowd, 1958) showed that participants had more difficulty construing a tachistoscopic jumbled word when the initial letters were transposed (e.g., *vaiation*) than when two internal letters were transposed (e.g., *avitaion*). Similarly, Estes et al. (1976) reported more transposition errors for internal than final letters using a tachistoscopic identification task. Using a single-presentation lexical-decision task, Chambers (1979) found that TL nonwords were more difficult to reject as words when they were constructed by transposing two internal letters (e.g., *eviednce*) than when they were constructed by transposing two initial or two final letters (e.g., *amgazine* or *domestci*). More recent studies also showed that transposing two final letters of a word could cause the TL effects to decrease and even vanish; in contrast, transposing two internal letters showed robust TL effects (Johnson et al., 2007; Perea & Lupker, 2003a, 2003b; Schoonbaert & Grainger, 2004). In summary, results strongly suggest that, in Latin script, the positions of initial and final letters are more important for word recognition than the position of internal letters.

Letter transposition effects have been observed for both adjacent and nonadjacent letter transpositions (one or more intervening letters between the transposed letters; Acha & Perea, 2008; Johnson, 2007; Lupker et al., 2008; Marcet et al., 2019; Perea & Carreiras, 2006a, 2006b, 2008; Perea et al., 2008; Perea & Estevez, 2008; Perea & Fraga, 2006; Perea & Lupker, 2004; Perea et al., 2016; Winskel & Perea, 2013). To examine the flexibility of letter position coding in Latin scripts, some studies have shown that the within-word distance between transposed letters affects the size of TL effects. Perea et al. (2008) manipulated the distance between transposed letters to examine the effect of the number of intervening letters on TL effects. Participants were presented with masked prime TL nonwords where the transposition was adjacent or one or two letters apart within the word. They found a large decrease in the magnitude of the TL effect from adjacent to nonadjacent transpositions with one intervening letter, but a similar TL effect for nonadjacent transpositions from one to two intervening letters. Similarly, Ktori et al. (2014) found a stronger TL effect for an adjacent transposition than a nonadjacent transposition with two intervening letters in lexical decisions.

Similarly, eye-movement studies also showed that the distance between transposed letters increased reading time during sentence reading (see Blythe et al., 2014; Pagán et al., 2016). For instance, Pagán et al. (2016) found that TL effects were stronger in position 2 and 3 transpositions (e.g., *cpatain*) than in position 1 and 2 (e.g., *acptain*) or position 1 and 3 transpositions (e.g., *pactain*). When a word's first letter was involved in transpositions, TL effects decreased considerably compared with internal letter transpositions, regardless of whether letter transpositions were adjacent or nonadjacent. Additionally, Pagán et al. (2021) found that position 1 and 3 transpositions caused more disruption than position 2 and 3 transpositions during a reading-like task. These results suggest that nonadjacent transpositions that included the word's initial letter caused more reading cost than adjacent transpositions that only included internal letters. Thus, results show that the distance between two transposed letters affects word processing in Latin scripts.

Current models of word recognition can easily capture the differences in letter position encoding between initial, internal, and final letter positions and the differences between adjacent and nonadjacent transpositions. For instance, in the models based on the idea of "open bigrams" (open bigram model: Grainger, & van Heuven, 2003; Schoonbaert & Grainger, 2004; SERIOL model: Whitney, 2001), a letter string is coded in terms of all of the ordered letter pairs that it contains, which corresponds to a set of open-bigram units. Bigrams closer to the word beginning are activated earlier and to a greater extent than those located farther into the word. This positional gradient of activation across words leads to stronger activation of word-initial letters relative to word-internal letters. In addition, the activation of the word-final letter would be greater than the interior letters because it suffers less lateral interference due to the following space. For the effect of distance, bigrams with closer proximity between the two letters are activated to a larger extent than those where the two letters are farther apart (see Whitney, 2008). Thus, adjacent letter transpositions are more effective than nonadjacent transpositions from one to two intervening letters; thus, resulting in longer reading times in nonadjacent transpositions than in adjacent transpositions. Similarly, other models of word recognition can explain these same effects that rely on different mechanisms (e.g., spatial coding model, Davis, 2010; overlap model, Gomez et al., 2008; Bayesian reader, Norris & Kinoshita, 2012). For instance, in the overlap model, both effects can be explained by perceptual uncertainty associated with each letter position, where the initial letter position has the smallest variability.

Overall, letter position encoding has been studied thoroughly in alphabetic writing systems, and results have shown that letter position coding in word identification is quite flexible. Notably, the degree of flexibility in letter position coding can be influenced by various factors, including the position of transposed letters within a word (external vs. internal) and the distance between the transposed letters. However, few studies have been designed to investigate character position encoding in Chinese. Unlike alphabetic writing systems, a Chinese text comprises successive characters that are separated by equal-sized small spaces. A word can consist of 1, 2, 3, 4, or more characters. About 6% of Chinese words are single-character words, 72% are two-character words, 12% are three-character words, and 10% are four-character words. Less than .3% of Chinese words are longer than four characters (Lexicon of Common Words in Contemporary Chinese Research Team, 2021). There are no spaces or other physical cues that demarcate words in Chinese texts. Therefore, Chinese readers must determine word boundaries and segment strings of characters into words using their lexical knowledge (see Li et al., 2009, 2013, 2014; Ma et al., 2014). This property might affect how Chinese readers encode character orders during sentence reading.

Previous research has demonstrated that character position encoding is not absolutely strict in Chinese. Gu et al. (2015) examined how character position information is encoded in isolated word identification (via masked priming) and sentence reading (via the boundary technique). In Experiment 1, Gu et al. found that response latencies on the two-character words were longer in the unrelated nonword condition (e.g., “灿橡”) than in the transposed-character (TC) nonword condition (e.g., “讽嘲”), which in turn were longer than the identity condition (e.g., “嘲讽,” meaning *taunt*). These results suggest that robust TC priming effects exist in word recognition—the TC priming effect was 126 ms. Also, they found a similar pattern in a parafoveal preview experiment during sentence reading (a 50 ms TC effect in gaze duration). In addition, Yang et al. (2019, 2020) found a large masked priming effect (more than 50 ms) with four-character Chinese words in which the primes were presented in a backward direction (right-to-left; i.e., 是为以自-自以为是 [self-righteousness]; see Yang et al., 2019, 2020). Thus, the encoding of character position appears to be flexible in Chinese. Of note, a recent study on a related phenomenon, the transposed-word effect (e.g., “you that read wrong” being processed as “you read that wrong”; see Mirault et al., 2018), showed that this effect was quite robust in Chinese regardless of the length of the transposed word (one character, e.g., “接我” vs. “我接”; two characters, e.g., “山上看见” vs. “看见山上”; three characters, e.g., “看上去很” vs. “很看上去”) in a grammatical decision task (see Liu et al., 2020). Thus, these findings suggest a high degree of flexibility when encoding serial order in Chinese reading, both for characters within words and words within sentences.

Additionally, one study has shown that cross-word character transpositions are more disruptive than within-word character transpositions in sentence reading (Gu & Li, 2015). Gu and Li embedded two types of target words, four-character words (one-word condition; e.g., “言简意赅”) and two two-character words (two-word condition; e.g., “逻辑清晰”), in one sentence frame, and then manipulated the previews of the words using the boundary paradigm. The middle two characters of target words were manipulated, and there were three preview conditions for each target: identity, TC, and SC (substituted-character) conditions. Fixation durations on the target word in the TC condition were much longer than those in the identity condition for the two-word condition; however, they were not significantly different for the one-word condition. Also, for the one-word condition, gaze durations were longer in the SC than in the TC condition, while for the two-word condition, the difference between the TC and SC conditions was not significant. These findings suggest that a cross-word character transposition (two-word condition) affects character position processing. At the same time, TC effects are robust for a within-word character transposition (one-word condition). Thus, word boundaries play an important role during character position encoding in Chinese reading (Gu & Li, 2015).

We should note that the findings and theories of letter order encoding developed for reading of alphabetic writings cannot necessarily be generalized to Chinese reading because the characters in Chinese script have many unique properties (Li et al., 2022). On the one hand, Chinese characters are salient visual units in Chinese reading, like letters in alphabetic writing systems. Therefore, one could argue that character order encoding could be similar to letter order encoding in an alphabetic writing system. On the other hand, each Chinese character simultaneously represents a syllable and a morpheme. Furthermore, Chinese characters are constituted by radicals, which in turn are constituted by a number of strokes (e.g., “一” means one, and “餐” means meal; see Yan et al., 2012). Therefore, one might argue that character order encoding in Chinese cannot be simply analogous to letter order encoding in alphabetic writing systems. To some extent, character order encoding could be analogous to morpheme order encoding in reading of alphabetic writings, and radical order encoding could be analogous to letter order encoding in alphabetic writings systems. Given these differences in writing systems, it is hard to say whether Chinese character order encoding is similar to letter order encoding or morpheme order encoding in alphabetic writings systems. Indeed, previous studies have shown that the effect of transposing two radicals is different from that transposing two letters in alphabetic writing systems. Taft et al. (1999) examined the radical position coding of transposable characters (e.g., “杏” vs. “呆,” “陪” vs. “部”) with character decision and naming tasks. Results suggest that the radical-level representation activated in each transposable character is easily distinguished and leads to minimal interference. Based on these findings, Taft et al. argued that radicals have position-specific representations, and radical position encoding is not flexible in Chinese character processing. This conclusion does not support the argument that radical position encoding in Chinese reading is analogous to letter order encoding in alphabetic writing systems. Taken together, how Chinese readers encode character orders may have some unique properties. Therefore, how the brain encodes the order of characters in Chinese words in Chinese may be quite different to how the brain encodes letter position in words in alphabetic languages; thus, requiring specific models of word recognition and reading in Chinese reading. The current study attempted to understand how Chinese readers encode the order of characters in words.

In the present study, we seek to answer the questions: (a) "How does the position of transposed characters within a word modulate the effects of TC distance in Chinese reading?" and (b) "How does nonadjacent character transposition affect word recognition during Chinese reading?" While there have been several studies examining transposed-character effects in Chinese (see above), none of the above effects (position: initial, internal, final; distance: adjacent, nonadjacent) have yet been studied. To date, models of word recognition and reading in Chinese (e.g., Li & Pollatsek, 2020; Perfetti et al., 2005; Taft & Zhu, 1997) have not yet been expanded to deal with the encoding of character position during lexical access. Thus, the answer to the two above questions would not only help determine to what degree these phenomena may be dependent on the nuances of the writing system, but they may also serve to refine and constrain models of word recognition in reading in Chinese.

Regarding the first question, we examined whether character encoding of the initial and final characters play similar or different roles. As reviewed above, previous studies on alphabetic writing systems showed that external letters are more important than internal letters concerning letter order encoding, particularly the word-initial position (Bruner & O'Dowd, 1958; Johnson & Eisler, 2012; Rayner et al., 2006; White et al., 2008). However, we must consider that there are spaces between words to demarcate words in alphabetic writing systems, which could be the reason why external letters have the greatest importance. If low-level visual features caused the differences in letter position coding of the initial versus final characters (e.g., interword spaces) in Latin script, one would not expect a parallel effect in Chinese reading. However, if this effect was caused by other factors, such as higher-level cognitive factors—note that no cues are marking the word boundaries in Chinese, one would expect a prominent role for the initial character position in Chinese reading. The model of word processing and eye-movement control during Chinese reading (Chinese Reading Model, CRM) proposed by Li and Pollatsek (2020) predicts that the left character of a multicharacter word has processing advantages over other characters of the word. According to CRM, all characters in the perceptual span are processed in parallel with the constraint of visual acuity, and all words constituted by these activated characters are activated and compete for a winner. Because the eyes move from left to right, characters on the left have priority of processing and play more important roles when activating the constituted word. Thus, the initial character plays a more critical role than the final character in the Li and Pollatsek model.

The second question examined how transposing characters with different distances affects word processing and how they interact with character position within a word. All models of letter order encoding (i.e., those based on position uncertainty and those based on an intermediate level of open bigrams) assume that transposing letters with more intervening letters affects letter order encoding more than transposing neighboring letters (see Perea et al., 2008, for discussion). Our focus here was not to test a general effect of distance, but rather to examine whether the distance effect in Chinese is shaped depending on whether transposition effects occur at the beginning or end of a word. If character position is encoded similarly across word positions, as occurs in an unspaced alphabetic script such as Thai (Winskel et al., 2012), the distance effect should be similar regardless of the position of the transposed characters.[1] This outcome would reveal that, in Chinese, a character's identity is more important than its exact position within a word. Alternatively, if the initial character plays a central role during word processing, character transpositions that include the beginning character should modulate the effect of transposed-character distance more than the transposition of characters that include the ending character. Also, in this latter scenario, the reading cost should be much stronger when the first character is involved in transposition, regardless of whether it is an adjacent or nonadjacent transposition.

To test the above predictions, we designed Experiment 1. We used three-character words as targets, and these words were embedded in sentences. Participants had to read normally regardless of whether some of the characters could be jumbled while an eye movement device recorded their eye movements. There were four conditions for each target word: (a) the target word was presented correctly (intact condition); (b) the adjacent transposition including the beginning character of the target word (1–2 initial condition); (c) the adjacent transposition including the last character of the target word (2–3 final condition); and (d) the nonadjacent transposition with the first and last characters transposed (1–3 nonadjacent condition). An effect of distance would be reflected in longer fixation durations in the nonadjacent than in the adjacent conditions, and an effect of position (initial vs. final) would be reflected in a stronger disruption when the beginning character was involved in transposition. To examine in further detail whether the effects of TC distance were related to positions of transposed characters, we designed Experiment 2. The procedure was similar to Experiment 1, but using four-character words as targets. Critically, the increased length allowed us to have five display conditions for each target word: (a) intact condition; (b) adjacent transposition including the beginning character of the target word (1–2 condition); (c) nonadjacent transposition, including the beginning character of the target word (1–3 condition); (d) adjacent transposition including the last character of the target word (3–4 condition); and (e) nonadjacent transposition, including the last character of the target word (2–4 condition). Thus, Experiment 2 allowed us to examine whether character positions (initial vs. final) had a different impacts on effects of TC distance. If the initial character position has a special role in Chinese (see Li & Pollatsek, 2020), character transpositions involving the beginning character might affect the effect of TC distance to a greater degree than would the transposition of characters included the ending character.

It should be noted that many of three- and four-character words we used in the present study are idioms or set-phrases. We refer these items as words in the present article for the following reasons. First, according to an influential textbook on Chinese Linguistics (Huang & Liao, 2007), set phrases and idioms are usually

[1] Recent research using individual letter strings in Thai has found that the initial letter is less salient than in Latin-based scripts when encoding letter position (see Perea et al., 2018)—note that, unlike English or Chinese, some of the initial letters in Thai may be misaligned (e.g., the initial letter of a stimulus like "ebn" would be pronounced as if it were the second letter, as in "ben"; see Perea et al., 2018, for details).

categorized as words because they have fixed structural forms and have stable meanings. Second, most set phrases are listed as words in Chinese dictionaries (Lexicon of Common Words in Contemporary Chinese Research Team, 2021, 7th edition). Finally, recent experimental studies have shown that idioms and set phrases in Chinese are processed as a whole, just as words (e.g., see Li & Ma, 2012; Li et al., 2009; Zang, 2019; Zang et al., 2021; Zhou & Li, 2021). For instance, Li et al. (2009) asked Chinese readers to report as many characters as possible after they saw four briefly presented Chinese characters, participants could usually report all of the four characters when they belonged to a word, but they could only report the first two characters when the four characters belonged to two words. In Li et al.'s stimuli, most four characters words were indeed set phrases. Based on these findings, Li et al., argued that words (even for four-character set phrases) are processed as a whole during Chinese reading. Likewise, using a boundary paradigm, Zang et al. (2021) showed that some three-character idioms such as "垫脚石" (means steppingstone) are processed as a whole with parafoveal vision. Moreover, some Chinese reading models also assume that these idioms are stored as an item in the lexicon so that they could be processed as a whole (see Li et al., 2009; Li & Pollatsek, 2020). As made clear by the Multi-Constituent Units (MCU) theory (Zang, 2019; Zang et al., 2021), these findings indicated that idioms have been lexicalized so that they are processed like words during Chinese reading. Indeed, the MCU Hypothesis (Zang, 2019; Zang et al., 2021) specifies that frequently occurring multiword units are lexicalized and processed (segmented and identified) as a whole, that is, they are processed as words even though they are formed from multiple elements that themselves could be individual words. Indeed, many words are formed by lexicalization (Packard, 2004, p. 216). For example, the word "吃饭" (means have a meal) are constituted by two morphemes ("吃" means eat, and "饭" means rice), with both "吃" and "饭" can be words by themselves. In summary, idioms and set phrases in Chinese appear to be lexicalized; thus, we refer them as words in the current study.

Experiment 1

Method

Participants

A total of 40 native Chinese speakers (average age: 22.0 years) who were undergraduate or postgraduate students from universities near the Institute of Psychology, Chinese Academy of Sciences, participated in the study. They were paid 30 RMB (approximately $4) to participate in the experiment. All participants had normal or corrected-to-normal vision, and all were naive regarding the purpose of the experiment. The study was approved by the ethics committee of the Institute of Psychology, Chinese Academy of Sciences, and each participants provided written consent in accordance with the approved protocols.

Materials and Design

The experimental items included 64 single-line sentences, each containing a three-character target word. All three-character words are listed as words in a dictionary (Lexicon of Common Words in Contemporary Chinese Research Team, 2021). Also, none of the two contingent characters of a target word constitutes a two-character word by itself. The sentence ranged from 20 to 29 characters. The target words were in the middle of the sentence, such that the distance was at least six characters away from the beginning and the end of the sentence. Additionally, participants read eight sentences for practice before the formal experiment.

Four display conditions were generated for each target word: (a) the intact condition, where the target word was presented correctly (e.g., "燕尾服," C1C2C3, meaning *tuxedo*); (b) the 1–2 initial condition, where an adjacent transposition including the beginning character of the target word was presented (e.g., "尾燕服," C2C1C3); (c) the 2–3 final condition, where an adjacent transposition including the last character of the target word was presented (e.g., "燕服尾," C1C3C2); and (d) the 1–3 nonadjacent condition, where the first and last characters were transposed nonadjacently (e.g., "服尾燕," C3C2C1). In all four conditions, the first character of the target region did not form a word with the character(s) before it. Similarly, the last character of the target region did not form a word with the character(s) following it. The frequencies of the three-character target words ranged from .05 to 3.15 occurrences per million (M = .76, SD = .67). In addition, the frequency of three characters (the first character: M = 801 occurrences per million, SD = 1420; the second character: M = 784 occurrences per million, SD = 1002; the last character: M = 828 occurrences per million, SD = 1649) was matched, and they did not differ from one another ($F(2, 126) < 1$). The strokes of three characters (the first character: M = 9.03, SD = 3.08; the second character: M = 8.98, SD = 3.01; the last character: M = 9.14, SD = 3.22) were matched, and they did not differ from one another ($F(2, 126) < 1$).

To ensure that the TC nonwords could be correctly identified, eight participants were asked to read experimental sentences and mark the words they could not understand. None of the TC nonwords was marked as not understandable. All participants could give the original word of transposed-character nonword. These participants did not participate in the eye-tracking section of the experiment. Each participant read 16 items in each of the four display conditions, and no sentence was viewed more than once. A sample sentence frame is shown in Table 1.

To ensure that the target words were plausible in the sentence context, 10 participants were recruited to judge how well each target word matched the given sentence frame on a scale of 1 = *not natural at all* to 7 = *very natural*. All target words were rated as natural within their respective sentence frames (M = 6.25, SD = .25; range = 5.80–6.90). These participants did not participate in the eye-tracking section of the experiment.

To evaluate the predictability of target words, 10 participants, who did not participate in the eye-movement experiment, read the

Table 1
Sample Experimental Sentence in Experiment 1

Display	Example
Intact	老伯爵穿着蓝色燕尾服走到跳舞的年轻人跟前。
1–2 initial	老伯爵穿着蓝色尾燕服走到跳舞的年轻人跟前。
2–3 final	老伯爵穿着蓝色燕服尾走到跳舞的年轻人跟前。
1–3 nonadjacent	老伯爵穿着蓝色服尾燕走到跳舞的年轻人跟前。

Note. The target word is 燕尾服. English translation: The old count in his blue **tuxedo** went up to the young people who had been dancing.

first part of the experimental sentence up to but not including the target word and were asked to predict the next word in the sentence. The predictability of the items was near zero, indicating that the target words were not predictable from their preceding contexts.

Apparatus

Eye movements were recorded using an SR EyeLink 1000 tracker, which had an arc resolution of approximately 30′. Participants read the target sentences (printed horizontally from left to right) on a 21-in. CRT monitor (SONY Multiscan G520) connected to a Dell computer. Each sentence was displayed on a single line in Song 20-point font, and the characters are shown in black on a gray background. The eye-tracking system was sampled at 1,000 Hz and provided eye-movement data for analysis using 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, each character subtended .8° of the visual angle.

Procedure

Participants were instructed to read the sentences normally and to answer the questions by pressing a button on the button box to respond. First of all, the eye tracker was calibrated at the beginning of the experiment and then recalibrated when required. For calibration and validation, participants were asked to look at a dot shown at each of the three locations horizontally arranged at the center of the display in a random order. The maximum permitted error for validation throughout the experiments was .5°. After validation, participants were asked to read eight practice sentences to familiarize themselves with the procedure.

Experimental sentences were presented randomly and one at a time in the center row of the monitor. Each trial began with a drift check procedure, during which the participant fixated on a circle located at the center of the monitor. After a drift check, a white square box (1° × 1°) appeared on the monitor at the location corresponding to the area where the first character of the sentence would appear. Once the eye tracker detected that the participant was looking at the box, a sentence was shown. The sentence remained on the screen until the participant finished reading the sentence. Participants were told to read silently and at a normal pace, and to press a button on the response box when they had finished reading the sentence. There were 32 filler items intermixed with the 64 experimental items, and the experimental procedure was repeated until all sentences had been read.[2] A Latin square design was used, and the presentation of the 96 items occurred in a random order for each participant. For the experimental items, the sentences were counterbalanced across conditions, and participants saw only one condition with each sentence frame and saw an equal number of each type of target. Participants were required to answer comprehension questions after approximately 30% of the sentences to ensure that they were reading the sentences carefully. Participants pressed a button on a response box to answer multiple-choice questions. The entire experimental procedure took approximately 20 min. Experimental materials, data, and analysis code can be found at Open Science Framework (OSF; https://osf.io/vpbqt/).

Results and Discussion

The accuracy of the sentence comprehension questions was high (95%), suggesting that the participants understood the sentences well. 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 track loss occurred during a trial. Extremely short (<80 ms) isolated fixations and extremely long (>1,000 ms) fixations were excluded from the data set before analysis. A total of 4.4% of the data were eliminated.

We calculated first fixation duration, gaze duration, go-past time, total time, skipping probability, and refixation probability in the target region, which were three characters long for all conditions (see Table 2). First fixation duration refers to the amount of time spent on the initial fixation on the target word, regardless of whether one or more fixations occurred. Gaze duration is the sum of fixation durations on the target word before the reader leaves that target. Go-past time is the amount of time that the reader looked at the target word, and any time spent rereading earlier parts of the sentence before moving ahead to inspect new portions of the sentence. Total time represents the sum of the duration of all fixations on the target, including regressions. Skipping probability refers to the probability that the target word was skipped on first-pass reading. Refixation probability is the probability that readers make more than one fixation in the first pass reading on the target word.

Data were analyzed using a linear mixed-effect model (LMM) with the *lme4* package (Bates et al., 2014) within the R Environment for Statistical Computing (R Development Core Team, 2016). For fixation duration measures, we report regression coefficients (b), which estimate the effect size, and the t-value of the effect coefficient. We also estimated and reported the p-values for the effects using the summary function from the *lmerTest* package (Kuznetsova et al., 2014). Because fixation durations were not normally distributed, individual (trial-based) fixation durations were log-transformed. Following Schad et al. (2020), we directly tested theoretically motivated hypotheses using customized contrasts with the linear mixed-effect model. In this study, we tested the following three customized contrasts: (1) a transposition comparison that compares the intact condition with the mean of the other three conditions in which two characters were transposed; (2) a transposition position comparison that compares the 1–2 initial condition with the 2–3 final conditions; and (3) a transposition distance comparison that compares the 1–2 initial condition with the 1–3 nonadjacent condition. Following Barr et al. (2013), we started with a maximum random factor structure. For each of the three contrasts, participants and items were entered as crossed random effects, including intercepts and slopes. When a maximum model failed to converge, we used a zero-correlation parameter model and dropped random components that generated the smallest variances until the model converged.

[2] Filler items were all intact well-written sentences.

Table 2
Means Fixation Durations (and Standard Errors) by Display Condition in Experiment 1

Measure	Intact	2–3 final	1–2 initial	1–3 nonadjacent
First fixation	272 (7)	272 (6)	284 (6)	299 (7)
Gaze duration	416 (17)	432 (19)	495 (27)	586 (34)
Go-past time	526 (22)	589 (37)	699 (39)	891 (50)
Total time	637 (27)	836 (62)	910 (59)	1,120 (61)
Skipping probability	.04 (.01)	.04 (.01)	.05 (.01)	.03 (.01)
Refixation probability	.51 (.03)	.51 (.03)	.58 (.04)	.67 (.04)

Reading times of the target regions in the intact condition were shorter than the mean of the other three conditions (first fixation duration: $b = -.03$, $SE = .02$, $t = -2.00$, $p = .050$; gaze duration: $b = -.13$, $SE = .03$, $t = -5.07$, $p < .001$; go-past time: $b = -.22$, $SE = .04$, $t = -6.05$, $p < .001$; and total time: $b = -.31$, $SE = .04$, $t = -8.12$, $p < .001$). Reading times in the 1–2 initial condition were longer than those in the 2–3 final condition (first fixation duration: $b = .02$, $SE = .01$, $t = 2.37$, $p = .020$; gaze duration: $b = .06$, $SE = .02$, $t = 3.85$, $p < .001$; go-past time: $b = .08$, $SE = .02$, $t = 3.39$, $p = .001$; total time: $b = .06$, $SE = .02$, $t = 2.87$, $p = .006$). Reading time in the 1–3 nonadjacent condition was longer than that in the 1–2 initial condition. This effect was significant for gaze duration, $b = -.07$, $SE = .02$, $t = -4.17$, $p < .001$, go-past time, $b = -.11$, $SE = .02$, $t = -5.21$, $p < .001$, and total time: $b = -.11$, $SE = .02$, $t = -5.85$, $p < .001$. However, this effect was not significant for first fixation duration, $b = -.01$, $SE = .01$, $t = -1.25$, $p = .219$—we defer a discussion of the small effects on first-fixation durations until Experiment 2. In addition, there was no significant difference between the intact condition and the mean of the other three conditions in the skipping probability, $b = .23$, $SE = .27$, $t = .88$, $p = .378$. There was no significant difference between the 1–2 initial condition and the 2–3 final condition, $b = .24$, $SE = .18$, $t = 1.35$, $p = .178$. There was no significant difference between the 1–3 nonadjacent condition and the 1–2 initial condition, $b = .22$, $SE = .16$, $t = 1.37$, $p = .172$. The refixation probability of the target regions in the intact condition were lower than the mean of the other three conditions, $b = -.39$, $SE = .12$, $t = -3.18$, $p = .001$. The refixation probability in the 1–2 initial condition were higher than those in the 2–3 final condition, $b = .16$, $SE = .06$, $t = 2.44$, $p = .015$. The refixation probability in the 1–3 nonadjacent condition was higher than that in the 1–2 initial condition, $b = -.25$, $SE = .08$, $t = -3.30$, $p < .001$.

The results of Experiment 1 revealed two main phenomena. First, there is a reading cost with transposed-character nonwords compared with its corresponding intact sentence; thus, extending earlier research using Latin script (e.g., see Rayner et al., 2006; for the first demonstration; see also Gu et al., 2015; for evidence with two-character words in Chinese). Second, there is an effect of transposed-character distance in Chinese reading. Specifically, a stronger disruption was associated with nonadjacent character transpositions than adjacent character transpositions. This pattern is consistent with previous findings in alphabetic writing systems (Blythe et al., 2014; Perea et al., 2008). Also, for adjacent character transpositions, word-beginning character transpositions produce larger disruptions than word-ending character transpositions in word processing. This finding suggests that word-beginning characters may be more important than word-ending characters in word identification in Chinese.

Experiment 2

In Experiment 1, we examined the effect of transposed-character distance in Chinese reading. However, both word-beginning and word-ending characters were involved in the nonadjacent transposition condition in Experiment 1. It is unknown, however, about whether positions of transposed characters within a word affect nonadjacent character transpositions. Therefore, in Experiment 2, we used four-character target words to investigate whether word-beginning or word-ending character transpositions modulate the effect of transposed-character distance in Chinese sentence reading.

Method

Participants

A total of 50 native Chinese speakers (average age = 21.4 years) who were from the same participant pool as that in Experiment 1 participated in Experiment 2. They were paid 30 RMB (approximately $5) to participate in the experiment, and none of them had participated in Experiment 1. All participants had normal or corrected-to-normal vision, and were all unaware of the purpose of the experiment.

Materials

The experimental items included 80 single-line sentences, each containing one 4-character word. All these words are listed as words in a dictionary (Lexicon of Common Words in Contemporary Chinese Research Team, 2021), and all of these four-character words are set phrases. In Chinese, most set phrases are composed of four characters with fixed structural form. Also, no two or three contiguous characters in the four-character words constituted a two- or three-character word. The sentences ranged from 22 to 30 characters in length. The target words were in the middle of the sentence, such that the distance was at least seven characters away from the beginning and the end of the sentences. Additionally, eight sentences were read for practice before the formal experiment.

Five display conditions were generated for each target word: (a) the intact condition, where the target word was presented correctly (e.g., "目不转睛," C1C2C3C4, meaning *fixate eyes on*); (b) the 1–2 condition involved an adjacent transposition including the beginning character of the target word (e.g., "不目转睛," C2C1C3C4); (c) the 1–3 condition involved a nonadjacent transposition including the beginning character of the target word (e.g., "转不目睛," C3C2C1C4); (d) the 3–4 condition involved an adjacent transposition including the ending character of the target word (e.g., "目不睛转," C1C2C4C3); and (e) the 2–4 condition involved a nonadjacent transposition including the ending character of the target word (e.g., "目睛转不," C1C4C3C2). The four-character string after transposing two characters within the target words did not constitute any word, nor did any two or three contiguous characters. The frequencies of the four-character words ranged from .05 to 3.16 occurrences per million ($M = .71$, $SD = .58$). In addition, the frequency of four characters (the first character: $M = 1{,}374$ occurrences per million, $SD = 1{,}707$; the second character: $M = 1{,}624$

occurrences per million, SD = 2,559; the third character: M = 1,698 occurrences per million, SD = 2,193; and the last character: M = 1,323 occurrences per million, SD = 1,104) was matched, and they did not differ from one another ($F(3, 237) < 1$). The strokes of four characters (the first character: M = 8.18, SD = 2.59; the second character: M = 7.84, SD = 3.38; the third character: M = 7.85, SD = 2.82; and the last character: M = 8.29, SD = 3.08) were matched, and they did not differ from one another ($F(3, 237) < 1$).

We recruited 20 participants to estimate the naturality and predictability of the experimental sentence frames. All target words were rated as natural within their respective sentence frames (M = 6.19, SD = .30, ranging from 5.50 to 6.70). The predictability of the items was near zero, indicating that the target words were not predictable from their preceding contexts. These participants did not participate in the formal experiment. There were five versions for each sentence frame. Each participant was asked to read only one version of each sentence frame. Thus, each participant read 16 items in each of the five display conditions, and no sentence was viewed more than once. The sample sentence frame is shown in Table 3.

Apparatus

The apparatus was identical to that used in Experiment 1.

Procedure

The procedure was identical to that used in Experiment 1. There were 48 filler items.

Results and Discussion

The accuracy of the sentence comprehension questions was high (94%), suggesting that the participants understood the sentences well. Approximately 3.6% of the trials were excluded using the same selection criterion as in Experiment 1. We measured first fixation duration, gaze duration, go-past time, total time, skipping probability, and refixation probability in the target region, which were four characters long for all conditions (see Table 4). Similar to Experiment 1, individual (trial-based) fixation durations were log-transformed. For each of the four eye-movement measures, we tested the following customized contrast in the linear mixed effect model: (a) a transposition comparison that compared the intact condition with the mean of the other four conditions in which two characters were transposed; (b) a main effect of the positions of transposed characters, comparing the transposition involving the first character or the last character of the target words (1–2 and 1–3 against 2–4 and 3–4); (c) a main effect of transposed-character distance (1–2 and 3–4 against 2–4 and 1–3); and (d) the interaction of the positions of transposed characters and transposed-character distance. Similar to Experiment 1, we started with a maximum random factor structure, with character transposition positions, character transposition distance, and their interaction being entered as fixed effects. Participants and items were entered as crossed random effects, including intercepts and slopes. When a maximum model failed to converge, we used a zero-correlation parameter model and randomly dropped the components that generated the smallest variances until the model converged.

Reading times on the target region in the intact condition were shorter than the mean of the other four nonintact conditions. The effects were significant for gaze duration ($b = -.07$, SE = .02, $t = -4.37$, $p < .001$), go-past time ($b = -.12$, SE = .02, $t = -4.98$, $p < .001$), and total time ($b = -.12$, SE = .02, $t = -5.41$, $p < .001$). However, the effect was not significant for first fixation duration ($b = -.02$, SE = .01, $t = -1.44$, p = .157). Reading times were longer when the transposed characters included the first character compared with the last character. This effect was significant for gaze duration ($b = -.05$, SE = .02, $t = -2.44$, p = .017), go-past time ($b = -.12$, SE = .02, $t = -5.02$, $p < .001$), and total time ($b = -.08$, SE = .02, $t = -3.91$, $p < .001$), but was not significant for first fixation duration ($b = -.01$, SE = .01, $t = -.95$, p = .343). Reading times were longer in the nonadjacent character transposition condition than the adjacent character transposition condition. This effect was significant for gaze duration (b = .06, SE = .02, t = 2.57, p = .014), go-past time (b = .07, SE = .02, t = 2.94, p = .005), and total time (b = .07, SE = .02, t = 3.19, p = .002), but was not significant for first fixation duration (b = .02, SE = .01, t = 1.57, p = .119). The interaction between character transposition positions and character transposition distance was not significant for first fixation duration (b = .04, SE = .03, t = 1.42, p = .163), go-past time (b = .03, SE = .05, t = .52, p = .606), and total time (b = .03, SE = .05, t = .60, p = .554). The interaction between character transposition positions and character transposition distance only approached significance for gaze duration (b = .08, SE = .04, t = 1.81, p = .079).[3]

None of the effects of skipping probability on the target region approached significance (the main effect of transposition, $b = -.19$, SE = .87, $t = -.22$, p = .823; the main effect of transposition position, b = .07, SE = .44, t = .16, p = .874; the main effect of transposed-character distance, b = .24, SE = .43, t = .56, p = .576; and the interaction between the two factors, $b = -.64$, SE = .99, $t = -.65$, p = .515). The refixation probability on the target region in the intact condition was lower than the mean of the other four nonintact conditions, $b = -.36$, SE = .08, $t = -4.72$, $p < .001$, and was higher in the nonadjacent character transposition condition

Table 3
Sample Experimental Sentence in Experiment 2

Display	Example
Intact	大厅里的人们都在目不转睛地盯着日元汇率的走向。
1−2	大厅里的人们都在不目转睛地盯着日元汇率的走向。
1−3	大厅里的人们都在转不目睛地盯着日元汇率的走向。
3−4	大厅里的人们都在目不睛转地盯着日元汇率的走向。
2−4	大厅里的人们都在目睛转不地盯着日元汇率的走向。

Note. The target word is 目不转睛. English translation: The people in the lobby looked at the trend of yen rate **with all their eyes**.

[3] During the revision phase of a previous version of this paper, we ran an additional 15 participants to examine whether the numerical trend towards an interaction between character position and transposition distance for gaze duration could be real. With these extra participants, the interaction reached significance (b = 0.09, SE = 0.03, t = 2.71, p = .010). However, testing additional participants after seeing the results may increase the chance for a false positive (e.g., see Simmons et al., 2011). Thus, we prefer not to over-interpret this finding with the additional participants and we only included the original analyses in the main text. Indeed, none of the other dependent variables show this interaction in either analysis. Of note, for gaze durations, the Bayes Factor ratio between a model with interaction and a model without interaction was .644 in the original analyses (i.e., no evidence in favour of an interaction)—it increased to 4.063 after adding the 15 extra participants.

Table 4
Means Fixation Durations (and Standard Errors) by Display Condition in Experiment 2

Measure	Intact	1–2	1–3	3–4	2–4
First fixation	262 (5)	272 (7)	268 (6)	259 (5)	272 (6)
Gaze duration	440 (21)	514 (30)	519 (31)	438 (20)	498 (27)
Go-past time	538 (29)	716 (55)	754 (61)	579 (41)	641 (46)
Total time	689 (49)	866 (69)	925 (79)	757 (61)	849 (75)
Skipping probability	.01 (.01)	.01 (.01)	.02 (.01)	.02 (.01)	.01 (.01)
Refixation probability	.56 (.03)	.63 (.04)	.67 (.04)	.60 (.04)	.67 (.04)

than the adjacent character transposition condition, b = .28, SE = .09, t = 3.14, p = .002. None of the other effects was significant (the main effect of transposition position, b = −.09, SE = .09, t = −1.03, p = .305; and the interaction between the two factors, b = .18, SE = .18, t = 1.01, p = .312).

Thus, Experiment 2 showed both the effect of positions of transposed characters and the effect of transposed-character distance during Chinese reading. First, reading times were longer in the nonadjacent character transposition condition than in the adjacent character transposition condition. Thus, there is an effect of transposed-character distance existed in four-character words in Chinese reading. Second, reading times were longer when the transposed characters included the first character than the last one. This finding revealed that the initial character was more important than the final character.

Concerning first-fixation durations, the differences between the intact condition and the mean of the other four nonintact conditions, and the differences between the nonadjacent character transposition condition and the adjacent character transposition condition were small and nonsignificant—note that a similar pattern also occurred in Experiment 1. Critically, these same effects were sizable and statistically robust for other eye-movement measures. One possible reason for this dissociation is that character order encoding in Chinese during sentence reading—perhaps because of the complexity of the characters—does not occur as early as in alphabetic languages (e.g., see White et al., 2008, for evidence of sizable transposed-letter effects on first-fixation durations when reading English sentences). Further research is necessary to shed light on this dissociative pattern in English and Chinese (e.g., running an experiment with Chinese-English bilinguals in both languages), but this would be beyond the scope of this article.

General Discussion

We investigated how transposed-character distance and the position of the transposed characters within a word (initial vs. final) jointly affect word processing in Chinese reading in two eye-movement experiments. Three major findings were observed. First, fixation durations on the target word were longer when transposing two characters compared with intact sentences. Second, the cost of character transposition was greater when the transposition involved the first character of a word than when it involved the ending character of a word. Third, the reading cost for the jumbled words was greater when they were created with nonadjacent characters than when they were created with adjacent characters. We now discuss the implications of these findings for models of visual word recognition.

Reading times were longer for words with transposed characters than intact words, revealing a reading cost with transposed-character nonwords compared with its corresponding intact sentence. This result confirmed previous findings with two-character word targets in Chinese reading (Gu et al., 2015). In Chinese, as also occurs in Latin-based scripts (e.g., Rayner et al., 2006), there is a cost involved in reading words with transposed characters compared with intact text. While readers can effectively read sentences with jumbled words, as deduced from the comprehension scores, this comes with a cost in terms of longer fixation durations. The reader's difficulty reading sentences with jumbled words indicates that character position information is processed during word recognition, and character position encoding is important for lexical access in Chinese reading.

The finding that transposing two characters involving the first character of a word is more disruptive than those involving the ending character strongly suggests that the word-beginning character in Chinese is more important than the word-ending character. In Experiment 1, fixation durations were longer in the 1–2 initial condition than in the 2–3 final condition for the target words, suggesting that 1–2 character transpositions hindered word identification more severely than 2–3 character transpositions during normal silent reading. In Experiment 2, the main effect of character transposition positions was significant, and fixation duration was longer when the transposed characters included the first character than the last character. These results show that word-beginning character transpositions had a greater impact on word recognition than word-ending character transpositions. This pattern is also consistent with the findings for spaced, alphabetical languages (e.g., see Bruner & O'Dowd, 1958; Johnson & Eisler, 2012; Rayner et al., 2006; White et al., 2008). However, this pattern is different from the findings for unspaced alphabetic script such as Thai, which implies that the differences between the initial and final characters are not caused by low-level visual features such as interword spaces.

We now consider why initial characters are more important than ending characters during character position encoding in Chinese. There are two possibilities. First, the beginning character is essential for providing constraints on the number of lexical candidates possible than characters in other positions (see Clark & O'Regan, 1999; Grainger & Jacobs, 1993; Ma et al., 2014). For example, the beginning character has fewer word neighbors than other characters and may also provide morphological cues. Second, the stronger role of the initial characters may be caused by reading direction. Readers read from left to right, and thus, eyes move from left to right. According to a recent model of Chinese word reading (Li & Pollatsek, 2020), all characters in the perceptual span are processed simultaneously with the constraint of visual acuity. When the characters' activation passes a threshold, all corresponding words are activated and compete for a winner. Visual acuity is lower when the character is farther from the fixation. Because the eyes move from left to right, the beginning character of a word is more likely to be activated earlier than the ending character. Thus, if the initial character of a word is not correct, the correct word would be activated more slowly. In contrast, if the ending character is not correct, the correct word can still be activated by the beginning characters, and the processing of the ending characters can be facilitated through an interactive process. Thus, the initial characters are more important than the ending characters during Chinese processing.

An interesting question that immediately arises is whether the effect of the increased disruption associated with the initial character is orthographically or phonologically mediated. Recently, some researchers have found that previewing a word with initial characters that are orthographically or phonologically similar to those of the target word facilitated both adults' and children's processing of the target word (Milledge et al., 2021; Milledge, Liversedge, & Blythe, 2022; Milledge et al., 2022). These studies raised the possibility that word initial transposition disruption may be driven by both orthography and phonology. The present study was not designed to answer this question, but it should be an important avenue in further research.

The third principal finding of this study is that transposing two nonadjacent characters of a word is more disruptive than transposing two adjacent characters of a word, revealing a sizable effect of transposed-character distance on word processing during Chinese reading. Again, this finding parallels the findings reported in Latin script (e.g., see Pagán et al., 2016; Perea et al., 2008). In Experiment 1, the fixation duration in the nonadjacent transposition condition was longer than that in the adjacent transposition conditions for the target. In Experiment 2, the main effect of character transposition distance was significant, and fixation duration was longer when character transposition with one character apart than adjacent transposition for the target. These results showed that distant character transpositions had a greater impact on word recognition than close character transpositions. Adjacent transposed-character nonwords appeared to be more similar to their base words than nonadjacent transposed-character nonwords, resulting in a greater reading cost. These findings suggest that, parallel to letters-in-words in alphabetic languages, the degree of perceptual similarity between a word and its corresponding transposed-character nonword in Chinese is a function of the distance between their constituent characters.

To date, no formal models of character position encoding have been developed for Chinese reading. However, the effects of transposed character distance can be captured by models of word recognition in alphabetic writing systems. For instance, one could argue that the strength of the activation differs as a function of character position, with activation levels decreasing systematically from left to right (Davis, 2010; see also Whitney, 2001).

For models of eye-movement control on reading (e.g., E-Z Reader model, Reichle et al., 2003; CRM, Li & Pollatsek, 2020), a mechanism for letter/character position encoding has not yet been implemented. Nonetheless, a recently proposed model of eye movement control on reading—Über-Reader (Reichle, 2020; see also Veldre et al., 2020)—used a similar assumption as the overlap model (Gomez et al., 2008) to capture TL effects in English. According to the Über-Reader model, the certainty of letter position decreases as visual acuity decreases. The model successfully predicts the dynamic process of letter order encoding as eyes move from left to right in English reading. However, the Über-Reader model has not yet been applied to Chinese.

Models of Chinese reading must be expanded to accommodate the main findings of this study. We now describe how the multilevel activation model proposed by Taft and Zhu (1997) could be modified to account for the present findings. The lexical processing system in this model 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; similarly, activation 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 activates the whole-word representation via character-level representations, but the position of character activation is not defined precisely. Thus, the original Taft and Zhu (1997) model cannot account for the findings of this study. Notably, this model could be modified to account for these results by introducing a flexible character position encoding assumption similarly to Davis's (2010) spatial coding model. For example, at the character level, in character position encoding of the word 燕尾服 (tuxedo), the first character 燕 is coded by a value of 1, the second character 尾 is coded by a value of 2, and the third character 服 is coded by a value of 3. These three TC nonwords (尾燕服, 燕服尾, and 服尾燕) share the same character nodes, but the transposition of two characters alters the corresponding spatial gradient representation. Then, different spatial gradient representations of three nonwords result in different spatial patterns. Thus, compared with the nonadjacent TC nonword with one intervening letter, the spatial patterns of adjacent TC nonwords (尾燕服 and 燕服尾) are more similar to the base word (燕尾服). Generally, the character level of the lexical processing system of Taft and Zhu (1997) could capture an effect of transposed-character distance by assuming that it follows a spatial coding scheme.

The findings of the present study showed that transposing characters involving the initial character of a word and transposing nonadjacent characters yields a large cost in reading time during sentence reading. These findings appear to diverge from the findings of Yang et al. (2019, 2020), who found a large degree of flexibility in Chinese reading using masked priming in Chinese (e.g., the reversed prime 是为以自 produced a priming effect on 自以为是 relative to an unrelated control). Critically, one key difference across these studies is the procedures used. In Yang et al.'s (2019, 2020) experiments, the prime and target stimuli were presented sequentially, and the primes were presented briefly sufficient to prevent their identification. In this study, the target words were embedded in sentences, and all participants were aware of the presence of transpositions; participants had to "reconstruct" the original order of the characters when reading. Encoding a transposed-character nonword 是为以自 in isolation (the base word is 自以为是) is different than encoding in the context of sentence reading (e.g., an example including the jumbled word 是为以自 in a sentence). Thus, we believe that Yang et al.'s (2019, 2020) masked priming experiments in Chinese may reflect different cognitive processes than those captured during natural sentence reading.

We should also note that the words with transposed characters might cause readers to notice that the characters are out of order. This might have disrupted readers from reading normally. The presence of differential effects across positions (e.g., initial vs. final) suggests that this paradigm is informative to study the character order encoding in Chinese reading. Indeed, this same paradigm had previously been used in studies of English reading (Rayner et al., 2006; see also Johnson & Eisler, 2012; Pagán et al., 2021; White et al., 2008). In the future, more research is needed to investigate how character order is encoded with boundary paradigms. Using a boundary paradigm, the characters may be transposed with parafovel vision, and the transposed characters change to normal after the eyes cross an invisible boundary. In that situation, transposing characters might be less disruptive. If studies using different paradigms can generate converging evidence, the findings will be more informative—note that this is the case in alphabetic scripts (e.g., see Johnson et al., 2007, for findings with the boundary technique in the same line as in the original Rayner et al., 2006).

In summary, this study represents an initial step toward understanding the subtleties of the mechanism of character position encoding in Chinese reading. We examined how transposing adjacent and nonadjacent characters affects word processing in Chinese, and whether this process could be affected by their position in words (e.g., initial, and final). We found that nonadjacent character transposition was more disruptive than adjacent character transposition during Chinese reading. Also, the beginning character of a word plays a more important role than the ending character in word identification. Thus, the privileged status of the beginning character across writing systems appears to be intrinsically related to how we access lexical information.

References

Acha, J., & Perea, M. (2008). The effects of length and transposed-letter similarity in lexical decision: Evidence with beginning, intermediate, and adult readers. *British Journal of Psychology*, *99*(2), 245–264. https://doi.org/10.1348/000712607X224478

Andrews, S. (1996). Lexical retrieval and selection processes: Effects of transposed-letter confusability. *Journal of Memory and Language*, *35*(6), 775–800. https://doi.org/10.1006/jmla.1996.0040

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). *lme4: Linear mixed-effects models using Eigen and S4*. R package version 1.1-7. http://CRAN.R-project.org/package=lme4

Blythe, H. I., Johnson, R. L., Liversedge, S. P., & Rayner, K. (2014). Reading transposed text: Effects of transposed letter distance and consonant-vowel status on eye movements. *Attention, Perception, & Psychophysics*, *76*(8), 2424–2440. https://doi.org/10.3758/s13414-014-0707-2

Bruner, J. S., & O'Dowd, D. (1958). A note on the informativeness of parts of words. *Language and Speech*, *1*(2), 98–101. https://doi.org/10.1177/002383095800100203

Chambers, S. M. (1979). Letter and order information in lexical access. *Journal of Verbal Learning and Verbal Behavior*, *18*(2), 225–241. https://doi.org/10.1016/S0022-5371(79)90136-1

Christianson, K., Johnson, R. L., & Rayner, K. (2005). Letter transpositions within and across morphemes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(6), 1327–1339. https://doi.org/10.1037/0278-7393.31.6.1327

Clark, J. J., & O'Regan, J. K. (1999). Word ambiguity and the optimal viewing position in reading. *Vision Research*, *39*(4), 843–857. https://doi.org/10.1016/S0042-6989(98)00203-X

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review*, *117*(3), 713–758. https://doi.org/10.1037/a0019738

Estes, W. K., Allmeyer, D. H., & Reder, S. M. (1976). Serial position functions for letter identification at brief and extended exposure durations. *Perception & Psychophysics*, *19*(1), 1–15. https://doi.org/10.3758/BF03199379

Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *39*(2), 211–251. https://doi.org/10.1080/14640748708401785

Gomez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: A model of letter position coding. *Psychological Review*, *115*(3), 577–600. https://doi.org/10.1037/a0012667

Grainger, J., & Jacobs, A. M. (1993). Masked partial-word priming in visual word recognition: Effects of positional letter frequency. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(5), 951–964. https://doi.org/10.1037/0096-1523.19.5.951

Grainger, J., & van Heuven, W. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *The mental lexicon* (pp. 1–24). Nova Science.

Gu, J., Li, X., & Liversedge, S. P. (2015). Character order processing in Chinese reading. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(1), 127–137. https://doi.org/10.1037/a0038639

Gu, J., & Li, X. (2015). The effects of character transposition within and across words in Chinese reading. *Attention, Perception, & Psychophysics*, *77*(1), 272–281. https://doi.org/10.3758/s13414-014-0749-5

Holmes, V. M., & Ng, E. (1993). Word-specific knowledge, word-recognition strategies, and spelling ability. *Journal of Memory and Language*, *32*(2), 230–257. https://doi.org/10.1006/jmla.1993.1013

Huang, B., & Liao, X. (2007). 现代汉语 [Contemporary Chinese language]. Higher Education Press.

Johnson, R. L. (2007). The flexibility of letter coding: Nonadjacent letter transposition effects in the parafovea. In R. P. G. van Gompel, M. H. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye movements: A window on mind and brain* (pp. 425–440). Elsevier. https://doi.org/10.1016/B978-008044980-7/50021-5

Johnson, R. L., & Eisler, M. E. (2012). The importance of the first and last letter in words during sentence reading. *Acta Psychologica*, *141*(3), 336–351. https://doi.org/10.1016/j.actpsy.2012.09.013

Johnson, R. L., Perea, M., & Rayner, K. (2007). Transposed-letter effects in reading: Evidence from eye movements and parafoveal preview. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(1), 209–229. https://doi.org/10.1037/0096-1523.33.1.209

Kasisopa, B., G Reilly, R., Luksaneeyanawin, S., & Burnham, D. (2013). Eye movements while reading an unspaced writing system: The case of Thai. *Vision Research*, *86*, 71–80. https://doi.org/10.1016/j.visres.2013.04.007

Kinoshita, S., & Norris, D. (2009). Transposed-letter priming of prelexical orthographic representations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(1), 1–18. https://doi.org/10.1037/a0014277

Ktori, M., Kingma, B., Hannagan, T., Holcomb, P. J., & Grainger, J. (2014). On the time-course of adjacent and non-adjacent transposed-letter priming. *Journal of Cognitive Psychology*, *26*(5), 491–505. https://doi.org/10.1080/20445911.2014.922092

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2014). *lmerTest: Tests for random and fixed effects for linear mixed effect models (lmer* *objects of lme4 package)*. R package version 2.0-6. http://CRAN.R-project.org/package=lmerTest

Lexicon of Common Words in Contemporary Chinese Research Team. (2021). *Lexicon of common words in contemporary Chinese*. Commercial Press.

Li, X., Bicknell, K., Liu, P., Wei, W., & Rayner, K. (2014). Reading is fundamentally similar across disparate writing systems: A systematic characterization of how words and characters influence eye movements in Chinese reading. *Journal of Experimental Psychology: General*, *143*(2), 895–913. https://doi.org/10.1037/a0033580

Li, X., Gu, J., Liu, P., & Rayner, K. (2013). The advantage of word-based processing in Chinese reading: Evidence from eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(3), 879–889. https://doi.org/10.1037/a0030337

Li, X., & Ma, G. (2012). Word boundaries affect visual attention in Chinese reading. *PLoS ONE*, *7*(11), e48905. https://doi.org/10.1371/journal.pone.0048905

Li, X., & Pollatsek, A. (2020). An integrated model of word processing and eye-movement control during Chinese reading. *Psychological Review*, *127*(6), 1139–1162. https://doi.org/10.1037/rev0000248

Li, X., Rayner, K., & Cave, K. R. (2009). On the segmentation of Chinese words during reading. *Cognitive Psychology*, *58*(4), 525–552. https://doi.org/10.1016/j.cogpsych.2009.02.003

Li, X., Huang, L., Yao, P., & Hyönä, J. (2022). Universal and specific reading mechanisms across different writing systems. *Nature Reviews Psychology*, *1*(3), 133–144. https://doi.org/10.1038/s44159-022-00022-6

Liu, Z., Li, Y., Paterson, K. B., & Wang, J. (2020). A transposed-word effect in Chinese reading. *Attention, Perception, & Psychophysics*, *82*(8), 3788–3794. https://doi.org/10.3758/s13414-020-02114-y

Logan, G. D. (2021). Serial order in perception, memory, and action. *Psychological Review*, *128*(1), 1–44. https://doi.org/10.1037/rev0000253

Lupker, S. J., Perea, M., & Davis, C. J. (2008). Transposed-letter priming effects: Consonants, vowels and letter frequency. *Language and Cognitive Processes*, *23*(1), 93–116. https://doi.org/10.1080/01690960701579714

Ma, G., Li, X., & Rayner, K. (2014). Word segmentation of overlapping ambiguous strings during Chinese reading. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(3), 1046–1059. https://doi.org/10.1037/a0035389

Marcet, A., Perea, M., Baciero, A., & Gomez, P. (2019). Can letter position encoding be modified by visual perceptual elements? *Quarterly Journal of Experimental Psychology*, *72*(6), 1344–1353. https://doi.org/10.1177/1747021818789876

Milledge, S. V., Blythe, H. I., & Liversedge, S. P. (2021). Parafoveal preprocessing in children reading English: The importance of external letters. *Psychonomic Bulletin & Review*, *28*(1), 197–208. https://doi.org/10.3758/s13423-020-01806-8

Milledge, S. V., Liversedge, S. P., & Blythe, H. I. (2022). The importance of the first letter in children's parafoveal preprocessing in English: Is it phonologically or orthographically driven? *Journal of Experimental Psychology: Human Perception and Performance*, *48*(5), 427–442. https://doi.org/10.1037/xhp0000998

Milledge, S. V., Zang, C., Liversedge, S. P., & Blythe, H. I. (2022). Phonological parafoveal pre-processing in children reading English sentences. *Cognition*, *225*, 105141. https://doi.org/10.1016/j.cognition.2022.105141

Mirault, J., Snell, J., & Grainger, J. (2018). You that read wrong again! A transposed-word effect in grammaticality judgments. *Psychological Science*, *29*(12), 1922–1929. https://doi.org/10.1177/0956797618806296

Norris, D., & Kinoshita, S. (2012). Reading through a noisy channel: Why there's nothing special about the perception of orthography. *Psychological Review*, *119*(3), 517–545. https://doi.org/10.1037/a0028450

O'Connor, R. E., & Forster, K. I. (1981). Criterion bias and search sequence bias in word recognition. *Memory & Cognition*, *9*(1), 78–92. https://doi.org/10.3758/BF03196953

Packard, J. L. (2004). *Goucifa: The morphology of Chinese. A Linguistic and Cognitive Approach*. Cambridge University Press.

Pagán, A., Blythe, H. I., & Liversedge, S. P. (2016). Parafoveal preprocessing of word initial trigrams during reading in adults and children. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(3), 411–432. https://doi.org/10.1037/xlm0000175

Pagán, A., Blythe, H. I., & Liversedge, S. P. (2021). The influence of children's reading ability on initial letter position encoding during a reading-like task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *47*(7), 1186–1203. https://doi.org/10.1037/xlm0000989

Perea, M., & Acha, J. (2009). Does letter position coding depend on consonant/vowel status? Evidence with the masked priming technique. *Acta Psychologica*, *130*(2), 127–137. https://doi.org/10.1016/j.actpsy.2008.11.001

Perea, M., & Carreiras, M. (2006a). Do transposed-letter similarity effects occur at a syllable level? *Experimental Psychology*, *53*(4), 308–315. https://doi.org/10.1027/1618-3169.53.4.308

Perea, M., & Carreiras, M. (2006b). Do transposed-letter similarity effects occur at a prelexical phonological level? *Quarterly Journal of Experimental Psychology*, *59*(9), 1600–1613. https://doi.org/10.1080/17470210500298880

Perea, M., & Carreiras, M. (2006c). Do transposed-letter effects occur across lexeme boundaries? *Psychonomic Bulletin & Review*, *13*(3), 418–422. https://doi.org/10.3758/BF03193863

Perea, M., & Carreiras, M. (2008). Do orthotactics and phonology constrain the transposed-letter effect? *Language and Cognitive Processes*, *23*(1), 69–92. https://doi.org/10.1080/01690960701578146

Perea, M., & Estevez, A. (2008). Transposed-letter similarity effects in naming pseudowords: Evidence with children and adults. *The European Journal of Cognitive Psychology*, *20*(1), 33–46. https://doi.org/10.1080/09541440701306941

Perea, M., & Fraga, I. (2006). Transposed-letter and laterality effects in lexical decision. *Brain and Language*, *97*(1), 102–109. https://doi.org/10.1016/j.bandl.2005.08.004

Perea, M., & Lupker, S. J. (2003a). Does jugde activate COURT? Transposed-letter similarity effects in masked associative priming. *Memory & Cognition*, *31*(6), 829–841. https://doi.org/10.3758/BF03196438

Perea, M., & Lupker, S. J. (2003b). Transposed-letter confusability effects in masked form priming. In S. Kinoshita & S. J. Lupker (Eds.), *Masked priming: The state of the art* (pp. 97–120). Psychology Press.

Perea, M., & Lupker, S. J. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with non-adjacent letter positions. *Journal of Memory and Language*, *51*(2), 231–246. https://doi.org/10.1016/j.jml.2004.05.005

Perea, M., Duñabeitia, J. A., & Carreiras, M. (2008). Transposed-letter priming effects for close versus distant transpositions. *Experimental Psychology*, *55*(6), 384–393. https://doi.org/10.1027/1618-3169.55.6.384

Perea, M., Jiménez, M., Martín-Suesta, M., & Gómez, P. (2015). Letter position coding across modalities: Braille and sighted reading of sentences with jumbled words. *Psychonomic Bulletin & Review*, *22*(2), 531–536. https://doi.org/10.3758/s13423-014-0680-8

Perea, M., Marcet, A., & Gómez, P. (2016). How do Scrabble players encode letter position during reading? *Psicothema*, *28*(1), 7–12.

Perea, M., Rosa, E., & Gómez, C. (2005). The frequency effect for pseudowords in the lexical decision task. *Perception & Psychophysics*, *67*(2), 301–314. https://doi.org/10.3758/BF03206493

Perea, M., Winskel, H., & Gomez, P. (2018). How orthographic-specific characteristics shape letter position coding: The case of Thai script. *Psychonomic Bulletin & Review*, *25*(1), 416–422. https://doi.org/10.3758/s13423-017-1279-7

Perea, M., Winskel, H., & Ratitamkul, T. (2012). On the flexibility of letter position coding during lexical processing: The case of Thai. *Experimental Psychology*, *59*(2), 68–73. https://doi.org/10.1027/1618-3169/a000127

Perfetti, C. A., Liu, Y., & Tan, L. H. (2005). The lexical constituency model: Some implications of research on Chinese for general theories of reading. *Psychological Review*, *112*(1), 43–59. https://doi.org/10.1037/0033-295X.112.1.43

R Development Core Team. (2016). *R: A language and environment for statistical computing* [Computer software]. R Foundation for Statistical Computing. https://www.R-project.org

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, *7*(1), 65–81. https://doi.org/10.1016/0010-0285(75)90005-5

Rayner, K., White, S. J., Johnson, R. L., & Liversedge, S. P. (2006). Raeding wrods with jubmled lettres: There is a cost. *Psychological Science*, *17*(3), 192–193. https://doi.org/10.1111/j.1467-9280.2006.01684.x

Reichle, E. D. (2020). *Computational models of reading: A handbook*. Oxford University Press.

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences*, *26*(4), 445–476. https://doi.org/10.1017/S0140525X03000104

Schad, D. J., Vasishth, S., Hohenstein, S., & Kliegl, R. (2020). How to capitalize on a priori contrasts in linear (mixed) models: A tutorial. *Journal of Memory and Language*, *110*, 104038. https://doi.org/10.1016/j.jml.2019.104038

Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes*, *19*(3), 333–367. https://doi.org/10.1080/01690960344000198

Simmons, J. P., Nelson, L. D., & Simonsohn, U. (2011). False-positive psychology: Undisclosed flexibility in data collection and analysis allows presenting anything as significant. *Psychological Science*, *22*(11), 1359–1366. https://doi.org/10.1177/0956797611417632

Taft, M., & Zhu, X. (1997). Sub-morphemic processing in reading Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*(3), 761–775. https://doi.org/10.1037/0278-7393.23.3.761

Taft, M., Zhu, X., & Peng, D. (1999). Positional specificity of radicals in Chinese character recognition. *Journal of Memory and Language*, *40*(4), 498–519. https://doi.org/10.1006/jmla.1998.2625

Tiffin-Richards, S. P., & Schroeder, S. (2015). Children's and adults' parafoveal processes in German: Phonological and orthographic effects. *Journal of Cognitive Psychology*, *27*(5), 531–548. https://doi.org/10.1080/20445911.2014.999076

Veldre, A., Yu, L., Andrews, S., & Reichle, E. D. (2020). Towards a complete model of reading: Simulating lexical decision, word naming, and sentence reading with über-reader. In *CogSci 2020: Proceedings of the 42nd Annual Conference of the Cognitive Science Society: developing a mind: learning in humans, animals, and machines* (pp. 151–157). Cognitive Science Society. https://hdl.handle.net/2123/22990

White, S. J., Johnson, R. L., Liversedge, S. P., & Rayner, K. (2008). Eye movements when reading transposed text: The importance of word-beginning letters. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(5), 1261–1276. https://doi.org/10.1037/0096-1523.34.5.1261

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review*, *8*(2), 221–243. https://doi.org/10.3758/BF03196158

Whitney, C. (2008). Comparison of the SERIOL and SOLAR theories of letter-position encoding. *Brain and Language*, *107*(2), 170–178. https://doi.org/10.1016/j.bandl.2007.08.002

Winskel, H., & Perea, M. (2013). Consonant/Vowel asymmetries in letter position coding during normal reading: Evidence from parafoveal previews in Thai. *Journal of Cognitive Psychology*, *25*(1), 119–130. https://doi.org/10.1080/20445911.2012.753077

Winskel, H., Perea, M., & Ratitamkul, T. (2012). On the flexibility of letter position coding during lexical processing: Evidence from eye movements when reading Thai. *Quarterly Journal of Experimental Psychology*, *65*(8), 1522–1536. https://doi.org/10.1080/17470218.2012.658409

Yan, G., Bai, X., Zang, C., Bian, Q., Cui, L., Qi, W., Rayner, K., & Liversedge, S. P. (2012). Using stroke removal to investigate Chinese character identification during reading: Evidence from eye movements. *Reading and Writing*, *25*(5), 951–979. https://doi.org/10.1007/s11145-011-9295-x

Yang, H., Chen, J., Spinelli, G., & Lupker, S. J. (2019). The impact of text orientation on form priming effects in four-character Chinese words. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(8), 1511–1526. https://doi.org/10.1037/xlm0000655

Yang, H., Hino, Y., Chen, J., Yoshihara, M., Nakayama, M., Xue, J., & Lupker, S. J. (2020). The origins of backward priming effects in logographic scripts for four-character words. *Journal of Memory and Language*, *113*, 104107. https://doi.org/10.1016/j.jml.2020.104107

Zang, C. (2019). New perspectives on serialism and parallelism in oculomotor control during reading: The multi-constituent unit hypothesis. *Vision*, *3*(4), 50. https://doi.org/10.3390/vision3040050

Zang, C., Fu, Y., Bai, X., Yan, G., & Liversedge, S. P. (2021). Foveal and parafoveal processing of Chinese three-character idioms in reading. *Journal of Memory and Language*, *119*, 104243. https://doi.org/10.1016/j.jml.2021.104243

Zhou, J., & Li, X. (2021). On the segmentation of Chinese incremental words. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *47*(8), 1353–1368. https://doi.org/10.1037/xlm0000984

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