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The importance of the positional probability of word final (but not word initial) characters for word segmentation and identification in children and adults' natural Chinese reading

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Abstract

Word spacing is important in guiding eye movements during spaced alphabetic reading. Chinese is unspaced and it remains unclear as to how Chinese readers segment and identify words in reading. We conducted two parallel experiments to investigate whether the positional probabilities of the initial and the final characters of a multi-character word affected word segmentation and identification in Chinese reading. Two-character words were selected as targets. In Experiment 1, the initial character's positional probability was manipulated as being either high or low, and the final character was kept identical across the two conditions. In Experiment 2, an analogous manipulation was made for the final character of the target word. We recorded adults' and children's eye movements when they read sentences containing these words. In Experiment 1 reading times on targets did not differ in the two conditions for both children and adults, providing no evidence that a word initial character's positional probability contributes to word segmentation. In Experiment 2, adults had shorter reading times, and made fewer refixations on targets that were comprised of final characters with high relative to low positional probabilities; a similar effect was observed in children, but this effect had a slower time course. The results demonstrate that the positional probability of the final (but not the initial) character of a word influences segmentation commitments in reading. It suggests that Chinese readers identify where a currently fixated word ends, and via this commitment, by default, they identify where the subsequent word begins.

Keywords: word segmentation, character positional probability, eye movements, Chinese reading

Introduction

From the past four decades of eye movement research, it is widely accepted that a range of word properties influence how easily words are processed in reading (see Clifton et al., 2017; Kliegl, Nuthmann, & Engbert, 2006; Juhasz et al., 2008; Rayner, 1998, 2009; Rayner & Duffy, 1986). Words, therefore, are generally considered as the basic units of processing in reading (Rayner, 1998, 2009). In most alphabetic writing systems (like English), words are visually delimited by interword spaces, which have been demonstrated to play a very important role in word identification (e.g., Morris et al.,1990; Pollatsek & Rayner, 1982; Rayner, 1979; Rayner et al., 1998; Spragins et al., 1976; Winskel et al., 2009) and in saccadic targeting (e.g., Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner, 1979; Rayner et al., 1998; Sheridan et al., 2013). Written Chinese, however, is printed as a string of continuous characters without salient word boundaries like word spacing. There are no clear visual demarcations for Chinese readers to determine where the word boundaries lie within a sentence, raising a fundamental theoretical question, namely, how do Chinese readers segment words in continuous text without visual cues for word boundaries? Recently, there has been a significant amount of research focusing on the issue of whether word boundaries demarked by visual segmentation cues (like word spacing, highlighting, and alternating color shadings) facilitate lexical identification (e.g., Bai et al., 2008; Leyland et al., 2013; Liu & Li, 2014; Perea & Acha, 2009; Perea et al., 2015; Shen et al., 2012; Zang et al., 2013; Zhou et al., 2018) and lexical acquisition (e.g., Bai et al., 2013; Blythe et al., 2012; Liang et al., 2015; Liang et al., 2017; Liang et al., 2021) in Chinese reading. This body of research demonstrates that word segmentation is critical in relation to word identification in Chinese reading, and that the presence of visual word boundary information facilitates the segmentation and identification of novel words (see Blythe et al., 2012). It does not affect the reading of known words in native Chinese readers (e.g., see Bai et al., 2008), but does facilitate reading in non-native Chinese readers (e.g., Shen et al., 2012). More recently, further work investigating word segmentation during Chinese reading and novel word learning has demonstrated that the positional probability of a word's constituent characters is an important statistical word segmentation cue (see Yen et al., 2012 & Liang et al., 2015, 2017). In the present study, the theoretical issue that we will investigate concerns how a character's positional probability within a word influences the ease with which it is segmented and identified from the (unspaced) character stream that forms a Chinese sentence as it is read naturally. Given that segmentation is a necessary part of word identification which itself is a core process associated with reading, and given that lexical processing is frequently argued to be the engine driving eye movements in reading (see Li & Pollatsek, 2020), our lack of understanding of how these processes operate represents a limitation with respect to current theoretical accounts of Chinese written language comprehension.

Character positional probability processing in Chinese reading

In the modern Chinese lexicon, over 70% of words are made up of two or more characters (Lexicon of Common Words in Contemporary Chinese Research Team, 2008). Some Chinese characters frequently occur at word beginnings, for example, the character “每” (meaning *every*) is a constituent character of 25 two-character words in total, 24 of which include it as a word initial character, whilst in only 1 does it appear as a word ending character (Corpus of SUBTLEX-CH, see Cai & Brysbaert, 2010). Also, some characters frequently occur at word endings, for example, 17 two-character words contain the character “恨” (meaning *hate*) in the word final position, whilst only 1 word contains this character at its beginning. Such statistical properties of characters in relation to the words they comprise might offer a cue to the likely positions of word boundaries during Chinese reading and, therefore, it is of interest to determine whether positional probability information associated with a character is used by Chinese readers to segment and identify words in reading.

In the study by Yen et al. (2012), two sets of two-character words were selected as targets. One set of target words was made up of words with final characters that had high word-ending positional probability, and the other set was comprised of words with final characters with a low word-ending probability. Each target word was embedded into a sentence frame. Participants were instructed to read sentences normally as their eye movements were recorded. Yen et al. found that Chinese adult readers had longer gaze durations and made more refixations on target words in which the final character was less rather than more likely to be word final. Although the results from this experiment are very suggestive and interesting, the sentence frames within which counterpart target words were presented across conditions differed, meaning that differential effects across conditions could not be unambiguously attributed to the experimental manipulation of character positional probability.

Later experiments by Liang and her colleagues (2015, 2017) adopted somewhat more tightly controlled manipulations. These experiments investigated the role of a character's positional probability during lexical acquisition in Chinese reading. In their studies, three types of two-character pseudowords (C1C2) were constructed and presented in sentences as novel words. For each of these novel words, the positional probability characteristics and the position of the constituent characters was manipulated such that they were congruent, incongruent, or neutral in relation to each other. Each of these three types of pseudowords was embedded within 6 sentence frames (three for a learning phase, and three for a test phase) that provided different contexts to understand the meaning of these new words. Importantly, sentence frames were kept constant across conditions to avoid confounds. In this way, readers processed the sentences and learnt the novel words, instantiating a novel lexical representation via reading. Liang et al. also manipulated the format of sentence presentation such that sentences were either presented unspaced or with inter-word spaces. In one experiment adults were tested and in the other experiment children around 8 years old were tested. Arguably, the most striking finding in the two studies was that Chinese readers (both children and adults) were sensitive to a character's positional probability when acquiring and then subsequently processing novel words in sentential contexts. Furthermore, Liang et al. found no interaction between a character's positional probability and the spacing manipulation, indicating that the two segmentation cues influence lexical acquisition and word processing independently. The lack of interactive effects may suggest that word spacing directly impacts aspects of visual processing associated with the identification of target visual objects to which attention may be allocated in the parafovea to allow for saccade metric computations, whilst character positional probability information may be associated with processing required for lexical identification, that is, processes intrinsic to early linguistic processing.

Once again, whilst the findings from Liang et al.'s (2015, 2017) studies have contributed to current understanding of positional probability effects in lexical identification and lexical acquisition during Chinese reading, there were limitations to the studies. For example, Liang et al. (2015, 2017) simultaneously manipulated the positional probabilities of both word initial and word final characters in order to make their manipulations maximally effective. Thus, on the basis of Liang et al.'s studies, it is unclear whether the initial, the final, or both constituent characters' positional probabilities contribute to the word segmentation and word identification effects they reported for Chinese reading. For this reason, in the present study, two parallel experiments were designed to directly investigate whether word initial, or word ending characters are more or less important for word segmentation during natural Chinese reading.

Word segmentation and word identification in Chinese reading

In spaced languages (like English), decisions regarding word segmentation are predominantly driven by interword spaces. Spaces allow readers to identify the length of an upcoming word in the parafovea which in turn allows for guidance in relation to saccadic targeting (e.g., McConkie et al., 1988; see also Cutter et al., 2017, 2018). Spacing may also enhance word identification by unambiguously demarcating which characters belong in a word (e.g., Li, Rayner, & Cave, 2009), and by reducing lateral masking (Townsend, Taylor, & Brown, 1971; Sheridan, Rayner, & Reingold, 2013). When spaces are removed, reading is slowed by 30-50%, and eye movements through the text and word identification processes are disrupted (Morris et al., 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998; Spragins et al., 1976). Therefore, in the reading of spaced languages (like English), the relationship between word segmentation and word identification is widely considered to be one where word segmentation is a necessary precedent of word identification. To be clear, it is widely assumed that word segmentation is likely completed earlier than word identification.

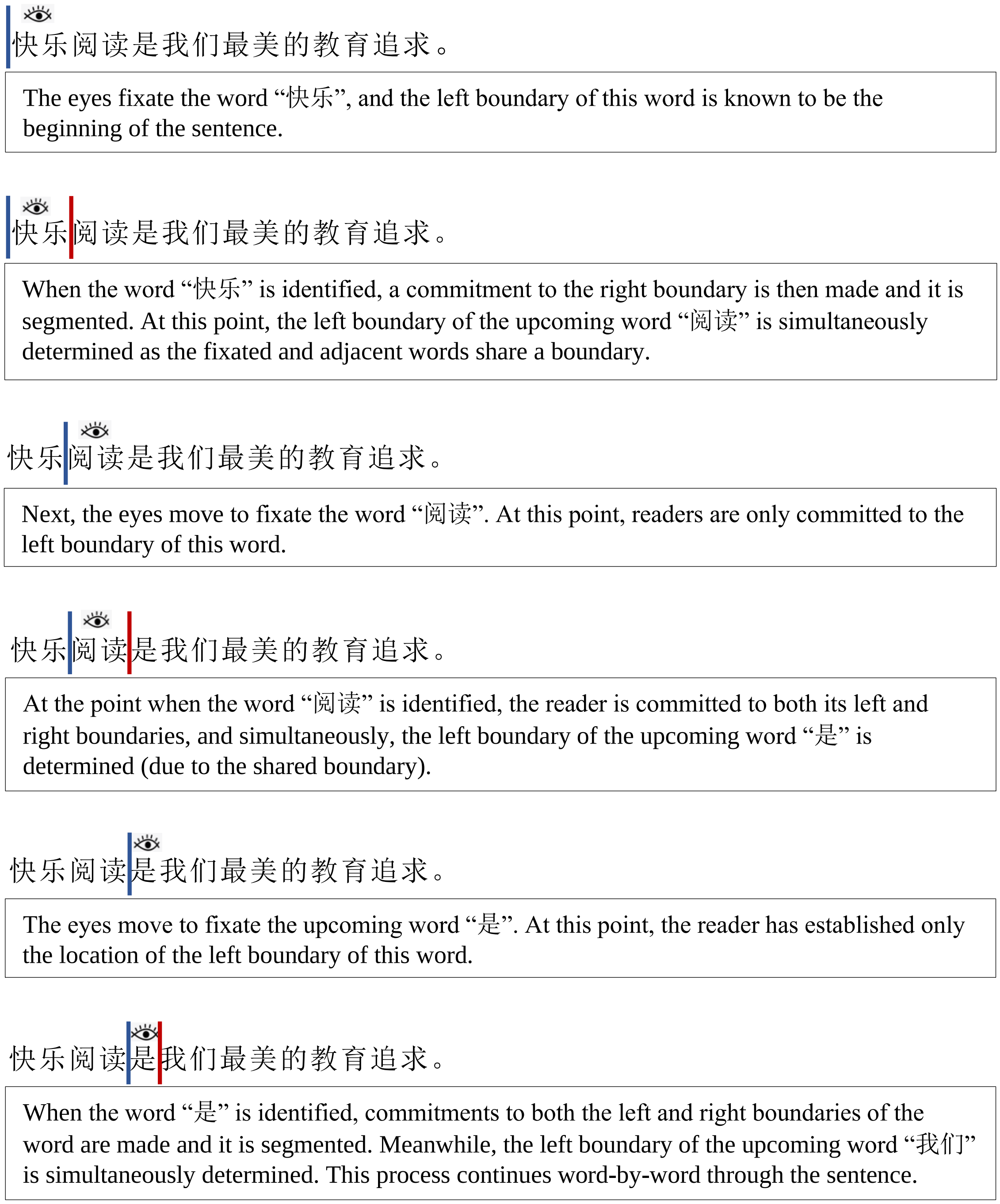
In natural unspaced Chinese reading, there are no salient visual word segmentation cues (like word spaces) to demark where words begin or end, yet Chinese skilled readers process a comparable amount of text content as efficiently as English readers, processing roughly 400 characters (equal to 260 words) per minute (see Liversedge et al., 2016; Sun et al., 1985). Thus, it appears that processes associated with segmentation and identification of words in Chinese operate with comparable efficiency despite the absence of cues to word boundaries. This raises the question of how Chinese readers engage in such processing in an efficient and effective manner. It is arguably fair to say that in the last two decades, the issue of how word segmentation and identification occurs during reading of unspaced languages has become an issue of theoretical significance with many researchers undertaking experimentation to investigate how such processing occurs. Such work all rests on the notion that within a string of unsegmented text (e.g., natural written Chinese), presumably, it is impossible to identify a word lexically without making a commitment to where in the stream of text the word begins and where it ends. To be clear, the underlying assumption here is that prior to a word being ultimately identified, it is a necessity that the processor makes a commitment to the characters that comprise that word or lexically represented unit (for relevant discussion, see Zang, 2019).

Recently, Li and Pollatsek (2020) developed an integrated model of word processing and eye movement control in Chinese reading (CRM, see also Li, Rayner, & Cave, 2009), which provides a strong hypothesis in relation to questions of word segmentation and identification. It stipulates that word segmentation and word identification in Chinese reading occur via a unified process whereby all the characters in the perceptual span (1 character to the left of the currently fixated character and up to 3 characters to its right, see Inhoff & Liu, 1998) are processed in parallel, and all the words that share content (characters) with the characters activated in the perceptual span, are themselves activated, to some extent, in parallel. These lexical candidates compete against each other over time within an Interactive-Activation framework (see McClelland & Rumelhart, 1981). When one of the activated word units wins the competition, it is automatically simultaneously segmented from the string of characters within the perceptual span and identified as a word. These theoretical stipulations are interesting and important. However, if possible, it would be helpful to determine with greater specificity the exact nature and time course of the processing steps required to ultimately segment and identify a word during Chinese reading. A primary aim of the present paper is to provide increased understanding of these processing stages.

Across multiple studies of Chinese word identification, it has been repeatedly demonstrated that the characteristics of both a two character word's initial and its final constituent characters influence word identification. For example, Yan et al (2006) conducted an eye movement study in which they orthogonally manipulated the frequency of the initial and the final characters of two character target words that themselves were high or low frequency. The results showed that fixation times on target words were influenced to a greater degree by the frequency of the initial character of the target word than the frequency of the final character when the target words were low frequency (see also Li & Pollatsek, 2011 for similar results in an isolated word processing paradigm). Yan et al.'s effects were much diminished when the target words were high frequency. The pattern of effects reported by Yan et al. is noteworthy in that it suggests (1) that influence of a two character word's initial character is greater relative to that of a word's final character, and (2) that the contributory influences of a word's constituent characters are themselves modulated by that word's overall frequency. We find these results interesting because they indicate that word identification in Chinese reading is a process with temporal extent, operating over a stimulus that has spatial extent. Thus, it is our contention that particular processing commitments in relation to different aspects of the lexical stimulus might occur at different points during the process of Chinese word identification (rather than all occurring simultaneously). If this is the case, then via careful experimentation, it should be possible to illustrate the sequential (and potentially dependent) nature of any such processing commitments.

A second study providing results that are very relevant to the present discussion is that of Ma and Li (2015). In their study, Ma and Li examined how saccades were targeted to two character words for which the stroke complexity of the initial or the final character was manipulated. Of course, in examining saccadic targeting behaviour, Ma and Li explored processing commitments (parafoveal target selection) that were made prior to the target being directly fixated. From our perspective, the most interesting aspect of these results was that Ma and Li obtained robust influences of the visual complexity of the initial character of the upcoming word on saccadic targeting behaviour (saccades targeted further into a word with more visually simple word beginning characters), however, similar influences of the final character of the target word were very much reduced. Again, these results illustrate that commitments in relation to oculomotor decisions and processing of an upcoming word in Chinese are influenced by when that word’s constituent elements first influence processing, and this in turn is affected by how visually available the constituent parts of that word are in relation to the position of the current fixation. There are at least three possible explanations of why word beginning constituents might be more influential than word final constituents during the formation of oculomotor decisions. First, it might be that a word's initial character is simply intrinsically more important due to the fact that written words are processed from left to right in reading. Thus, the initial character will have increased critical status during identification. Second, word initial characters may be particularly important for lexical identification because of the way in which words are visually processed during natural reading, that is, with the eyes moving from left to right through the word the availability of word beginning information precedes that of word ending information. Third, in order to recover the phonological form of a word, it is necessary to process characters (or a word’s letters in an alphabetic languages) in their sequential order. Thus, there are good reasons why processing of a word's initial constituent(s) might take precedence in word identification. From the evidence described, and based more broadly on general assumptions associated with lexical processing, it seems reasonable to suggest that the left to right sequence of characters in Chinese words will likely have important implications for their identification and segmentation. If these assumptions are correct, then it is perhaps worth considering, a priori, the logical order in which such sub-processes might occur during word segmentation and word identification in Chinese reading.

Recall that there are no visually salient spaces between words within Chinese written text, and two horizontally adjacent words (i.e., word N-1 and word N) share a boundary, such that the right boundary of word N-1 represents the left boundary of word N. Furthermore, it is clear that when word N-1 is identified and segmented, necessarily, its boundaries on both sides (i.e., the word beginning and word ending) are determined. To be clear, from our perspective, it is impossible to unambiguously lexically identify a word unless a commitment is made as to its constituent characters (i.e., a commitment is made to where the word begins and where it ends). However, note that this claim has a very important processing implication. If, as we have argued, word boundary commitments are made upon the identification of word N-1, then not only do such commitments relate to the location of the end of word N-1, but also this commitment, in turn, represents a commitment to the left boundary of the upcoming word N (since Chinese is unspaced and this boundary is shared by both words N-1 and word N). Further, it seems reasonable to suggest that this commitment to the leftward boundary of word N (simultaneous with the commitment to the rightward boundary of word N-1) must occur, temporally, at a point prior to the identification of the rightward boundary of word N (since if these commitments occurred simultaneously, by default, readers would be able to instantaneously segment a full line of text into words upon its initial fixation – something of an impossibility). Hence, based on this logical argument, during reading of Chinese, it appears that there must be a commitment on the part of the reader to a word's leftward boundary relatively early during lexical processing, and this must occur at a point during processing prior to the identification of that word's rightward boundary and its full lexical identification. Figure 1 illustrates the successive processing steps of word segmentation and word identification over the first three words in the Chinese sentence: 快乐阅读是我们最美的教育追求。



快乐阅读是我们最美的教育追求。

The eyes fixate the word “快乐”, and the left boundary of this word is known to be the beginning of the sentence.

快乐阅读是我们最美的教育追求。

When the word “快乐” is identified, a commitment to the right boundary is then made and it is segmented. At this point, the left boundary of the upcoming word “阅读” is simultaneously determined as the fixated and adjacent words share a boundary.

快乐阅读是我们最美的教育追求。

Next, the eyes move to fixate the word “阅读”. At this point, readers are only committed to the left boundary of this word.

快乐阅读是我们最美的教育追求。

At the point when the word “阅读” is identified, the reader is committed to both its left and right boundaries, and simultaneously, the left boundary of the upcoming word “是” is determined (due to the shared boundary).

快乐阅读是我们最美的教育追求。

The eyes move to fixate the upcoming word “是”. At this point, the reader has established only the location of the left boundary of this word.

快乐阅读是我们最美的教育追求。

When the word “是” is identified, commitments to both the left and right boundaries of the word are made and it is segmented. Meanwhile, the left boundary of the upcoming word “我们” is simultaneously determined. This process continues word-by-word through the sentence.

(Translation: Happy reading is our most beautiful educational pursuit.)

Figure 1. Illustration of the sequence of processing steps associated with word segmentation and word identification in Chinese reading. Three fixations are represented here, with the position of each fixation denoted by the “eye” icon. The blue line represents the left boundary of a word. The red line represents the right boundary of a word.

This account of word segmentation commitments in relation to stages of lexical processing during Chinese reading fits quite readily with findings from studies described above wherein influences of word initial characters are often larger and appear earlier than influences of later characters within a word. A simple and parsimonious suggestion might be that during word identification in natural Chinese reading, initiation of processing of a second constituent character occurs somewhat downstream in time from initiation of processing of the initial character. Or, alternatively, processing of the initial character of a word progresses more rapidly than processing of subsequent constituent characters. To be clear, whichever of these possibilities might be correct, it appears that word beginning segmentation commitments are made prior to word ending segmentation commitments, and that both such commitments occur simultaneous with full word identification. Thus, within the period required for a word to be identified, the constituent characters of the word are processed, at least to some degree, from left to right with word beginning and word ending boundary commitments being made earlier and later during word identification respectively.

To summarize, we accept that word identification and word segmentation (when considered as processes in their entirety and up to completion) do occur simultaneously and we acknowledge that this is as per the specifications of the CRM. However, from our perspective, it is important to note that, within such a specification, it remains the case that word initial and word final segmentation commitments are made at different time points (relatively early vs. late) during the process of word identification. If these theoretical suggestions are correct, then they have significant implications for influences of the positional probabilities of characters within Chinese words in respect of reading times during word segmentation and identification. We next introduce the theoretical rationale for the present study and make predictions on the basis of the processing account for word segmentation and word identification developed above.

The present study

The first purpose of the present study is to investigate whether the positional probabilities of each character of a two-character Chinese word influence word segmentation and processing in natural Chinese reading. To meet this goal, we conducted two parallel experiments. In Experiment 1, a target word initial character's positional probability was manipulated such that it either frequently or less frequently appeared as a word beginning character. We kept the word final characters identical across these two conditions. In Experiment 2, a counterpart manipulation was made for the target word final character. A pair of target words for each of these experimental conditions was embedded into the same sentence frame in Experiment 1 and in Experiment 2. Participants' eye movements were recorded when they read sentences containing the target words. This experimental design allows us to evaluate the independent influence of the word initial and the word final characters' positional probability on lexical identification in natural Chinese reading.

According to the theoretical account of the time course of word segmentation and identification in Chinese reading that we specified earlier, word initial and word final segmentation commitments are likely made at different time points (early vs. late) during the process of word identification. Further, it has been established that a character's positional probability provides a strong influence over word segmentation in Chinese reading (see Liang et al., 2015, 2017; Yan et al., 2012). Therefore, if as we specified, a commitment to word N beginning boundary occurs simultaneous with the identification of the end of the preceding word (N-1), then the visual or linguistic characteristics of the initial character of word N should have little influence on processing of word N. That is to say, in Experiment 1 the positional frequency characteristics of the initial character of word N should not influence lexical processing of this word (since the commitment to this word boundary will be made in relation to characteristics of the constituent characters of the preceding word, word N-1). In contrast to this prediction for the word N initial character, it is our suggestion that the commitment to the rightward boundary of word N occurs somewhat downstream in processing, and that the positional frequency characteristics of the word final character will likely influence the formation of such a decision. If this was the case, then we would observe strong effects of the positional frequency of the word final character on processing times for word N. Thus, we predict contrasting effects of character positional frequency across our two experiments such that word initial character positional frequency characteristics of word N will exert little influence on target word processing (i.e., for reading time measures), whilst prominent such effects should occur in relation to positional frequency manipulations associated with the final character of word N.

The second purpose of the present study was to investigate how within-word character position specificity impacts word segmentation and processing in children compared with adults. Focusing on age-related differences in the literature on word segmentation and recognition in Chinese reading, it appears that the usage and influence of either visual (e.g., word spacing) or statistical word segmentation cues (e.g., character positional probability) follow a typical developmental pattern of change. As mentioned earlier, interword spaces do not influence adults', nor children's reading of known words (see Zang et al., 2013), but spacing does show a greater beneficial influence for children than adults when reading and learning novel words in sentential contexts (see Blythe et al., 2012). For child readers, facilitatory word spacing effects even extend to subsequent, unspaced reading (Blythe et al., 2012). This suggests that children are more dependent on visual word segmentation cues (like word spacing) than adults particularly when the reading task is more difficult (i.e., learning new words vs. reading text formed from known words). In relation to age-related differences in respect of a character's positional probability characteristics, the two recent studies conducted by Liang et al. (2015, 2017; see also Liang et al 2021 for effects of word familiarity) provide insight. It should be clarified here, that, although Liang et al. (2015; 2017) carried out two separate studies to examine how children and then adults utilize within-word positional probability cues during word learning, it is still reasonable to directly compare performances between the two groups, since the experimental stimuli and paradigms were exactly the same in the two studies. Recall that Liang et al. reported a processing cost both in children and adults when pseudowords comprised of characters in positions incongruent with their positional probabilities were learnt and then read later. Recall also that this processing cost occurred early and persisted through to later stages of processing for adult readers, however, the effect emerged only in later stages of processing for child readers. Similar findings have also been shown to occur in a lexical decision task (see Liu et al., 2014). It appears that there is a sensitivity to a character's positional probability characteristics at a relatively early age (probably around 9 years old, or perhaps even younger), however, immaturity remains in relation to how effectively that information may be used to facilitate processing during reading in children relative to adults. On this basis, we might reasonably predict that children and adults process positional probability information associated with the initial and the final character of a word in a similar way, however, any such effect will likely be more pronounced (greater in magnitude and with an earlier time course) for adults than children.

Experiment 1

In this experiment, we examined whether a two-character word's initial character positional probability characteristics are used by adults and children as a cue to facilitate segmentation and word identification in natural Chinese reading. We manipulated the initial character's positional probability such that it appeared at word beginning with high or low probability. Meanwhile, we kept the final character of the two-character word identical across the two conditions controlling its within-word positional probability characteristics such that it was equally likely to be a word beginning, or a word ending character. Given that the commitment to where a word begins might be made on the basis of a commitment to where the preceding word ends, then we anticipated that the positional probability of the initial character would exert little influence on word segmentation and processing in Chinese reading in both children and adults. Hence, we would expect to see quite comparable patterns of eye movements when processing target words comprised of an initial character in a position congruent with its positional probability characteristics, compared to those for words comprised of an initial character with incongruent positional probability characteristics in both child and adult readers.

Method

Participants

Forty-eight undergraduates at Tianjin Normal University (33 females, 15 males, mean age = 22.2 years) and forty-eight children in Grade 3 of Jinnan Experimental Primary School (28 males, 20 females; mean age 9.5 years, range 9-10 years) took part in the experiment. Participants were native Chinese speakers with normal or corrected-to-normal vision, and no known reading difficulties. They were all naïve regarding the purpose of the present study.

The sample size was selected to be comparable to our previous studies on children and adults that have explored the effect of character positional probability when segmenting and identifying novel words in Chinese reading (see Liang et al., 2015, 2017). The means and standard deviations from these studies were used to approximate effect sizes and the necessary sample sizes computed to ensure adequate power. For example, total fixation durations from the two studies suggest that the average effect size (d) for the main effect of character positional probability in children and adults is 0.48. Using this estimate, G-Power calculations developed by Buchner et al. (2007) approximated a sample size of 37 necessary to test the character positional probability effect in each age group. Our sample size of 48 participants in each age group meant that the power in the present study exceeded the minimum required.

Materials and design

Forty-five pairs of two-character words (C1C2) were selected as target words. The positional probability of the initial character (C1) of the target word was manipulated, and the final character (C2) of the targets were the same for each pair of target words. We calculated within-word positional probability of initial or final characters as the number of two-character words containing the initial character as a word beginning or word ending character respectively, divided by the total number of two-character words containing that character. In the high-probability condition, C1 frequently appeared as the word initial character of two-character words (mean = 0.81, range = 0.70 to 1.00, based on the data from the corpus of SUBTLEX-CH, Cai & Brysbaert, 2010). That is, it was consistent with its most frequent within-word position in two-character words, thereby, providing congruent information about the likely location of the left boundary of the target words. In the low-probability condition, C1 infrequently appeared as the initial character of a two-character word (mean = 0.22, range = 0.07 to 0.30). Thus, these characters provided incongruent information regarding the likely location of the left boundary of the target words. The mean number of two-character words containing the initial character as a word-beginning was significantly higher in the high-probability condition (mean = 31.31, SD = 25.83) relative to the low-probability condition (mean = 9.68, SD = 11.83), $t(44) = 4.91$, $p < 0.001$. The final characters of the target words were each selected such that they had approximately 50% probability of occurring at the beginning or end of two-character words (mean = 0.50, range = 0.36 to 0.65). Thus, the second characters of the target words provided no cue to the likely location of the right boundary of the target words. The mean number of two-character words containing the final characters of the target words as word beginnings (mean = 36.32, SD = 27.92) and as word endings (mean = 35.98, SD = 23.21) were matched ($t(44) = 0.14$, $p > 0.05$). We also matched as closely as possible counterpart first characters for the number of constituent strokes, their word frequencies and the frequency of word final character across the two experimental conditions. The mean number of strokes of initial characters of the target words was 8.1 (SD = 2.7) in the high probability condition and 8.5 (SD = 2.4) in the low probability condition, the mean frequency of the target words was 59 (SD = 153) per million in the high probability condition and 33 (SD = 77) in the low probability condition, and the mean frequency of word initial characters was 963 (SD = 2910) per million in the high probability condition and 436 (SD = 824) per million in the low probability condition. Neither of these differences was statistically significant (*t*s < 1.28, *p*s > 0.05). Note that our matching of frequency of the target words ensured that our character positional probability manipulations also captured the frequency with which high and low probability initial characters appeared in the language. To ensure that the target words were equally familiar to children and adults, 15 undergraduates and 15 children in Grade 3 (each different from those tested in the other pre-screen tests and those tested in the main experiment) rated the familiarity of the target words using a 5-point scale (a score of “1” meant the target was very unfamiliar, and a score of "5" meant the target was very familiar). The mean familiarity rating was 4.70 (SD = 0.15) for adults and 4.61 (SD = 0.18) for children, and again, there were no significant differences across the two groups of participants ($t(44) = 0.32$, $p > 0.05$), indicating that both child and adult participants were equally familiar with the target words in the experiment.

Each pair of target words was embedded within the same sentence frame (see examples in Figure 2). The mean length of the sentences was 12.0 characters, ranging 10 to 14 characters. The target words were never presented at the beginning or the end of a sentence.

High-probability condition: 少年发现湖水不太干净。

Translation: The young man found the lake water was not very clean.

Low-probability condition: 少年发现泉水不太干净。

Translation: The young man found the spring water was not very clean.

Figure 2. Example sentences and target words from Experiment 1. The shading did not appear when the sentences were presented to participants.

We undertook pre-screen tests to assess the contextual predictability of the target word, sentence naturalness and sentence difficulty in the two experimental conditions. For each of the pre-screen tests, 15 undergraduates and 15 children in grade 3 were tested. The contextual predictability of the target was assessed by a cloze task. Sentence fragments up to, but not including the target word were provided. Participants were instructed to fill in the next word that they felt could continue the sentence fragment naturally. In the naturalness and difficulty pre-screen tests, we used two 5-point scales, one from "1" to "5" to assess sentence naturalness (a score of “1” meant the sentence was unnatural to read, and a score of “5” meant the sentence was perfectly natural to read), and a second to assess sentence difficulty (a score of “1” meant the sentence was very difficult to read, and a score of “5” meant the sentence was perfectly easy to read). The mean ratings from the three pre-screen tests are summarized in Table 1. The results of linear mixed models showed that, the main effects of *Experiment Condition* and *Age Group,* as well as their interactions were not significant in any of the pre-screen tests (all *t*s < 0.89), indicating that the above properties of the experiment stimuli did not differ between the two experimental conditions, nor between children and adults.

Table 1. The scores of pre-screen tests in each experiment condition in Experiment 1. Standard deviations are shown in parentheses.

		High-probability	Low-probability
Mean sentence completion ratio	Adults	0.11(0.03)	0.13(0.04)
	Children	0.12(0.03)	0.14(0.05)
Mean score of sentence naturalness rating	Adults	4.19(0.21)	4.24(0.19)
	Children	4.21(0.25)	4.16(0.21)
Mean score of sentence difficulty rating	Adults	4.56(0.15)	4.49(0.16)
	Children	4.44(0.14)	4.48(0.15)

Two lists of trials were constructed, one list contained 22 trials for the high-probability condition and 23 trials for the low-probability condition, and the other list contained 22 trials for the low-probability condition and 23 trials for the high-probability condition. Each participant read a list of 45 sentences that were presented in a random order. There were 15 yes/no comprehension questions to ensure that readers were reading effectively for comprehension.

Apparatus

Participants’ eye movements were recorded using a SR Research EyeLink 1000 eye tracker (sampling rate = 1000Hz) as they read sentences from a computer monitor at a viewing distance of 75 cm. Sentences were presented in black, Song font size 18 (25×25 pixels), on a 19-inch DELL monitor with a 1024 × 768 pixel resolution. Each character covered 0.74° of horizontal visual angle.

Procedure

Participants were instructed to sit in front of the eye-tracker and lean on chin and forehead rests to minimize head movements. Prior to the start of the experiment, a three-point horizontal calibration and validation were performed until maximum error was less than 0.2 deg. After a successful calibration, the sentences were presented one at a time. Participants were informed that they should read the sentences as naturally as they could and try to understand the meaning of each sentence. They were also asked to click the left button of the mouse to end the display when they had finished reading each sentence. Recalibration and revalidation were conducted when necessary (i.e., when tracker error increased beyond 0.2 deg). Each trial started with a fixation box (0.74 deg × 0.74 deg) at the location of the first character of the sentence. Four practice sentences were presented at the beginning of the experiment. Each sentence in turn was presented on the screen once the participants successfully fixated the box. Participants were asked to answer the comprehension questions by pressing one of the two pre-specified keys on a button box. The experiment took approximately 20 minutes.

Results and Discussion

All participants scored 90% or higher on reading comprehension questions. The mean scores for the comprehension questions were not significantly different in children (96.7%) and adults (97.2%), indicating that both groups of readers understood the sentences well.

We conducted analyses of eye movement data for the target word in each sentence. We report first fixation duration (the duration of the initial fixation on the target word), single fixation duration (the duration of the initial fixation when readers made only one fixation on the word), gaze duration (the sum of all the fixations on the target from the first fixation until a fixation on another word), and total fixation time (the sum of all the fixations on the target word). First fixation, single fixation duration and gaze duration are generally considered to be relatively early measures of processing, often reflecting lexical processing of the target word. Total reading time is considered to include later processing of the word often associated with its integration into sentential context (Rayner et al., 1989). In addition to these four reading time measures, we also report skipping probability (the probability that readers skipped the target word during first pass reading), refixation probability (the probability that readers made two or more fixations on the target word during first pass reading, again a measure often taken to reflect potential difficulty associated with lexical processing) and regression in probability (the probability that the readers move their eyes back from downstream in the sentence in order to refixate the target word). Again, this measure is often taken to reflect processing associated with the integration of the word with the sentential context.

We excluded (a) fixations longer than 1200ms and shorter than 80ms, (b) trials for which blinks and tracker loss occurred on the target, and (c) trials in which 3 or fewer than 3 fixations in total were made. At a later stage, any data points that were more than 3 standard deviations from the age group mean for all the eye movement measures were excluded from the analyses. In total, 3.2% of the data was removed from the analyses.

We constructed Linear Mixed Models (LMMs) by using the lme4 package (Bates et al., 2015) in R 3.6.2 (R Core Team, 2019) and RStudio (2019). We used linear mixed-effects models for continuous variables (i.e., data for the four fixation duration measures) and generalized mixed-effects models for binary variables (i.e., data for the fixation probability measures) in which the participants and items were considered as random effects (Baayen, Davidson, & Bates, 2008). We included fixed effects of *Initial Character Positional Probability* (high vs. low), *Age Group* (adults vs. children) and random effects of participants and items (novel words). We conducted our analyses with the full random structure for the models (e.g., Barr et al., 2013) that included slopes for the main effects and their interactions. The random structure was systematically simplified when failure to converge occurred, first by removing correlations between random effects, and then by removing their interactions. For each contrast we report beta values (*b*), Coefficient intervals (*CI*), standard errors (*SE*), and *t* or *z* statistics. *T* or *z* values greater than 1.96 were considered significant at the 5% level. We performed log transformations of fixation duration data to reduce distribution skewing (Baayen et al., 2008). Our dataset and the R script used to analyze it are available through the Open Science Framework
(DOI 10.17605/OSF.IO/SMX6W)

The means of each of the seven dependent variables are presented in Table 2, and the linear mixed-effect models are summarized in Table 3.

Table 2. Mean reading times, skipping probabilities, refixation probabilities, and regression in probabilities on target words in the two conditions for children and adults in Experiment 1. Standard deviations are shown in parentheses.

	Children		Adults	
	High-probability	Low-probability	High-probability	Low-probability
Skipping probability	25.8% (43.8%)	25.1% (36.1%)	15.6% (36.3%)	15.4% (36.1%)
First fixation duration	249 (102)	252 (103)	244 (83)	243 (83)
Single fixation duration	246 (99)	248 (106)	245 (86)	243 (85)
Gaze duration	346 (215)	349 (222)	302 (157)	299 (152)
Refixation probability	30.5% (46.1%)	29.7% (45.7%)	21.8% (41.3%)	22.0% (41.5%)
Regression in probability	38.5% (48.7%)	36.4% (48.1%)	18.3% (38.7%)	19.4% (39.6%)
Total reading time	787 (495)	804 (522)	413 (241)	417 (247)

Table 3. Linear Mixed Model analyses for all the eye movement measures in Experiment 1.

		b	*CI*	*SE*	*t/z*
Skipping probability	Intercept	-1.83	[-2.16, -1.51]	0.16	-11.13
	Age Group	0.82	[0.28, 1.36]	0.28	2.98
	Initial Character Positional Probability	-0.06	[-0.06, 0.09]	-0.64	0.52
	Age Group * Initial Character Positional Probability	0.03	[-0.31, 0.36]	0.17	0.15
First fixation duration	Intercept	5.44	[5.41, 5.47]	0.02	353.35
	Age Group	-0.005	[-0.06, 0.05]	0.03	-0.17
	Initial Character Positional Probability	0.004	[-0.02, 0.03]	0.01	0.26
	Age Group * Initial Character Positional Probability	0.01	[-0.04, 0.06]	0.03	0.43
Single fixation duration	Intercept	5.44	[5.40, 5.47]	0.02	329.06
	Age Group	-0.01	[-0.07, 0.05]	0.03	-0.38
	Initial Character Positional Probability	-0.002	[-0.03, 0.03]	0.02	-0.10

	Age Group * Initial Character Positional Probability	0.006	[-0.05, 0.06]	0.03	0.19
	Intercept	5.62	[5.57, 5.67]	0.03	220.79
	Age Group	0.07	[-0.02, 0.15]	0.04	1.54
Gaze duration	Initial Character Positional Probability	-0.008	[-0.05, 0.03]	0.02	-0.39
	Age Group * Initial Character Positional Probability	0.001	[-0.07, 0.08]	0.03	0.02
	Intercept	-1.28	[-1.48, -1.08]	0.10	-12.48
	Age Group	0.45	[0.12, 0.79]	0.17	2.64
Refixation probability	Initial Character Positional Probability	-0.06	[-0.24, 0.12]	0.09	-0.63
	Age Group * Initial Character Positional Probability	-0.08	[-0.41, 0.25]	0.17	-0.47
	Intercept	-1.15	[-1.37, -0.92]	0.11	-10.09
	Age Group	1.18	[0.85, 1.50]	0.17	6.99
Regression in probability	Initial Character Positional Probability	0.04	[-0.17, 0.26]	0.11	0.39
	Age Group * Initial Character Positional Probability	-0.24	[-0.65, 0.17]	0.21	-1.16
	Intercept	6.15	[6.08, 6.22]	0.04	167.39
	Age Group	0.58	[0.45, 0.71]	0.07	8.84
Total fixation time	Initial Character Positional Probability	-0.006	[-0.06, 0.05]	0.03	-0.20
	Age Group * Initial Character Positional Probability	-0.01	[-0.09, 0.07]	0.04	-0.30

The main effect of *Age Group* was also significant for the measure of skipping probability, with adults skipping the target words less often compared to children. This result was somewhat surprising in that it is most typically noted that children have reduced skipping rates relative to adults in the domain of reading development (for reviews in Blythe & Joseph, 2011; Blythe, 2014). To ensure that this effect was not solely associated with the target words in our experiment, we also computed the skipping probability for all the one and two character words in our sentences (we excluded the first and last word in each sentence from these analyses). Skipping rates for single character words were high and comparable between children and adults (children: M = 60.0%, SD = 49.0%; adults: M = 56.9%, SD = 49.5%), presumably due to a ceiling effect.

However, as with the local analyses, for two character words, skipping occurred to a greater degree in children (M = 29.6%, SD = 45.6%) relative to adults (M = 20.7%, SD = 40.5%). This effect was significant (*b* = 0.44, *SE* = 0.18, *CI* = [0.09, 0.78], *t* = 2.45). There are a number of points to make in relation to the finding that skipping was increased for children relative to adults. First, we must reiterate that the present stimuli were designed to be relatively simple for our Grade 3 participants to read, and for this reason, we might anticipate that skipping rates should be quite high for these stimuli. Second, whilst the skipping rates might initially appear to suggest that children processed two character words more effectively than adults, in fact this was clearly not the case. As can be seen from the reading time data for the children (in both the local and the global results we report here), it is clearly the case that children were more likely to make regressions in order to re-read words, and spent more time overall reading words than did adults. Thus, it would be incorrect to conclude that children were more efficient than adults in their processing. Instead, it appears to be the case that children here adopted a slightly risky strategy whereby they skipped upcoming words, presumably particularly when they felt that those words were more familiar to them, but then later returned to those words in order to verify that they had indeed processed them correctly. To be clear, these results suggest that children were inclined to make return visits and spend longer overall processing words in compensation for having more likely skipped a word when it as initially encountered, and they did this to a greater extent than adults. This reflects a risky strategy, perhaps due to children’s increasing (over) confidence with their reading as they develop. The final point pertinent to the consideration of this aspect of our results concerns the extent to which it is established in the current literature that there are indeed robust differences between children and adults in skipping behavior during Chinese reading. It is unquestionably the case that there are very robust differences in reading times for words between children and adults across almost every eye movement study that has been reported in the literature. However, when we examined skipping behavior in children relative to adults across 4 published studies (5 experiments) investigating Chinese reading, the pattern is not so consistently clear (see Table 4).

Table 4. Summarized skipping probability data in Chinese reading

		Age-appropriate stimuli		
Yan, Pan, & Kliegl (2019)		Grade 3	Grade 5	Adults
		14.0%	16.8%	18.1%
		Same stimuli across Age Group		
		Grade 3	Grade 5	Adults
Yan, Pan, & Kliegl (2019)		12.7%	18.3%	17.5%
Yan, Liu, Liang, Liu, & Bai (2015)		17.7%		19.6%
Zang, Liang, Bai, Yan, & Liversedge (2012)		7.0%		13.0%
Liang, Ma, Bai, & Liversedge (2021)		18.2%		20.0%
The present study	Experiment 1	29.6%		20.7%
	Experiment 2	25.5%		20.4%

Whilst it is the case that three of these experiments (Yan et al., 2019, Zang et al. 2012 & Liang et al., 2021) showed reduced skipping in children relative to adults, the pattern of effects across the remaining (majority of) studies that used identical stimuli for the participant groups was far less consistent. What is also clear is that any effects that are apparent in these studies are far less pronounced and consistent than is the case for counterpart reading time differences. Consideration of these studies leads us to suggest that we need to be somewhat cautious in predicting robust differences in skipping behavior between adults and children in future eye movement studies, particularly in relation to those investigating Chinese reading.

The main effect of *Age Group* was not significant for the measures of first fixation duration, single fixation duration and gaze duration, but this effect was robust for the measures of refixation probability, regression in probability and total fixation time, such that adults had shorter total reading times, and made less refixations and less with fewer regressions back to the target words as compared to children. Note that, we did not find robust age-related differences on the earliest measures of lexical processing (first fixation duration, single fixation duration and gaze duration), though there were substantial numerical differences, and the effects were robust for refixation probability and later measures. The lack of reliable effects on first fixation, single fixation and gaze duration are unexpected and inconsistent with the previous findings (e.g., Zang et al., 2013). It is very well documented that the size of effects in eye movement measures are usually smaller in earlier relative to later measures (in part due to later measures often subsuming earlier measures). Thus, the smaller effects for first fixation, single fixation and gaze duration would be less likely to be robust than for later measures. Finally, it is worth adding that the refixation measure that reflects the likelihood that the target word attracted additional fixations beyond the initial fixation, itself a relatively early measure, did show robust age effects. Thus, whilst the lack of robust effects in the earliest measures is something of a surprise, there appear to be reasonable explanations as to why this might have occurred. And again, the numerical differences alongside the robust effects for the other measures do give us confidence that the age effects we anticipated did occur.

Given the failure to find age-related effects in the early eye movement measures, we undertook further investigations across a larger region of analysis, that is, we compared sentence-level eye movement measures in children and adults. The means of three such measures (average fixation duration, total sentence reading time and number of fixations) for each condition are presented in Table 5, and the corresponding linear mixed-effect models are summarized in Table

6. There was a robust effect of *Age Group* for all these eye movement measures. Children had longer mean fixation durations, longer overall sentence reading times and made more fixations than adults when reading sentences. This is a typical pattern of results reflecting developmental change in eye movements during reading. It is clearly the case that the children in our experiment were less proficient readers than adults. Further, as mentioned earlier, it is likely that age-related differences did not occur for the early eye movement measures because of the high frequency of the target words, the small regions associated with our analyses and the reduced data set (relative to the those adopted for the global measures).

Table 5. Sentence-level eye movement measures in Experiment 1. Standard deviations are shown in parentheses.

	Children		Adults	
	High-probability	Low-probability	High-probability	Low-probability
Mean fixation duration	259 (46)	260 (47)	237 (43)	236 (41)
Number of fixations in sentence	10.7 (5.3)	11.1 (5.4)	8.1 (3.3)	7.9 (3.2)
Sentence reading time (ms)	4622 (2863)	4772 (2902)	2886 (1575)	2840 (1506)

Table 6. Linear Mixed Model analyses for sentence-level eye movement measures.

		b	CI	SE	t/z
Mean fixation duration (ms)	Intercept	5.50	[5.47, 5.52]	0.02	463.57
	Age Group	0.09	[0.05, 0.14]	0.02	4.04
	Initial Character Positional Probability	-0.001	[-0.01, 0.009]	0.005	-0.17
	Age Group * Initial Character Positional Probability	0.002	[-0.01, 0.02]	0.008	0.26
Number of fixations in sentence	Intercept	9.41	[8.75, 10.06]	0.33	28.33
	Age Group	2.85	[1.61, 4.09]	0.63	4.51
	Initial Character Positional Probability	0.05	[-0.43, 0.53]	0.24	0.20

	Age Group * Initial Character Positional Probability	0.37	[-0.11, 0.85]	0.24	1.50
Sentence reading time (ms)	Intercept	8.05	[7.95, 8.16]	0.05	151.67
	Age Group	0.46	[0.32, 0.61]	0.07	6.24
	Initial Character Positional Probability	-0.02	[-0.14, 0.09]	0.06	-0.37
	Age Group * Initial Character Positional Probability	0.03	[-0.02, 0.08]	0.03	1.07

Very importantly in relation to our primary theoretical hypotheses, neither the effect of *Initial Character Positional Probability*, nor the interaction between *Age Group* and *Initial Character Positional Probability* were significant for all six eye movement measures, showing that for both children and adults, reading times on target words did not differ irrespective of the positional probability of the initial character[1]. This result is entirely in line with our prediction and is consistent with the suggestion that both children and adults were insensitive to the positional probability characteristics of the initial character of a two-character word when segmenting and identifying words in natural Chinese reading.

We also undertook analyses of initial landing positions on target words to check whether a word initial character's positional frequency influenced saccadic targeting behavior in Chinese reading. The means for each condition are presented in Table 7, and the corresponding linear mixed-effect models are summarized in Table 8. Neither the effect of *Initial Character Positional Probability*, nor the interaction between *Initial Character Positional Probability* and *Age Group* were significant when we included all initial fixation data in the analysis. This indicates that an

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[1] We undertook analyses of fixation durations (first fixation, gaze duration and total fixation duration) on pre-target words and the final fixation prior to a saccade to the target to check for potential parafoveal-on-foveal effects. Neither the effect of *Initial Character Positional Probability* (*t*s < 0.95), nor the interaction between *Initial Character Positional Probability* and *Age Group* (*t*s < 0.96) were significant in any of these analyses, suggesting that there was no robust parafoveal on foveal influence of initial character positional frequency.

upcoming word's initial character positional probability did not influence where Chinese readers target their initial saccades on the word. Note, though, that it is very well documented that quite different distributions of initial landing positions exist in Chinese reading for words that receive a single fixation compared with words that receive multiple fixations (see Pan et al., 2014; Yan et al., 2010; Zang et al., 2013; Liang et al., 2021). Given this, we also undertook analyses in which we split the data set accordingly. The effects of *Initial Character Positional Probability were not* significant for both single and multiple fixations case (*t*s < 1.43). The interactions between *Initial Character Positional Probability* and *Age Group* were not reliable for both multiple fixation cases (*t* = -1.06) and single fixation cases (*t* = 1.75, though this effect was marginal here). These findings are consistent with the suggestion that initial character positional frequency did not influence initial saccadic landing positions on target words in our experimental conditions.

Table 7. Initial landing positions on target words in the two conditions for children and adults in Experiment 1. Standard deviations are shown in parentheses.

	Children		Adults	
	High-probability	Low-probability	High-probability	Low-probability
Mean initial fixation position	0.88 (0.56)	0.85 (0.56)	0.89 (0.55)	0.91 (0.56)
Single fixation position	0.99 (0.52)	0.90 (0.51)	0.99 (0.52)	1.00 (0.51)
First fixation position in multiple fixation cases	0.76 (0.57)	0.78 (0.60)	0.60(0.51)	0.67 (0.59)

Table 8. Linear Mixed Effects Model analyses for initial landing positions in Experiment 1.

		b	CI	SE	t/z
Mean initial fixation position	Intercept	0.89	[0.85, 0.93]	0.02	47.47
	Age Group	-0.03	[-0.10, 0.03]	0.03	-0.96

	Initial Character Positional Probability	-0.005	[-0.05, 0.04]	0.02	-0.22
	Age Group * Initial Character Positional Probability	0.006	[-0.15, 0.03]	0.05	-1.35
Single fixation position	Intercept	0.97	[0.94, 1.00]	0.02	56.61
	Age Group	-0.05	[-0.11, 0.01]	0.03	-1.65
	Initial Character Positional Probability	-0.04	[-0.10, 0.02]	0.03	-1.43
	Age Group * Initial Character Positional Probability	-0.10	[-0.21, 0.01]	0.06	-1.75
First fixation position in multiple fixation cases	Intercept	0.75	[0.69, 0.84]	0.04	20.61
	Age Group	0.16	[0.001, 0.28]	0.07	2.33
	Initial Character Positional Probability	0.04	[-0.13, 0.06]	0.04	0.95
	Age Group * Initial Character Positional Probability	-0.08	[-0.12, 0.23]	0.07	-1.06

Next, we conducted Bayes Factor analyses for linear mixed models (Morey et al., 2018) to obtain further statistical support for the null effect of *Initial Character Positional Probability*, and the null interaction between *Initial Character Positional Probability* and *Age Group*. Bayes factors for the four models were calculated, including the full model (i.e., BF_{Full}, including the main effects of *Initial Character Positional Probability*, *Age Group*, and their interaction), the model with two main effects (i.e., BF_{Main}, containing the main effects of *Initial Character Positional Probability* and *Age Group*), and the model with the main effect of *Age Group* alone (i.e., BF_{Age}). We evaluated the non-significant main effect of *Initial Character Positional Probability by* comparing the two models (*BF*Full/*BF*Age), and evaluated the non-significant interactions between the two factors by comparing the two models (*BF*Full/*BF*Main). BF values smaller than 1 favor the null hypothesis, whilst BF values greater than 1 favor the alternative hypothesis. We used the default scale prior (r = .5) and 100,000 Monte Carlo iterations of the BayesFactor package for each of the eye movement measures (see Table 9). The results fully favored the null hypothesis.

Table 9. Bayes analyses for all the eye movement measures in Experiment 1.

	*BF*Main	*BF*Interaction
Skipping probability	0.04	0.05
First fixation duration	0.04	0.07
Single fixation duration	0.05	0.07
Gaze duration	0.04	0.06
Refixation probability	0.04	0.06
Regression in probability	0.04	0.09
Total reading time	0.05	0.06

Consistent with our hypothesis, the results of Experiment 1 provided no evidence that the positional probability of a word's initial character influenced lexical processing, suggesting that such statistical information associated with the initial character of a two-character word does not contribute to word segmentation commitments in natural Chinese reading. Since character positional probability information is widely accepted as one kind of statistical word segmentation cue in unspaced languages (e.g., in Thai and Chinese reading), the present findings suggest that the decision of where a word begins might be established simultaneously with the commitment as to where the preceding word ends. We suggest that this is due to the characteristic of unspaced written Chinese text, that a boundary is always shared by two adjacent words (word N-1 and word N) within a sentence (apart from the first and the last words). Furthermore, the present results are consistent with the suggestion that the decision about where a Chinese word begins occurs early in the time course of word segmentation and identification, occurring at a point in time when word N-1 is recognized. In such a situation, Chinese readers do not use positional probability characteristics associated with a word initial character to determine where word N begins – the decision is made primarily on the basis of the characteristics of the preceding word. We will return to this point in the General Discussion.

Experiment 2

In Experiment 1, we demonstrated that, in both children and adults, the positional probability of a word's initial character had little influence over word segmentation and identification in natural Chinese reading. In a counterpart, parallel experiment, Experiment 2, we investigated whether a similar statistical word segmentation cue associated with a word's final character influenced word segmentation and word identification in Chinese reading. We manipulated the positional probability of the final character of a two-character word such that it was either high or low probability as a word ending character, whilst keeping the initial character of the word constant across the two experimental conditions. Recall that, in contrast to our predictions (and findings) for Experiment 1, we stipulated that the visual and linguistic characteristics of a word final character would influence processing associated with the commitment to a word ending boundary. Furthermore, we anticipated that any such effects would imply that word final boundary decisions occurred somewhat later during processing associated with word identification in Chinese reading than decisions as to a word’s initial boundary. We, therefore, predicted that our manipulation of the positional probability of a word's final character should affect word segmentation and word identification in Chinese reading. We anticipated that reading times for the target words in our study would be increased when the final character of our target words had low compared with high positional probability. We also predicted that this effect would be more pronounced and have a more rapid time course for adults than children due to children's reduced sensitivity to this form of information (see Liang et al., 2015, 2017; Liu & Li, 2014). Of course, any such effects would be in stark contrast to the lack of effects that occurred in Experiment 1.

Method

Participants

The participants were the same as those tested in Experiment 1.

Materials and design

Thirty-four pairs of two-character words (C1C2) were selected as target words. The positional probability of the final characters (C2) of the target words were manipulated such that they had either a high positional probability or low positional probability. In the high-probability condition, C2 frequently appeared as the end of two-character words (mean = 0.81, range = 0.70 to 1.00), providing congruent word boundary information regarding the likely location of the right boundary of each of the target words. In the low-probability condition, C2 appeared infrequently in the final position of two-character words (mean = 0.22, range = 0.07 to 0.34), providing a very weak cue as to the likely location of the rightward boundary of each of the target words. The mean number of two-character words containing the final character as a word-ending was significantly higher in the high probability condition (mean = 40.82, SD = 37.76) relative to the low probability condition (mean = 13.53, SD = 10.30), $t(33) = 4.08$, $p < 0.001$. The initial characters of the target words were selected such that they had approximately 50% probability of occurring at the beginning or end of two-character words (mean = 0.50, range = 0.36 to 0.65). Thus, the first characters of the target words provided equivocal information as to the likely location of the left boundary of the target words. The mean number of two-character words containing the initial characters of the target words as word beginnings (mean = 35.26, SD = 22.04) and as word endings (mean = 33.94, SD = 22.66) did not differ ($t(33) = 0.56$, $p > 0.05$). As in Experiment 1, the number of strokes of the final characters (high-probability condition: mean = 8.42, SD = 2.17;

low-probability condition: mean = 8.27, SD = 2.35, $t(33) = 0.22$, $p > 0.05$), word frequencies (21.0 per million in the high-probability condition and 38.6 per million in the low-probability condition, $t(33) = 1.72$, $p = 0.10$), , and the frequencies of word initial characters were matched in the two experimental conditions (802 per million in the high-probability condition and 644 per million in the low-probability condition, $t(33) = 0.53$, $p > 0.05$). As per Experiment 1, frequency matching ensured that character positional probability manipulations also captured the frequency with which high and low probability initial characters appeared in the language. The same word familiarity ratings as in Experiment 1were conducted to assess the familiarity of target words in children and adults, and the mean rating scores did not differ in children and adults ($t(33) = 0.59$, $p > 0.05$).

The design was identical to Experiment 1. The mean length of the sentences was 11.8 characters, ranging 10 to 14 characters. We undertook the same pre-screen tests as in Experiment 1 to assess the contextual predictability of the target words, sentence naturalness and sentence difficulty in the two experimental conditions (see Table 10). The analyses of linear mixed models showed that neither the main effects of *Experiment Condition*, and *Age Group*, nor the interactions between the two factors were significant (all *t*s < 0.84). Again, this indicates that the above properties of the experimental stimuli were matched in the two experimental conditions, and in children and adults.

Table 10. The scores of pre-screen tests in each experimental condition in Experiment 2. Standard deviations are shown in parentheses.

		High-probability	Low-probability
Mean sentence completion ratio	Adults	0.08(0.04)	0.11(0.03)
	Children	0.11(0.05)	0.13(0.06)
Mean score of sentence naturalness rating	Adults	4.08(0.19)	4.18(0.14)
	Children	4.12(0.17)	4.05(0.22)

Mean score of sentence difficulty rating	Adults	4.23(0.09)	4.33(0.11)
	Children	4.17(0.12)	4.25(0.14)

Apparatus & Procedure

Both were identical to Experiment 1.

Results and Discussion

The mean score for the comprehension questions did not differ between children (97.4%) and adults (98.3%). Again, this result indicates that both child and adult participants understood the sentences well.

Prior to the analyses, the data were treated as in Experiment 1, and 2.7% of the data were excluded. The means of the six eye movement measures in each condition are presented in Table 11, and the linear mixed-effect models are summarized in Table 12.

Table 11. Skipping probabilities, mean reading times, refixation probability, and the probability of regressions back into the target words in the two conditions for children and adults in Experiment 2. Standard deviations are shown in parentheses.

	Children		Adults	
	High-probability	Low-probability	High-probability	Low-probability
Skipping probability	17.6% (38.1%)	15.4% (36.1%)	11.3% (31.7%)	9.0% (28.6%)
First fixation duration	258 (117)	259 (114)	231 (79)	241 (88)
Single fixation duration	259 (125)	253 (121)	237 (86)	245 (95)
Gaze duration	385 (281)	374 (235)	292 (145)	323 (173)
Refixation probability	34.5% (47.6%)	34.4% (47.5%)	23.4% (42.4%)	29.5% (45.6%)
Regression in probability	31.3% (46.3%)	37.8% (48.5%)	19.1% (39.3%)	24.9% (43.3%)
Total reading time	689 (508)	782 (575）	407 (245)	536 (380）

Table 12. Linear Mixed Model analyses for all the eye movement measures in Experiment 2.

		b	*CI*	*SE*	*t/z*
Skipping probability	Intercept	-2.28	[-2.57, -2.00]	0.15	-15.68
	Age Group	0.70	[0.26, 1.15]	0.23	3.08
	Final Character Positional Probability	-0.24	[-0.46, -0.02]	0.11	-2.10
	Age Group * Final Character Positional Probability	0.10	[-0.34, 0.54]	0.22	0.44
First fixation duration	Intercept	5.44	[5.41, 5.47]	0.01	363.74
	Age Group	0.06	[0.002, 0.13]	0.03	2.01
	Final Character Positional Probability	0.02	[-0.01, 0.05]	0.01	1.24
	Age Group * Final Character Positional Probability	-0.03	[-0.08, 0.03]	0.03	-0.93
Single fixation duration	Intercept	5.44	[5.41, 5.48]	0.02	323.09
	Age Group	0.04	[-0.03, 0.11]	0.04	1.10
	Final Character Positional Probability	0.004	[-0.03, 0.04]	0.02	0.24
	Age Group * Final Character Positional Probability	-0.05	[-0.12, 0.02]	0.03	-1.41
Gaze duration	Intercept	5.67	[5.62, 5.73]	0.03	203.92
	Age Group	0.14	[0.04, 0.23]	0.05	2.77
	Final Character Positional Probability	0.04	[-0.002, 0.08]	0.02	1.84
	Age Group * Final Character Positional Probability	-0.09	[-0.17, -0.01]	0.04	-2.34
	Contrast 1 [a]	-0.04	[-0.07, -0.02]	0.01	-3.29
	Contrast 2 [b]	0.005	[-0.02, 0.03]	0.01	0.41
Refixation probability	Intercept	-1.03	[-1.26, -0.81]	0.11	-8.99
	Age Group	0.46	[0.08, 0.83]	0.19	2.40
	Final Character Positional Probability	0.20	[0.01, 0.39]	0.10	2.12
	Age Group * Final Character Positional Probability	-0.37	[-0.72, -0.02]	0.18	-2.10
	Contrast 1 [a]	-0.17	[-0.29, -0.05]	0.06	-2.70
	Contrast 2 [b]	0.004	[-0.12, 0.12]	0.06	0.07
Regression in probability	Intercept	-1.10	[-1.33, -0.88]	0.11	-9.58
	Age Group	0.78	[0.45, 1.12]	0.17	4.55
	Final Character Positional Probability	0.37	[0.18, 0.56]	0.10	3.89
	Age Group * Final Character Positional Probability	-0.06	[-0.42, 0.30]	0.18	-0.32
Total reading time	Intercept	6.15	[6.06, 6.24]	0.05	131.80

	Age Group	0.41	[0.27, 0.55]	0.07	5.71
	Final Character Positional Probability	0.17	[0.07, 0.27]	0.05	3.29
	Age Group * Final Character Positional Probability	-0.11	[-0.27, 0.05]	0.08	-1.34

[a] Refers to the comparisons between the high and low-probability conditions for the adults;
[b] Refers to the comparisons between the high and low-probability conditions for the children.

There was a robust effect of *Age Group* for most eye movement measures (except single fixation duration), showing that adults had shorter fixation times, and made fewer refixations and fewer regressions back to the target words relative to children. Again, this is a typical pattern of results reflecting developmental change in eye movements during reading (Blythe, 2014). Consistent with the findings we reported for Experiment 1, in Experiment 2, adults again skipped the target words less often than children. We note, again, that this finding might initially be considered somewhat surprising, though the robust differences in regression behaviour and total reading times for target words indicate that adults processed words more proficiently than children. The points discussed earlier in relation to the counterpart findings for Experiment 1 are also relevant in relation to this finding.

Next, let us consider the effect of our manipulation of positional probabilities associated with the final character of two-character words. For skipping probability, the effect of *Final Character Positional Probability* was significant, showing that readers skipped the target words more often when the positional probability of the final constituent characters of target words was high than low. The interaction between *Final Character Positional Probability* and *Age Group* was no significant, indicating both children and adults were sensitive to the positional probability characteristics of a word's final character in parafovea during Chinese reading.

For first fixation and single fixation duration, neither the effect of *Final Character Positional Probability*, nor the interaction with *Age Group* were significant, indicating that in the very earliest stages of lexical processing both children and adults were not sensitive to the positional probability characteristics of a word's final character. This is consistent with the previous findings (see Yen et al., 2012).

For the measures of gaze duration and refixation probability, similar patterns of results were found. The effect of *Final Character Positional Probability* was marginal for the measure of gaze duration ((b = 0.04, SE = 0.02, t = 1.84), and this effect reached significance for the measure of refixation probability (b = 0.20, SE = 0.10, t = 2.12), showing that there was a tendency that readers made shorter gaze durations and fewer refixations on words with second characters with high- than low-positional probability. Furthermore, reliable interactions between *Age group* and *Final Character Positional Probability* were found. Adults had shorter gaze durations, and made fewer refixations on target words which were comprised of final characters with high compared to low positional probabilities. In contrast, there were no significant differences in the two conditions for child readers, suggesting that only the adults utilized positional probability information associated with a word's final character during fixations made prior to initially leaving that word in Chinese reading.

For the measures of regression in probability and total fixation time, we found robust effects of *Final Character Positional Probability*, showing that the participants had shorter reading times, and made fewer regressions back to target words that contained final characters appearing at word end with high compared to low positional probability. The interactions between *Final Character Positional Probability* and *Age Group* were not significant for these two later measures of processing. Both children and adults spent less time processing targets in the high compared to the low-probability condition, indicating that for these measures both children and adults were sensitive to the word boundary cue provided by the positional probability information associated with the final character of a two-character word. Clearly, these comparable effects in children and adults occurred during the somewhat later stages of processing in Chinese reading.

The dissociation in the time course of these effects between children and adults is interesting, and probably quite important, in that these results may have different implications for each of the participant groups. Since the adults showed early influences of character positional probability effects (i.e., as early as gaze duration and refixation probability), then it seems likely that they used this information to guide word identification and segmentation commitments during lexical processing of the target word. However, the somewhat later time course of similar effects in children, that is, effects in the regressions in measure and the total reading time measure (but no such effects in earlier measures) indicates that the sensitivity to positional probability information had a less immediate effect. To be clear, in children, positional probability only affected processing when words were revisited after the eyes had initially left them. If our reasoning here is correct, then this would suggest that probabilistic information regarding the likelihood of the rightward word boundary continued to exert an influence over both children and adult’s processing of a word even when the eyes had left the word, progressed to process a new word to the right and then returned to revisit the word. This might be due to that the readers are more likely to make errors when segmenting words comprised of word final characters with low positional probability during first pass reading, and they must rely more on the subsequent processing to correct their segmentation. These results suggest that children (and adults) maintained a degree of uncertainty as to the identity of a word until relatively late during processing, that is, until after a revisit to the word. The present results therefore suggest that the time course of word identification for words comprised of word final characters with low positional frequency is somewhat protracted, necessitating refixation and a repeated period of processing presumably reflecting scrutiny as to the validity of its identity.

General Discussion

From the literature on word segmentation and word identification in Chinese reading, a character's positional probability has been demonstrated to be a useful statistical word segmentation cue (see Liang et al., 2015, 2017; Yen et al., 2012). In the present study, we conducted two parallel experiments to further investigate whether the positional probability effect is driven by the initial, the final or both constituent characters of a two-character word. We were also interested to examine whether sensitivity to this statistical word segmentation cue differed in children and adults. The answer to these questions provides insight into how word segmentation and word identification might occur as part of a unified process (a core assumption of the recently developed CRM), but more importantly, specify more precisely the processing steps and commitments that must occur over time in order for a word to be ultimately segmented and identified during natural Chinese reading. We found that our manipulation of the positional probability of a word's final character affected processing times on target words, whilst this effect did not occur for our comparable manipulation associated with the initial character of a two-character word. This suggests that only the positional probability characteristics of the final character (but not the initial character) of a two-character word contribute to word segmentation and word identification in Chinese reading. In relation to age-related differences in processing this form of statistical word segmentation cue, both children and adults utilized the positional probability associated with the final character to facilitate word segmentation and word processing, though the time course of this influence was less immediate in children compared to adults. It should be noted here that the mean target words' frequencies in Experiment 1 (46 per million) was slightly higher than that in Experiment 2 (25 per million) though we tried out best to match the characteristics of the target words across the two experiments. In the future, it might be informative to further investigate whether word frequency modulates the roles of character positional frequency in lexical identification in Chinese reading.

The present results suggest that there is a sensitivity to the positional probability characteristics of a word's final character at a relatively early age (around 9 years old or younger), though immaturity remains in relation to when such information impacts processing in children relative to adults. Our results were consistent with our predictions and fit neatly with our account of the nature and time course of word segmentation and identification during natural Chinese reading. The insensitivity to the positional probability of a word's initial character is very likely related to the basic characteristic of written Chinese text, that words are not visually segmented (e.g., by spaces). As we stated earlier, this means that the left boundary of word N and the right boundary of word N-1 are coincident, and they are identified simultaneously. Thus, the identification of the leftward boundary of a word N actually occurs at the point that the rightward boundary of word N-1 is identified. This suggests that commitment to where a word begins in unspaced scripts occurs relatively early during the time course of the processing of that word. Under this circumstance, any segmentation cue provided by the positional probability information associated with the initial character of word N is redundant with respect to the identification of its leftward boundary. It is also important to understand that the commitment to determine where a word ends is critical for successful completion of word identification. Given our account of processing, in circumstances where the commitment to the word ending boundary occurs later in processing than the commitment to its beginning, the visual and linguistic characteristics of the final character of a two-character word (e.g., character positional frequency) will be important and influential in making this determination. It is our claim that this is the reason that we did observe character positional frequency influences for our manipulation of the final character of the word.

We also noted earlier that in Thai, an unspaced alphabetic language, although there is no spatial word segmentation cue to guide readers' eye movements, both the positional probabilities associated with word-initial and word-final characters influence saccadic targeting to optimal landing sites. In Thai reading, initial saccades were targeted closer to the center of a word comprised of an initial and/or final character with high than low positional probability (Kasisopa et al., 2013, 2016). Thus, it appears that the positional probability of word initial characters affects word processing in Thai reading, and on the basis of the current findings, this clearly contrasts with the situation in Chinese reading. Of course, this situation might initially appear somewhat odd, given that the arguments we have generated in relation to Chinese readers identifying the word initial boundary of a character string via it being coincident with the rightward boundary of the preceding word, and in principle, this might apply equally well to written Thai given that it is unspaced. Furthermore, such differential findings between Thai and Chinese suggest that the role of the positional probability of a word's initial character varies across different unspaced writing systems. However, to explain the different effects in the two languages it is necessary to consider the visual characteristics of the written form of Thai compared to Chinese. For all Thai words, it is estimated that 10 characters account for over 50% of all initial character occurrences and 5 characters account for roughly the same percentage in word-final position. The appearance of these characters in words is highly related to where word boundaries occur. Such characters, therefore, have very high visual saliency with respect to word-initial and word-final positions. This means that within-word Thai character position information very likely plays a much more prominent (likely visually mediated) role in word segmentation in Thai reading (see Kasisopa et al., 2013). In some regards, these characters may play a similar role to word spaces in English reading. Given the systematicity and prevalence of these characters in Thai, it seems very likely that they may be visually extracted parafoveally and used to guide segmentation and saccadic targeting in reading. If this explanation was correct, then we might predict that if spaces were artificially introduced between the words of a sentence in Thai, then we might expect the two forms of segmentation cue (word spacing and a character's positional probability) to interactively affect word segmentation and processing in Thai reading. We might expect this because the two forms of segmentation cue are visual and affect the segmentation process in a similar way. The findings in Kasisopa et al.'s (2013) study support this viewpoint. In their study, saccadic targeting was jointly affected by word spacing and word-initial and word-final position-specific character frequencies. That is, the most optimized landing site distributions on words in their study arose in the condition in which word-initial and word-final characters had high positional probability and appeared in the presence of inter-word spaces.

A character's positional probability within a word in Chinese is a segmentation cue that does not have the visual salience as is the case in Thai. It is reported that less than 20% of 5915 unique Chinese characters provide unambiguous word boundary information, that is, appearing in only one within-word position, such as in a single-character word, or as the initial character, or final character of a multi-character word (Yen et al., 2009). And, importantly, the total frequency of these characters' occurrence within the language is fairly low (1146.9 per million). In contrast, approximately 50% of Chinese characters can be used in all within-word positions, and again, importantly, these characters are relatively frequent (960976.9 per million). Given this, as we stated earlier, a character's within-word positional probability in Chinese offers a far less robust and systematic cue to a word’s boundary relative to the visual word segmentation cues offered by characters in Thai. Instead it is more likely that positional information in Chinese reading is encoded and represented, and consequently used in word segmentation and identification, in a much more graded manner in line with its more continuous character as a statistical linguistic feature. The findings in Liang et al.'s (2015, 2017) studies support this viewpoint. Recall that, in their studies, there was no interactive effect between two types of word segmentation cues (a character's positional probability and word spacing) when participants were required to read and learn a Chinese novel word in multiple sentential contexts, suggesting that processing of a character's positional probability might be more bound to early linguistic processing (assessment of visual familiarity and lexical access), rather than being associated with visual processing whereby clear and unambiguous cues to word segmentation are identified in relation to text in the parafovea. If our argument is correct, then it will likely have implications for current cross-linguistic theorizing in relation to processes of word segmentation and eye movement control in unspaced reading.

Next, we interpret how the positional probability associated with a word-ending character affects word segmentation and word recognition in Chinese reading. In relation to alphabetic reading, during lexical identification, letters that comprise a word activate the lexical entry for that word, as well as for words sharing these letters (orthographic neighbors). According to those models that assume an activation mechanism to explain lexical access (i.e., accounts that adopt an interactive activation based framework), for words with many neighbors, their constituent letters receive more top-down activation from representations of the word and its orthographic neighbors at the word unit level than do words with few neighbors (Andrews, 1989; Forster & Shen, 1996; Johnson & Pugh, 1994; Peereman & Content, 1995; Sears et al., 1995). Consequently, the speed of lexically identifying a word with many, relative to a word with few neighbors is accelerated (McClelland & Rumelhart, 1981).

Let us now consider character based word identification in Chinese reading. Previous studies have investigated the influence of position-specific orthographic neighbors on word identification time. Specifically, it has been shown that for Chinese words comprised of two or more characters, processing time is reduced for words with more character position-specific neighbors than words with fewer character position-specific neighbors in a lexical decision task and in natural sentence reading (Tsai et al., 2006). Thus, when a reader identifies a word with a final character that has high positional probability, it is the case that a large cohort of orthographic neighbors that share that character in that position will also become activated. In turn, this will, result in a boost of the activation of candidates with this final constituent character, and again in turn, through activation feedback, this will serve to strengthen target activation. It is in this way that facilitatory effects of characters with high position specific probability in words might occur in Chinese reading. If correct, then this suggestion implies that a character's positional probability will be deterministic in relation to commitments over character-to-word assignments during word segmentation and identification in Chinese reading. Furthermore, our findings suggest that current computational models of eye movement control in Chinese reading should likely be modified such that statistical information associated with the final character of multi-character words influences segmentation and word recognition, as well as consequent oculomotor computations.

In summary, the present study provides further insight into the mechanisms of word segmentation in Chinese reading. Here we have shown that the positional probability of a word-ending character affects segmentation commitments as well as the ease with which a word is identified, and this holds for children and adults (though the time course of the effects is slower for child relative to adult readers). However, this same feature of word initial characters has little such influence. Together, these results point to an important conclusion, namely, that in forming word segmentation commitments in Chinese reading, for each fixation on a word, the processing system makes a determination as to where the currently fixated word ends, and in forming this determination, the subsequent word beginning is identified by default.

References

Andrews, S. (1989). Frequency and neighborhood effects on lexical access: activation or search? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 802–814. http://dx.doi.org/10.1037/0278-7393.15.5.802

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59,* 390–412. http://dx.doi.org/10.1016/j.jml.2007.12.005

Bai, X., Liang, F., Blythe, H. I., Zang, C., Yan, G., & Liversedge, S. P. (2013). Interword spacing effects on the acquisition of new vocabulary for readers of Chinese as a second language. *Journal of Research in Reading*, *36,* S4–S17. https://doi.org/10.1111/j.1467-9817.2013.01554.x

Bai, X., Yan, G., Liversedge, S. P., Zang, C., & Rayner, K. (2008). Reading spaced and unspaced Chinese text: Evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 1277–1287. https://doi.10.1037/0096-1523.34.5.1277

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,* 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bates D, Mächler M, Bolker B, Walker S. (2015). "Fitting Linear Mixed-Effects Models Using lme4." *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01.

Blythe, H. I. (2014). Developmental changes in eye movements and visual information encoding associated with learning to read. *Current Directions in Psychological Science, 23*(3), 201–207. https://doi.org/10.1177/0963721414530145

Blythe, H. I., Liang, F., Zang, C., Wang, J., Yan, G., Bai, X., & Liversedge, S. P. (2012). Inserting spaces into Chinese text helps readers to learn new words: an eye movement study. *Journal of Memory and Language*, *67*, 241–254. https://doi.org/10.1016/j.jml.2012.05.004

Buchner, A., Erdfelder, E., Faul, F., & Lang, A. G. (2007). The G*Power Team. Retrieved from https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.html

Cai, Q., & Brysbaert, M. (2010). SUBTLEX-CH: Chinese word and character frequencies based on film subtitles. *PloS one*, *5*, e10729. https://doi.org/10.1371/journal.pone.0010729

Clifton, C., Ferreira, F., Henderson, J. M., Inhoff, A. W., Liversedge, S. P., Reichle, E. D., Schotter, E. R. (2016). Eye movements in reading and information processing: Keith

Rayner's 40 year legacy. *Journal of Memory and Language, 86*, 1–19. https://doi.org/10.1016/j.jml.2015.07.004

Cutter, M. G., Drieghe, D., & Liversedge, S. P. (2017). Reading sentences of uniform word length: Evidence for the adaptation of the preferred saccade length during reading. *Journal of Experimental Psychology: Human Perception and Performance, 43*(11), 1895–1911. https://doi.org/10.1037/xhp0000416

Cutter, M. G., Drieghe, D., & Liversedge, S. P. (2018). Reading sentences of uniform word length – II: very rapid adaptation of the preferred saccade length. *Psychonomic Bulletin & Review, 25*(4), 1435–1440. https://doi.org/10.3758/s13423-018-1473-2

Forster, K. I., & Shen, D. (1996). No enemies in the neighborhood: absence of inhibitory neighborhood effects in lexical decision and semantic categorization. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*, 696–713. https://doi.org/10.1037/0278-7393.22.3.696

Inhoff, A. W., & Liu, W. (1998). The perceptual span and oculomotor activity during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance, 24*(1), 20–34. http://dx.doi.org/10.1037//0096-1523.24.1.20

Johnson, N. F., & Pugh, K. R. (1994). A cohort model of visual word recognition. *Cognitive Psychology, 26*, 240–346. https://doi.org/10.1006/cogp.1994.1008

Juhasz, B. J., White, S. J., Liversedge, S. P., & Rayner, K. (2008). Eye movements and the use of parafoveal word length information in reading. *Journal of Experimental Psychology: Human Perception and Performance, 34*(6), 1560–1579. http://dx.doi.org/10.1037/a0012319

Kasisopa, B., Reilly, R. G., 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

Kasisopa, B., Reilly, R. G., Luksaneeyanawin, S., & Burnham, D. (2016). Child readers' eye movements in reading Thai. *Vision research, 123,* 8–19. https://doi.org/10.1016/j.visres.2015.07.009

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. J*ournal of Experimental Psychology: General, 135*(1), 12-35. https://doi.org/10.1037/0096-3445.135.1.12

Lexicon of Common Words in Contemporary Chinese Research Team. (2008). *Lexicon of Common Words in Contemporary Chinese*. Beijing, China: The Commercial Press.

Leyland, L. A, Kirkby, J.A., Juhasz, B.J., Pollatsek, A., & Liversedge, S.P., (2013). The Influence of word shading and word length on eye movements during reading. *Quarterly Journal of Experimental Psychology, 66,* 471–486. https://doi.org/10.1080/17470218.2011.599401

Li, X. S., & Pollatsek, A. (2011). Word knowledge influences character perception. *Psychonomic Bulletin & Review, 18,* 833–839. https://doi.org/10.3758/s13423-011-0115-8

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

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

Liang, F. F., Blythe, H. I., Bai, X. J., Yan, G. L., Li, X., Zang, C. L., & Liversedge, S. P. (2017). The role of character positional frequency on Chinese word learning during natural reading. *PloS one*, *12*, e0187656. https://doi.org/10.1371/journal.pone.0187656

Liang, F. F., Blythe, H. I., Zang, C. L., Bai, X. J., Yan, G. L., & Liversedge, S. P. (2015). Positional character frequency and word spacing facilitate the acquisition of novel words during Chinese children's reading. *Journal of Cognitive Psychology*, *27*, 594–608. https://doi.org/10.1080/20445911.2014.1000918

Liang, F. F., Ma, J., Bai, X. J., & Liversedge, S. P. (2021). Initial landing position effects on Chinese word learning in children and adults. *Journal of Memory and Language*, *116*, 104183. https://doi.org/10.1016/j.jml.2020.104183

Liu, D., Chung, K. K. H., Zhang, Y., & Lu, Z. (2014). Sensitivity to the positional information of morphemes inside Chinese compound words and its relationship with word reading. *Reading and Writing*, *27*, 431–450. https://doi.org/10.1007/s11145-013-9451-6

Liu, P. P., & Li, X. S. (2014). Inserting spaces before and after words affects word processing differently in Chinese: Evidence from eye movements. *British Journal of Psychology*, *105*, 57–68. https://doi.org/10.1111/bjop.12013

Liversedge, S. P., Drieghe, D., Li, X., Yan, G. L., Bai, X. J., & Hyönä, J. (2016). Universality in eye movements and reading: a trilingual investigation. *Cognition*, *147*, 1–20. https://doi.org/10.1016/j.cognition.2015.10.013

Ma, G. J., & Li, X. S. (2015). How character complexity modulates eye movement control in Chinese reading. *Reading and Writing*, *28*, 747–761. https://doi.org/10.1007/s11145-015-9548-1

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Pt. 1. An account of basic findings. *Psychological Review, 88*, 375–405. https://doi.org/10.1037/0033-295X.88.5.375

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research, 28,* 1107–1118. http://dx.doi.org/10.1016/0042-6989(88)90137-X

Morris, R. K., Rayner, K., & Pollatsek, A. (1990). Eye movement guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 268–281. http://dx.doi.org/10.1037/0096-1523.16.2.268

Morey, R. D., Rouder, J. N., Jamil, T., Urbanek, S., Forner, K., & Ly, A. (2018). BayesFactor: Computation of Bayes factors for common designs. http://CRAN.R-project.org/packageBayesFactor

Pan, J., Ming, Y., Laubrock, J., Shu, H., & Kliegl, R. (2014). Saccade-target selection of dyslexic children when reading chinese. *Vision research, 97*(4), 24-30. http://dx.doi.org/10.1016/j.visres.2014.01.014

Paterson, K. B., & Jordan, T. R. (2010). Effects of increased letter spacing on word identification and eye guidance during reading. *Memory & Cognition*, *38,* 502–512. http://dx.doi.org/10.3758/MC.38.4.502

Peereman, R., & Content, A. (1995). Neighborhood size effect in naming: lexical activation or sublexical correspondences? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 409–421. http://dx.doi.org/10.1037/0278-7393.21.2.409

Perea, M., & Acha, J. (2009). Space information is important for reading. *Vision Research, 49,* 1994–2000. https://doi.org/10.1016/j.visres.2009.05.009

Perea, M., Tejero, P., & Winskel, H. (2015). Can colours be used to segment words when reading? *Acta Psychologica, 159,* 8–13. https://doi.org/10.1016/j.actpsy.2015.05.005

Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 817–833. http://dx.doi.org/10.1037/0096-1523.8.6.817

R Core Team. (2019). *R: A language and environment for statistical computing.* Vienna, Austria: R Foundation for Statistical Computing. http://www.Rproject.org/

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception, 8,* 21–30. http://dx.doi.org/10.1068/p080021

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372– 422. http://dx.doi:10.1037/0033-2909.124.3.372

Rayner, K. (2009). The thirty fifth Sir Frederick Bartlett Lecture: Eye movements and attention during reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology, 62,* 1457–1506. http://dx.doi.org/10.1080/17470210902816461

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & cognition*, *14*, 191–201. http://dx.doi.org/10.3758/BF03197692

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research, 38,* 1129–1144. http://dx.doi.org/10.1016/S0042-6989(97)00274-5

Rayner, K., Sereno, S. C., Morris, R. K., Schmauder, A. R., & Clifton Jr, C. (1989). Eye movements and on-line language comprehension processes. *Language and Cognitive Processes*, *4*, SI21–SI49. https://doi.org/10.1080/01690968908406362

RStudio. (2019). *RStudio: Integrated development environment for R (Version 1.2.5033) [Computer software]*. Boston, MA: Author. Retrieved from http://www.rstudio.org/

Sears, C. R., Hino, Y., & Lupker, S. J. (1995). Neighborhood size and neighborhood frequency effects in word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 876–900. http://dx.doi.org/10.1037/0096-1523.21.4.876

Shen, D. L., Liversedge, S. P., Tian, J., Zang, C. L., Cui, L., Bai, X. J., Yan, G. L., & Rayner, K. (2012). Eye movements of second language learners when reading spaced and unspaced Chinese text. *Journal of Experimental Psychology: Applied*, *18*, 192–202. https://doi.org/10.1037/a0027485

Sheridan, H., Rayner, K., & Reingold, E. M. (2013). Unsegmented text delays word identification: Evidence from a survival analysis of fixation durations. *Visual Cognition*, *21*, 38–60. https://doi.org/10.1080/13506285.2013.767296

Sheridan, H., & Reingold, E. M. (2013). A further examination of the lexical-processing stages hypothesized by the e-z reader model. *Attention Perception & Psychophysics, 75*, 407–414. https://doi.org/10.3758/s13414-013-0442-0

Spragins, A. B., Lefton, L. A., & Fisher, D. F. (1976). Eye movements while reading and searching spatially transformed text: A developmental examination. *Memory & Cognition, 4,* 36–42. https://doi.org/10.3758/BF03213252

Sun, F., Morita, M., & Stark, L. W. (1985). Comparative patterns of reading eye movement in Chinese and English. *Perception & Psychophysics, 37*, 502–506. http://dx.doi.org/10.3758/bf03204913

Townsend, J. T., Taylor, S. G., & Brown, D. R. (1971). Lateral masking for letters with unlimited viewing time. *Perception & Psychophysics, 10*, 375–378. https://doi.org/10.3758/BF03207464

Tsai, J. L., Lee, C. Y., Lin, Y. C., Tzeng, O. J. L., & Hung, D. L. (2006). Neighborhood size effects of Chinese words in lexical decision and reading. *Language and Linguistic, 7*(3), 659–675.

Winskel, H., Radach, R., & Luksaneeyanawin, S. (2009). Eye movements when reading spaced and unspaced Thai and English: a comparison of Thai–English bilinguals and English monolinguals. *Journal of Memory and Language*, *61*, 339–351. https://doi.org/10.1016/j.jml.2009.07.002

Yan, M., Kliegl, R., Richter, E. M., Nuthmann, A., & Shu, H. (2010). Flexible saccade-target selection in Chinese reading. *Quarterly journal of experimental psychology, 63*(4), 705–725. https://doi.org/10.1080/17470210903114858

Yan, G. L., Liu, N. N., Liang, F. F., Liu, Z. F., & Bai, X. J. (2015). The comparison of eye movements between Chinese children and adults when reading disappearing text. *Acta Psychologica Sinica, 47*(3), 300–318. https://doi.org/10.3724/SP.J.1041.2015.00300

Yan, G. L., Tian, H. J., Bai, X. J., & Rayner, K. (2006). The effect of word and character frequency on the eye movements of Chinese readers. *British Journal of Psychology*, *97*, 259–268. https://doi.org/10.1348/000712605X70066

Yan, M., Pan, J., & Kliegl, R. (2019). Eye movement control in Chinese reading: a cross-sectional study. *Developmental Psychology, 55*(11), 2275-2285. https://doi.org/10.1037/dev0000819

Yen, M. H., Radach, R., Tzeng, O. J. L., Hung, D. L., & Tsai, J. L. (2009). Early parafoveal processing in reading Chinese sentences. *Acta Psychologica*, *131*, 24–33. https://doi.org/10.1016/j.actpsy.2009.02.005

Yen, M. H., Radach, R., Tzeng, O. J. L., & Tsai, J. L. (2012). Usage of statistical cues for word boundary in reading Chinese sentences. *Reading and Writing, 25*, 1007–1029. https://doi.org/10.1007/s11145-011-9321-z

Zang, C. L., Liang, F. F., Bai, X. J., Yan, G. L., & Liversedge, S. P. (2013). Interword spacing and landing position effects during Chinese reading in children and adults. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 720–734. https://doi.org/10.1037/a0030097

Zang, C. L. (2019). New Perspectives on Serialism and Parallelism in Oculomotor Control During Reading: The Multi-Constituent Unit Hypothesis. *Vision, 3,* 50. https://doi.org/10.3390/vision3040050

Zhou, W., Wang, A., Shu, H., Kliegl, R., & Yan, M. (2018). Word segmentation by alternating colors facilitates eye guidance in Chinese reading. *Memory & cognition*, *46,* 729–740. https://doi.org/10.3758/s13421-018-0797-5