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# Word Segmentation of Overlapping Ambiguous Strings During Chinese Reading

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In 3 experiments, we tested 3 possible mechanisms for segmenting overlapping ambiguous strings in Chinese reading. The first 2 characters and the last 2 characters in a 3-character ambiguous string could both constitute a word in the reported studies. The left-priority hypothesis assumes that the word on the left has an advantage in the competition and the other word cannot be processed until the word on the left is recognized. The independent processing hypothesis assumes that words in different positions are processed simultaneously and independently, and the word segmentation ambiguity cannot be settled without the help of sentence context. The competition hypothesis assumes that all of the words compete for a single winner. The results support a competition account that the characters in the perceptual span activate all of the words they can constitute, and any word can win the competition if its activation is high enough.

*Keywords:* Chinese reading, competition hypothesis, eye movements, word frequency, word segmentation

One important difference between reading Chinese and English is that there are no interword spaces to mark word boundaries in Chinese. The relatively narrow spaces between each two continuous characters only mark the morpheme boundaries. However, Chinese readers have no difficulty in reading Chinese text. This does not mean that word boundaries are not important in Chinese reading. Indeed, a number of studies have shown that Chinese words play a very important role in reading and that words have psychological reality in Chinese (Bai, Yan, Liversedge, Zang, & Rayner, 2008; Hoosain, 1992; Li, Gu, Liu, & Rayner, 2013; Li, Bicknell, Liu, Wei, & Rayner, in press; Shen et al., 2012; Zang, Liang, Bai, Yan, & Liversedge, 2012), suggesting that word segmentation is necessary in Chinese reading. Without interword spaces, Chinese readers have to depend on high-level information to segment words.

In Chinese texts, segmenting a string of characters, which we will refer to as an overlapping ambiguous string, is even more

challenging. The middle character of an overlapping ambiguous string can constitute words with the characters to both their left and their right (Gan, Palmer, & Lua, 1996; Li, Gao, Huang, & Li, 2003; Yen, Radach, Tzeng, & Tsai, 2012). For example, in the 3-character overlapping ambiguous string 学生活 (xue sheng huo), the middle character 生 can constitute a word 学生 (which means “student”) with the first character and another word 生活 (which means “life”) with the third character. Hence, the middle character 生 can belong to both the first word 学生 and the second word 生活. Whether it belongs to the first or second word must be settled using contextual clues. An overlapping ambiguous string in Chinese can be similarly (but not identically) illustrated in the string *mushroommate* in English. The middle word *room* can constitute a word with both the left-hand word *mush* (*mushroom*) and the right-hand word *mate* (*roommate*). Overlapping strings occur quite frequently in Chinese texts, and approximately 3.6% of characters can constitute words with both the characters to their left and their right (Yen et al., 2012). Successful segmentation of overlapping ambiguous strings is critical for successful comprehension of sentences in Chinese reading. In this article, we report three experiments which explore how Chinese readers segment such ambiguous strings.

Overlapping ambiguous strings have been examined in some previous reading studies (Hsu & Huang, 2000a, 2000b; Inhoff & Wu, 2005; Yen et al., 2012). Hsu and Huang (2000a, 2000b) explored the effects of inserting spaces in sentences with overlapping ambiguity such as 花生生长在屋后的田里. The first three characters 花生生长 represent an overlapping ambiguous string which can be segmented in two different ways. If it was segmented into the A-BC construction, it means “flower grows” and the whole sentence means “a flower grows in the field behind the house,” but when segmented into the AB-C construction it means “peanut grows” and the whole sentence means “a peanut grows in the field behind the house.” Hsu and Huang found that although inserting

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spaces between words did not facilitate reading in most situations, inserting a space as the cue for segmentation at the proper positions in the ambiguous strings decreased the sentence reading time when the text contained overlapping ambiguous strings. Their results indicate that Chinese readers have to pay more effort to segment the overlapping ambiguous string than other unambiguous words. Hence, the uncertainty in dealing with overlapping ambiguity might provide a window to understand how Chinese readers segment unspaced Chinese text.

For alphabetic languages like English, there are generally no problems in word segmentation because interword spaces provided distinct word boundaries. However, a similar segmentation problem exists in ambiguous polymorphic words such as *UNLOCKABLE*. If one groups the suffix with the root to get the right-branching structure *UN-LOCKABLE*, the word means “cannot be locked”; if one attaches the prefix to the root to get a left-branching structure *UNLOCK-ABLE*, it means “can be unlocked.” According to the prefix stripping hypothesis (Taft & Forster, 1975), the prefix *UN* must be stripped off before getting the lexical representation of *UNLOCKABLE*. Then *LOCKABLE* itself must be decomposed into *LOCK* and *ABLE*. How to interpret *UNLOCKABLE* depends on the order in which the components *UN*, *LOCK*, and *ABLE* are recombined. de Almeida and Libben (2005) investigated the representation of trimorphemic words in sentence context and they found these words indeed had two representations: *UNLOCK-ABLE* or *UN-LOCKABLE*. Pollatsek, Drieghe, Stockall, and de Almeida (2010) investigated whether there was a preferred interpretation for structurally ambiguous trimorphemic words. They embedded ambiguous trimorphemic words in sentences with prior context disambiguating the meaning or not and the pattern of fixation times on the ambiguous word and the following text revealed that the left-branching structure *UNLOCK-ABLE* was preferred. These studies might be suggestive regarding the processing of overlapping ambiguous strings in Chinese reading. If English readers prefer to parse *UNLOCKABLE* as *UNLOCK-ABLE*, then Chinese readers might also adopt the same strategy by preferring to group the first two characters as a word in the overlapping ambiguous string.

Returning to the issue of how Chinese ambiguous strings are processed, a similar possibility is that words are processed in a strictly serial order from left to right. According to this hypothesis, the parser processes words one by one: only when the words on the left of a sentence have been processed, can the other words on the right be processed. For Chinese reading, any character could only be assigned to one word, and it would have priority to be assigned to the word on the left. A model of this kind was proposed by Perfetti and Tan (1999) who suggested that Chinese readers might use a two-character assembly strategy to segment words. According to this view, readers prefer to group two continuous characters into a word. If the grouped two characters constitute a word, this two-character word would be stored in working memory and would not participate in the grouping action of the remaining characters. To test this possibility, they embedded overlapping ambiguous strings into sentences where the correct segmentation style should always be A-BC (e.g., 照顾顾客 embedded in the experimental sentence 经理同意照顾顾客的想法来设计产品, which means “the manager agreed to design products according to the customer’s requirements”). The control sentence was identical to the experimental sentence except that the first character of the ambiguous strings was substituted by another synonym so that

there was no overlapping ambiguity in the control sentence and the sentence meaning was not changed (e.g. 经理同意按顾客的想法来设计产品, which has identical meaning as the experimental sentence). Perfetti and Tan found that reading times after the overlapping ambiguous strings were longer than that in the control condition. They claimed that subjects might combine the first two characters of the ambiguous strings into a word in first-pass reading so that they had to correct the segmentation when they read the later part of the sentence, and this hence led to the processing cost following the ambiguous region. This result is consistent with the two-character assembly strategy.

Evidence against the strictly serial parsing hypothesis was provided by Inhoff and Wu (2005). They compared two possible word segmentation hypotheses to examine how Chinese readers segment overlapping ambiguous strings: the unidirectional parsing hypothesis and the multiple activation hypothesis. In the unidirectional hypothesis, it is assumed that grouping characters into words is strictly sequential from left to right in Chinese reading. When a character is assigned to the word on the left, it will not be assigned to any other word. On the other hand, in the multiple activation hypothesis, it is assumed that all of the words that Chinese characters in the perceptual span can constitute are activated without any directional constraints, so that one character can be a component of two or more activated words and a character grouped into the left-hand word might also be used in the next word’s grouping. Note that perceptual span in Chinese reading includes one character to the left of current fixation and 2–3 characters to its right (Chen & Tang, 1998; Inhoff & Liu, 1998). To compare these two hypotheses, Inhoff and Wu (2005) embedded different 4-character strings in the same sentence frames. Both the first two characters and the last two characters could constitute a word in all three conditions. In the ambiguous condition, the central two characters also constituted a 2-character word, while in the two control conditions the central two characters did not constitute a word. For example, in the ambiguous condition, the key four characters ABCD (e.g. 专科学学生, college students) could constitute three two-character words AB (专科, college), BC (科学, science), and CD (学生, students). However, in the unambiguous control conditions with identical onset or offset two-character words, the central two characters in both ABEF (专科毕业, college graduation, onset identical) and GHCD (外地学生, nonlocal students, offset identical) could not constitute a word. They found that first-pass reading times and total reading times were longer in the ambiguous condition than in either of the control conditions. They argued that these results were inconsistent with the unidirectional parsing hypothesis but were consistent with the multiple activation hypothesis.

Although the strictly serial parsing hypothesis was inconsistent with the findings of Inhoff and Wu (2005), the mechanism underlying the multiple activation hypothesis remains an open question. Recently, Li, Rayner, and Cave (2009) proposed a computational model of Chinese word segmentation that made three major assumptions about different aspects of word segmentation. First, all the characters in the perceptual span are processed in parallel (subject to constraints of visual acuity). Second, word recognition is a serial process such that only one word wins the competition although multiple words are initially activated in any given round. Finally, when a word is recognized, the word unit and the characters it contains are inhibited, and only the remaining characters

participate in the next round of competition. Hence, in this model it is assumed that word recognition is simultaneous with the detection of word boundaries. When a word is recognized, it is also segmented. Li et al.'s model can also explain the data provided by Inhoff and Wu (2005). When the characters ABCD in the ambiguous condition were inputted to that model, all of the words it contained were activated in parallel. The model also assumes that the word on the left has an advantage in competition so that the other words could not win the competition until the left word has been identified. It is not only because Chinese readers are accustomed to reading a sentence from left to right but also Chinese readers can perceive the words in the correct order in this way. Hence, the words AB, BC, and CD were activated at the word level, but only the word AB would win the competition in the first round. However, because the word in the middle (BC) participated in the competition, it took a longer time to settle the competition, thus the readers took a longer time to process these characters. In contrast, the other two control conditions, in which the middle two characters did not constitute a word, had fewer word candidates in competition; hence readers took less time to process these strings than the ambiguous four-character strings.

Both the data from Inhoff and Wu (2005) and the model proposed by Li et al. (2009) suggest that multiple words that are constituted by the characters in the perceptual span can be activated during reading. Once these words are activated, how do they compete with each other for selection? There are at least three possibilities. First, words are recognized from left to right in a strictly sequential order and the left-hand word has absolute priority to win the competition although the words on the right may be initially activated. Because word order is very important for successful comprehension, accessing words in the right order is critical (see Rayner, Angele, Schotter, & Bicknell, 2013 for English). Making the left-hand word have the highest priority in competition might be a good way to guarantee that the words are perceived in the right order. The E-Z Reader model (Rayner, Li, & Pollatsek, 2007; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003) makes this kind of assumption so that words are processed serially from left to right. Assuming that multiple words are initially activated is important because it could help to explain the findings like Inhoff and Wu (2005). We will refer to this possibility as the left-priority hypothesis. Second, all of the words at different positions are processed in parallel and independently. Hence, in the overlapping ambiguous string ABC, the words AB and BC could be processed in parallel and will not compete with each other. Whether the middle character B should be assigned to the left-hand word or the right-hand word is determined at a later stage based on sentence context or semantic information. No formal models of Chinese reading have implemented this kind of segmentation. However, it is still a valid hypothesis because the key assumption of this hypothesis is similar to models such as SWIFT (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005), which make the assumption that words are recognized in parallel and the processing of one word does not affect the processing of other words.<sup>1</sup> In addition, this hypothesis is similar to parallelism hypotheses in literatures dealing with lexical ambiguity and syntactic ambiguity (Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; see Clifton & Staub, 2008, for a review). These hypotheses assume that two meanings or syntactic structures are maintained in parallel at

an early stage, and the readers choose the one that best suits sentence context in a late stage. We refer to this possibility as the independent processing hypothesis. Third, all of the activated words compete equally for a single winner. The characters in the perceptual span could activate all of the words they could constitute, and any word could win the competition if its activation is high enough (e.g., when the frequency of the word on the right is higher than the word on the left). We refer to this hypothesis as the competition hypothesis. According to this hypothesis, either the word on the left or the word on the right could win the competition, so the word on the right could be recognized before the word on the left is recognized. In three experiments, we distinguished between these three possibilities regarding the segmentation of ambiguous strings during Chinese reading.

In Experiment 1, we explored whether the word on the right could win the competition when the ambiguous strings were presented in isolation using a partial report task. Subjects were asked to name the middle character of overlapping ambiguous 3-character strings. The middle character was a polyphone that is pronounced differently when constituting a word with the left-hand character and when constituting a different word with the right-hand character. For example, the middle character 校 in the 3-character ambiguous string 卫校订 (WEI XIAO/JIAO DING) is pronounced as XIAO when grouped with the first character, but is pronounced as JIAO when grouped with the third character. This can be similarly illustrated with an English word string *healthese*: the middle letter string *th* is pronounced differently when it constitutes a word with the letters to the left of it (*health*) and when it constitutes a different word with the letters to the right of it (*these*). Hence, the pronunciation of the middle character indicates which word wins the competition. The word frequency of the left- and right-hand words were manipulated so that the frequency of one word (either left or right) was higher than that of the other word. We manipulated word frequency because word frequency might play an important role in detecting word boundaries and recognizing the word. A great deal of research has indicated that word frequency affects the time spent on lexical decision and word naming tasks (Balota & Chumbley, 1984; Brysbaert et al., 2011; Yap & Balota, 2009) and that it affects fixation times in reading, for both alphabetic writing systems (Kuperman, Bertram, & Baayen, 2008; Rayner & Duffy, 1986; Rayner & Raney, 1996; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Reingold, Yang, & Rayner, 2010) and Chinese (Yan, Tian, Bai, & Rayner, 2006). All of these results suggest that high-frequency words take less time to process than low-frequency words, suggesting in turn that there is a high-frequency advantage in word activation.

The different hypotheses we identified make the following predictions regarding Experiment 1. First, the left-priority hypothesis predicts that the left-hand word will always win the competition and hence predicts that the middle character should always be pronounced as it is in the left-hand word. This should not vary

<sup>1</sup> The most recent version of SWIFT (Schad & Engbert, 2012) implies competition resulting from the foveal word. According to this version of SWIFT, the perceptual span is dynamically modulated by the level of processing difficulty in foveal vision. When the foveal word is highly activated because of processing difficulty, the perceptual span is small, which leads to less activation of the other words (i.e., to the right of fixation).

as a function of the word frequency manipulation. Second, the independent processing hypothesis does not make strong predictions regarding the results of Experiment 1. It assumes that the two words are activated independently without any competition. Because the naming task forces subjects to make a choice, most likely, the pronunciation of the middle character might be determined by which word is recognized faster. Hence, this hypothesis predicts that the middle character could be pronounced as it is in the left-hand word or in the right-hand word, and it should be affected by the word frequency manipulation. Third, the competition hypothesis predicts that whichever word has the most activation will win the competition, thus the pronunciation of the middle character should be biased to the higher-frequency word regardless of word position (left or right).

Experiment 2 was mainly designed to test the independent processing hypothesis when the ambiguous strings were embedded in sentences. Experiment 3 tested all three hypotheses in a single experiment. We will describe the logic of these experiments later.

### Experiment 1

Experiment 1 tested the left-priority hypothesis using a partial report task.

#### Method

**Subjects.** Ten undergraduate students (all native speakers of Chinese, 7 women and 3 men) from the China Agricultural University were paid to participate in this experiment. Their ages ranged from 18 to 26 years, with an average of 23 years and a standard deviation of 2 years.

**Apparatus.** Stimulus presentation and response registration were controlled by a personal computer. The task was programmed in Experimental Builder (SR Research Ltd). Stimuli were presented on a 21-inch CRT monitor (Sony G520) with a resolution of 1024 × 768 pixels and a refresh rate of 100 Hz. Subjects viewed the stimuli approximately 58 cm from the monitor. They placed their chins on a chin rest to minimize head movements. The character strings were shown in Song 24-point font in black (RGB: 0, 0, 0) on a gray background (RGB: 128, 128, 128).

**Materials and design.** To prepare the stimuli, we first chose 220 common Chinese polyphones. Then, we asked 21 undergraduate students to input the pronunciation of the isolated polyphone through a keyboard. None of these subjects participated in the main experiment. After that, we calculated the probability of each

pronunciation of the polyphones, and we chose 44 polyphones so that the probability of pronouncing either of the two pronunciations was close to 50% (see Table 1).

After the 44 polyphones were selected, we chose 44 corresponding pairs of characters to create overlapping ambiguous strings with the polyphone as the middle character. The frequency of one word in each overlapping ambiguous string (either AB or BC in the string ABC) was higher than the other word. For convenience, we refer to the high-low frequency condition to describe when the left-hand word was higher frequency and the right-hand word was lower frequency. Similarly, we refer to the low-high frequency condition to describe when the word frequencies of the two words were opposite. The number of strings in the high-low frequency condition was the same as that in the low-high frequency condition. The number of strokes and the frequency of the first character A and the third character C in the overlapping strings ABC were carefully controlled so that there were no differences between them on these dimensions. Another 44 overlapping ambiguous strings were selected as fillers, and the middle characters were not polyphones in these strings. These fillers were included to minimize the chances that the subjects would notice that the middle character was a polyphone.

**Procedure.** A fixation cross (in black) was presented at the center of the screen for 1,000 ms, and subjects were asked to fixate on it. Then, the overlapping ambiguous 3-character string was presented for 80 ms before it disappeared. The middle character of the string was presented at the same position as the fixation cross. Then, a blank screen was presented until subjects named the middle character aloud. Next, the instructional sentence “Please input the pronunciation and tone of the middle character” (translated Chinese instruction) was presented. The subsequent trial started when subjects pressed the “Enter” key (see Figure 1).

#### Results and Discussion

Approximately 0.8% of the trials were excluded from analysis because subjects did not input the pronunciation of the middle character. The probability of each pronunciation of the middle character was calculated. On some trials, subjects made wrong pronunciations which were not one of the alternative pronunciations, thus the sum of probabilities in the high-low frequency or the low-high frequency conditions was less than one. The data were analyzed using R (R core team, 2013) and the R package *rms* (Harrell, 2013). We used ordinary logit model (*lrm* function) (Jaeger, 2008) to analyze the dichotomic data (the same method

Table 1  
*Properties of the Stimuli in Experiment 1*

Example	HL			LH		
	利	率	性	卫	校	订
Character frequency	383	1110	329	572	1287	567
Number of stroke	8.8	8.8	9.1	9.1	9.1	8.8
Constituted word	利率	率性		卫校	校订	
Pronunciation	lì lǜ	shuài xìng		wèi xiào	jiào dìng	
Word meaning	interest rate	willful personality		health school	check and revise	
Probability of naming	0.51	0.43		0.45		0.5
Word frequency (left/right)	4237		252	258		5450

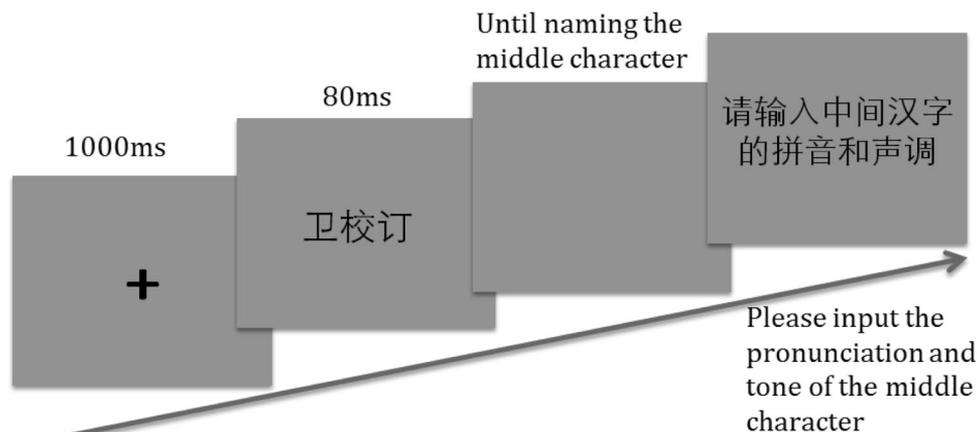


Figure 1. Procedure of Experiment 1.

was used for dichotomic data in Experiment 2 and Experiment 3). The effects of frequency manipulation (high-frequency or low-frequency), pronunciation type (left-hand or right-hand), and their interaction are reported.

The left-priority hypothesis predicts that the character in the middle should always be pronounced as that in the left-hand word and the probability is not affected by the word frequency manipulation. As shown in Figure 2, the results did not support the left-priority hypothesis. The middle characters were more likely to be pronounced as in the right-hand word ( $M = .52, SE = .02$ ) than that of the left-hand word ( $M = .42, SE = .02$ ),  $b = 0.483, SE = 0.197, Wald Z = 2.44, p = .014$  (see Footnote<sup>2</sup>). Most importantly, the middle character was more likely to be pronounced as in the high-frequency word ( $M = .64, SE = .03$ ) than that of the low-frequency word ( $M = .31, SE = .03$ ),  $b = -1.435, SE = 0.209, Wald Z = -6.85, p < .001$ . The interaction between frequency manipulation and pronunciation type was not significant,  $b = 0.096, SE = 0.291, Wald Z = 0.33, p = .741$ . The effect of frequency manipulation provided evidence against the left-priority hypothesis.

## Experiment 2

Experiment 2 was mainly designed to test the independent processing hypothesis when ambiguous strings were embedded in

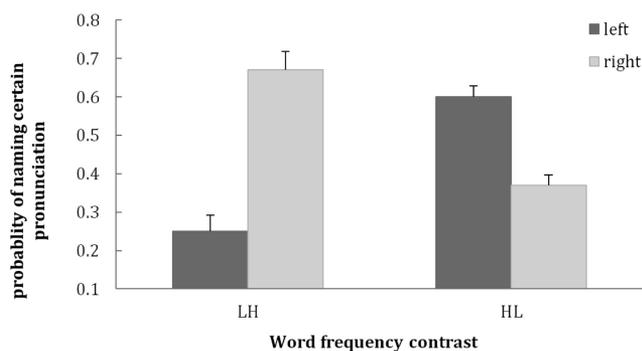


Figure 2. Probability of naming the middle character as it is pronounced in the left- or right-hand word in Experiment 1.

sentences. Readers' eye movements were monitored when they read these sentences. The critical 3-character strings ABC and ABD were embedded in the same sentence frame. All of these strings were overlapping ambiguous strings, but the middle character was not a polyphone so that the natural sentence frame could be constructed for the matched pairs of ambiguous strings. The last character of the ambiguous strings was manipulated so that the end two-character word of each overlapping ambiguous string was either a high-frequency word (BC) or a low-frequency word (BD). In this experiment, only the AB-C segmentation style was consistent with the sentence context. All of these strings can be disambiguated because of the high plausibility of the AB-C (or AB-D) segmentation construction. In addition, at least two characters after the overlapping ambiguous string were identical in the two conditions to ensure the same character strings could be previewed when fixating the ambiguous region.

Both the left-priority hypothesis and the competition hypothesis predict that the word frequency manipulation should affect reading time on the region AB. Note that although the left-priority hypothesis assumes competition between words in the perceptual span, it assumes that other words do not have a chance to win the competition until the left word has won the competition. However, the independent processing hypothesis predicts that the word frequency manipulation should not affect reading time on the region AB because all the words are processed independently without competition.

The effects predicted by the left-priority hypothesis and the competition hypothesis are similar to the parafoveal-on-foveal effect in some sense. Parafoveal-on-foveal effects have been observed in some studies with alphabetic writing systems (Kennedy & Pynte, 2005; Risse & Kliegl, 2012; see Schotter, Angele, & Rayner, 2012, for a review of contrary findings) and have been used as evidence to support parallel processing models in reading

<sup>2</sup> This effect might be related to the asymmetry of the effective visual field in reading, which develops as a function of reading direction. The perceptual span of English readers, who read from left to right, is larger to the right of the fixation than to the left of fixation (Rayner, Well, & Pollatsek, 1980). In contrast, the perceptual span of Hebrew readers, who read from right to left, is larger to the left of fixation than to the right of fixation (Pollatsek, Bolozky, Well, & Rayner, 1981).

such as the SWIFT model (Engbert et al., 2002; Engbert et al., 2005; Schad, & Engbert, 2012). These studies generally found that the properties of the word to the right of fixation influence how long the reader looks at the currently fixated word. Some studies found that the fixation duration on the target word was longer when the word to its right was difficult to process—either because the frequency of the word was low or the predictability of the word was low (Kennedy & Pynte, 2005; Risse & Kliegl, 2012; Wotschack, & Kliegl, 2013). This finding can be explained by an attention gradient hypothesis (Inhoff, Starr, & Shindler, 2000; Starr & Inhoff, 2004), which assumes that the peak of the attentional gradient is shifted toward regions of processing difficulty, therefore reducing processing resources for the fixated word. But other studies found that fixation times were shorter when the word on its right was harder to process (Hyönä & Bertram, 2004; Kennedy, 1998, 2000). This reversed parafoveal-on-foveal effect can be interpreted by an attention attractor hypothesis (Kennedy, 2000), which assumes that a difficult word in the parafovea functions like a magnet to attract an early saccade to the region, hence reducing fixation time on the target region. These two kinds of parafoveal-on-foveal effects are all used as evidence to support the parallel processing models by some researchers (Engbert et al., 2005; Schad, & Engbert, 2012).

Note that although the predicted competition effect is similar to the parafoveal-on-foveal effect, it is not really a parafoveal-on-foveal effect. The two words in our experiments are too close to each other so that they may both fall in the fovea in most situations. Each character extends about  $0.7^\circ$  visual angle and the ambiguous string is three characters long. Hence, all of the three characters fall in the fovea when the eyes fixate on the middle character. However, this does not affect the arguments made in Experiment 2. If the frequency manipulation affects fixation duration on region AB, we can preclude the independent processing hypothesis since it predicts that the frequency manipulation does not affect fixation durations on the region AB.

## Method

**Subjects.** Twenty-six undergraduate students (all native speakers of Chinese) from the same subject pool as that in Experiment 1 participated in this experiment. None of them participated in Experiment 1.

**Apparatus.** The materials were presented on a 21-inch CRT monitor (resolution:  $1024 \times 768$  pixels; refresh rate: 150 Hz) connected to a DELL PC. Each sentence was displayed on a single line in Song 20-point font and the characters were shown in black (RGB: 0, 0, 0) on a gray background (RGB: 128, 128, 128). Subjects were seated at a viewing distance of 58 cm from the computer monitor. At this viewing distance, each character sub-

tended a visual angle of approximately  $0.7^\circ$ . The head was stabilized by means of a chin rest and a forehead rest. Subjects read sentences binocularly, but only the right eye was monitored. Eye movements were recorded by an SR Research Eyelink 1000 eye tracking system with a sampling rate of 1,000 Hz.

**Materials and design.** Thirty-two overlapping ambiguous strings were used in the critical region in the sentences (see Figure 3). We manipulated the frequency contrast between word BC and word BD in the overlapping ambiguous strings. For the strings ABC, the frequency of the word BC was high ( $M = 263$  occurrences per million,  $SE = 51$ ; high-frequency condition). For the strings ABD, the frequency of the word BD was low ( $M = 7$  occurrences per million,  $SE = 0.9$ ; low-frequency condition). For all of these strings, the frequency of the word AB was high ( $M = 251$  occurrences per million,  $SE = 70$ ), and was comparable with the frequencies of that of word BC. Subjects also read 32 additional sentences as fillers. There was no overlapping ambiguous string in the filler sentences. The length of all the sentences in Experiment 2 ranges from 20–25 characters.

**Procedure.** When subjects came into the lab, they were given instructions for the experiment and a brief description of the apparatus. Then, the height of the chin rest or the chair was adjusted to make subjects feel comfortable. The eye tracker was calibrated at the beginning of the experiment and was calibrated again during the experiment when needed. A three-point calibration and validation procedure was used. The maximal error of the validation was 0.5 degrees in visual angle. Next, each subject read 6 sentences for practice, followed by 32 experimental sentences and 32 filler sentences for the formal experiment in a random order. The subjects were asked to read silently and answer questions following approximately one third of the sentences. Each sentence appeared after subjects successfully fixated on a character-sized box at the location of the first character of the sentence. After reading a sentence, the subjects pressed a response button to start the next trial.

## Results and Discussion

The accuracy of the comprehension questions was high (95%), suggesting that subjects understood the sentences well. One subject was excluded from analyses because accuracy on the comprehension questions was lower than 75%. Trials with three or more blinks or with one or more blinks in the overlapping ambiguous strings were excluded from analyses, resulting in a loss of 4% of the trials. Fixations with durations longer than 1,000 ms or less than 80 ms (approximately 0.6%) were also excluded from analysis.

We report two standard eye fixation time measures (Rayner, 1998, 2009), namely first fixation duration (the duration of the first

**High frequency condition:** 兴高采烈的销售员准备**马上去**地铁站会见朋友  
(The excited salesman was ready to *go to railway station at once* to see his friend.)

**Low frequency condition:** 兴高采烈的销售员准备**马上乘**地铁去会见朋友  
(The excited salesman was ready to see his friend *at once by railway*.)

Figure 3. Examples of stimuli in Experiment 2. The overlapping ambiguous strings are **bold** and segmented for the purpose of illustration (but characters were not bold or segmented in the experiment).

fixation on the target region) and gaze duration (the sum of all first-pass fixations on the target region before moving to another region) in the whole ambiguous string region (ABC) and the left-hand word region (the AB region) of the ambiguous string (other measures did not show any significant difference between the two conditions<sup>3</sup>). For each of these measures, we conducted a one-way repeated measure ANOVA with subjects ( $F_1$ ) and items ( $F_2$ ) as random variables.

Results were not consistent with the predictions of the independent processing hypothesis, but were consistent with the predictions of the left-priority hypothesis and the competition hypothesis. Both the left-priority hypothesis and the competition hypothesis predict that the word frequency manipulation of BC/BD should affect fixation time on AB. A high-frequency word BC should have a larger competition with the first word AB than that for low-frequency word BD. For the ABC region, first fixation durations were longer in the high frequency condition ( $M = 291$  ms,  $SE = 10$ ) than that in the low frequency condition ( $M = 275$  ms,  $SE = 9$ ),  $F_1(1,24) = 5.73$ ,  $MSE = 572$ ,  $p = .025$ ,  $F_2(1, 30) = 5.68$ ,  $MSE = 652$ ,  $p = .023$ , but there was no significant difference for gaze duration between the high frequency condition ( $M = 338$  ms,  $SE = 10$ ) and the low frequency condition ( $M = 336$  ms,  $SE = 10$ ),  $F_s < 1$ . However, the ABC region was not the key region differentiating the above three hypotheses and the AB region provided much more information. For the AB region, first fixation durations were longer in the high frequency condition ( $M = 291$  ms,  $SE = 10$ ) than in the low frequency condition ( $M = 272$  ms,  $SE = 9$ ),  $F_1(1,24) = 9.62$ ,  $MSE = 549$ ,  $p = .005$ ,  $F_2(1, 30) = 7.51$ ,  $MSE = 610$ ,  $p = .010$ . Gaze durations were also longer in the high frequency condition ( $M = 329$  ms,  $SE = 13$ ) than in the low frequency condition ( $M = 307$  ms,  $SE = 12$ ),  $F_1(1,27) = 5.06$ ,  $MSE = 1,486$ ,  $p = .034$ ,  $F_2(1, 30) = 5.04$ ,  $MSE = 1,550$ ,  $p = .032$ . These results argue against the independent processing hypothesis which predicts no competition between two continuous words. The data can be explained with the competition hypothesis. When the last two-character word of the string was a higher-frequency word, it was activated more than a lower-frequency word, which resulted in a larger competition with the first word, and hence resulted in longer fixation durations to settle the competition.

### Experiment 3

Experiment 3 tested all three hypotheses in a single experiment. We embedded the overlapping ambiguous strings in different sentences frames and manipulated the frequency of the two words in the overlapping ambiguous string. Thus, there was a 2 (local segmentation: high-low frequency vs. low-high frequency)  $\times$  2 (global segmentation: first word AB-C vs. second word A-BC) design (see Figure 4) design. Local segmentation was introduced by manipulating the frequencies of the two words. In half of the overlapping ambiguous strings, the frequency of the first word was higher than the second word (the high-low frequency condition). In the other half, the frequency of the first word was lower than that of the second word (the low-high frequency condition). This was done to test whether Chinese readers might be able to segment words using word frequency information during reading. For global segmentation, two sentence frames constrained the segmentation of the overlapping ambiguous string differently. In one

sentence frame, the first word segmentation (AB-C) fit with the sentence context, but in the other sentence frame, the second word segmentation (A-BC) fit with the sentence context. How the overlapping ambiguous region is segmented correctly is finally determined when the readers read the disambiguating region. Hence, the segmentation determined by word frequency (local segmentation) fit into the sentence context in one sentence (fit condition), but did not fit in the other sentence (misfit condition).

Because the ambiguous region and the disambiguating region were spatially separated and the disambiguating region was always on the right of the ambiguous region in this study, there might be two stages of word segmentation processes with respect to the overlapping ambiguous string. In an early stage, the segmentation outcome might be mainly determined by word frequency. In a later stage in which Chinese readers need to integrate the first stage word-segmentation outcome into the sentence, the readers need to check whether the initial segmentation agrees with the context of the rest of the sentence. If the initial segmentation does not fit with the sentence, they might need additional time to correct the segmentation. Hence, we expected the reading time in the region following the critical region to be longer in the misfit condition than in the fit condition for the above reasons. Furthermore, more regressions from the disambiguating region were expected in the misfit condition when readers detected a misfit; and hence second-pass reading time in the ambiguous region should be longer in the misfit condition than in the fit condition. This logic in Experiment 3 is similar to research dealing with lexical ambiguity phenomena in English reading (Duffy, Morris, & Rayner, 1988; Rayner & Duffy, 1986). Those studies suggested that there are two stages of processing. In an early stage of processing, more than one meaning of an ambiguous word is activated, and the degree of activation is influenced by frequency and prior context. As a result, one of the meanings may dominate the competition. After reading more information, if readers find out that the dominant meaning misfits with the sentence context, they have to adjust their understanding of the ambiguous word. This procedure will cause longer second-pass reading time on the ambiguous region and more regressions into the ambiguous words in the misfit condition than that of the fit condition.

The three hypotheses make the following predictions regarding the eye movement patterns in both the target region and the disambiguating region. The left-priority hypothesis assumes that the first word (AB) always wins the competition and hence predicts that second-pass fixation duration and regressions into the target region should be longer when the second word (BC) fits into

<sup>3</sup> For the ABC region, second-pass reading time did not reveal a significant difference between the high frequency condition ( $M = 167$  ms,  $SE = 16$ ) and the low frequency condition ( $M = 173$  ms,  $SE = 22$ ),  $F_s < 1$ . Regression-in probability also did not reveal a significant difference between the high frequency condition ( $M = .31$ ,  $SE = .03$ ) and the low frequency condition ( $M = .36$ ,  $SE = .04$ ), Wald  $Z = 1.26$ ,  $p > .2$ . For the AB region, for second-pass reading time there was no significant difference between the high frequency condition ( $M = 126$  ms,  $SE = 16$ ) and the low frequency condition ( $M = 130$  ms,  $SE = 17$ ),  $F_s < 1$ . Regression-in probability also did not show a significant difference between the high frequency condition ( $M = .23$ ,  $SE = .03$ ) and the low frequency condition ( $M = .28$ ,  $SE = .03$ ), Wald  $Z = 1.75$ ,  $p > .08$ . The null significance of late measure such as regression-in probability indicated that participants might rarely perceive the ambiguity explicitly when processing these strings.

**Low-high frequency, segA-BC:** 商家已经答应**按-时装**不同风格安排展销会  
(The businessman has promised to arrange the trade show *according to* the various styles of the *clothes*.)

**Low-high frequency, segAB-C:** 商家已经答应**按时-装**货物上船  
(The businessman has promised to *load* the goods *on time*.)

**High-low frequency, segA-BC:** 这位文学家**从-小吃**谈起了传统的北京文化  
(This writer talks about traditional Beijing culture starting *from food*.)

**High-low frequency, segAB-C:** 这位文学家**从小-吃**了许多苦才有今天成就  
(This writer *experienced* many hardships *from youth* before achieving accomplishments today.)

Figure 4. Examples of stimuli in Experiment 3. The overlapping ambiguous strings are **bold** and segmented for the purpose of illustration (but characters were not bold or segmented in the experiment).

the sentence than when the first word (AB) fits into the sentence. The independent processing hypothesis assumes words are processed independently so that both segmented constructions are activated and kept in working memory; thus, Chinese readers could choose one kind of segmentation later when they reach the disambiguating region. Readers only need to choose from the segmentation that fits into sentence context at the disambiguating region. Hence, there should be no difference in second-pass reading time on the target word region between the fit condition and the misfit condition. However, the competition hypothesis predicts that the higher-frequency word will win the competition more often and that the overlapping ambiguous string will be segmented differently depending on the frequency of the two words. For example, in a string ABC, if the word AB is a high-frequency word and BC is a low-frequency word, the string should be segmented into a 2-character word AB and a 1-character word C (first word segmentation). Otherwise, if BC is a high-frequency word and AB is a low-frequency word, it should be segmented into a 1-character word A and a 2-character word BC (second word segmentation). Hence, the competition hypothesis predicts that second-pass reading time should be longer in the misfit condition than that in the fit condition. For the disambiguating region, the left-priority hypothesis predicts that gaze duration should be shorter when the first word in the ambiguous region fits with the context than when it doesn't. The independent processing hypothesis does not predict any difference between the fit condition and the misfit condition. The competition hypothesis predicts that gaze duration should be shorter when the segmentation based on word frequency fits with context than when it does not.

## Method

**Subjects.** Twenty-eight undergraduate students (all native speakers of Chinese, 20 women and 8 men) from the Chinese Agricultural University participated in this experiment. None of them participated in Experiment 1 or 2.

**Apparatus.** The apparatus was identical to Experiment 2.

**Materials and design.** Thirty-two overlapping ambiguous strings were used in the critical region in the sentences. We manipulated the frequency contrast as in Experiment 1. In the

low-high frequency condition, the average word frequency for the first word ( $M = 9$  occurrences per million,  $SE = 2$ ) was lower than that of the second word ( $M = 127$  occurrences per million,  $SE = 55$ ),  $t(15) = -2.15$ ,  $p = .048$ . In the high-low frequency condition, the average word frequency for the first word ( $M = 104$  occurrences per million,  $SE = 21$ ) was higher than that of the second word ( $M = 16$  occurrences per million,  $SE = 6$ ),  $t(15) = 6.99$ ,  $p < .001$ . The first character of the ambiguous strings never constituted a word with the character to its left, and the last character of the strings never constituted a word with the character to its right.

Each overlapping ambiguous string was embedded into two sentences which only differed after the critical ambiguous three-character region.

Each subject viewed all of the overlapping ambiguous strings in only one sentence. For each overlapping ambiguous string, half of the subjects read it in the fit condition, and the other half read it in the misfit condition. We also controlled the predictability of the words constituted by the overlapping ambiguous strings ABC to make sure the predictability in the two conditions were similar. To measure predictability, we showed the part of sentences to the left of the critical region to four subjects, and asked them to fill in words that they thought were most suitable. The predictability of either the one-character word A or the two-character word AB in the overlapping ambiguous string was close to zero, suggesting that sentence context based on the information to the left of the target region did not provide any information about word segmentation in this region. Unlike in Experiment 2, the overlapping ambiguous strings used in Experiment 3 had equally high plausibility for the first word AB-C condition and second word A-BC condition. We asked another eight subjects to assess the plausibility of the sentence on a 5-point scale (1 = *very implausible*, 5 = *very plausible*). There was no difference between the first word AB-C condition ( $M = 4.4$ ,  $SE = 0.17$ ) and the second word A-BC condition ( $M = 4.5$ ,  $SE = 0.16$ ),  $t_s < 1$ . We asked four subjects to demarcate how many characters are needed to disambiguate the overlapping ambiguous strings, and the results showed that about two characters were needed. Thus, we defined the disambiguating region as the two characters following the ambiguous region. Both the numbers of strokes and frequency of two characters following

the ambiguous region showed no difference for the two global segmentation conditions ( $ps > .15$ ). The length of the sentences were also controlled so that the number of characters in the second word A-BC condition ( $M = 18.53$ ) and the first word AB-C condition ( $M = 19.40$ ) were not different,  $t(31) = 1.36$ ,  $p = .181$ . The ambiguous strings were presented in the middle of the sentences so that they were never presented in the first four or the last four characters in a sentence.

**Procedure.** The procedure was identical to Experiment 2.

## Results and Discussion

Trials exclusion standards and eye movement measures were identical to Experiment 2. The accuracy of the comprehension questions was high (96%), suggesting again that subjects understood the sentences well. Trials in which subjects made more than three blinks or in which they blinked one or more times on the overlapping ambiguous strings were excluded from analysis, resulting in a loss of 3.5% of the trials. Fixations with durations longer than 1,000 ms or less than 80 ms (approximately 0.8%) were also excluded from analysis.

We report eye movement measures in both the overlapping ambiguous region and the disambiguating region. We analyzed the following five indicators of eye movements: (a) first-fixation duration; (b) gaze duration; (c) second-pass reading time (the sum of all fixations in a region following the initial first pass time, including zero times when a region is not fixated, see Clifton, Staub, & Rayner, 2007); (d) regression-in probability (the percentage of regressions made back into the target region after leaving it); (e) regression-out probability (regressions made from the current interest area to earlier interest areas prior to leaving that interest area in a forward direction). For these measures except the regressions-in and regressions-out, we conducted a 2 (local segmentation: high-low frequency vs. low-high frequency)  $\times$  2 (global segmentation: first word AB-C vs. second word A-BC) repeated measure ANOVA with subjects ( $F_1$ ) and items ( $F_2$ ) as random variables. The data for the two regression measures are categorical, thus they were analyzed using an ordinary logit model.

**Overlapping ambiguous strings region.** All of the hypotheses predict that first-fixation duration and gaze duration on the ambiguous region should be shorter in the high-low frequency condition than the low-high frequency condition. Detailed eye movement measures are shown in Table 2. First-fixation durations were shorter in the high-low frequency condition ( $M = 278$  ms,  $SE = 9$ ) than in the low-high frequency condition ( $M = 304$  ms,

$SE = 8$ ),  $F_1(1,27) = 8.85$ ,  $MSE = 1,954$ ,  $p = .006$ ,  $F_2(1, 30) = 5.05$ ,  $MSE = 2,034$ ,  $p = .032$ ; they were also shorter in the second word A-BC condition ( $M = 279$  ms,  $SE = 8$ ) than in the first word AB-C condition ( $M = 303$  ms,  $SE = 10$ ),  $F_1(1, 27) = 6.63$ ,  $MSE = 2,104$ ,  $p = .016$ ,  $F_2(1, 30) = 7.15$ ,  $MSE = 1,210$ ,  $p = .012$ . The interaction between local segmentation and global segmentation was not significant ( $F_s < 1$ ).

Gaze durations showed a similar pattern. They were shorter in the high-low frequency condition ( $M = 543$  ms,  $SE = 26$ ) than in the low-high frequency condition ( $M = 622$  ms,  $SE = 27$ ),  $F_1(1, 27) = 13.01$ ,  $MSE = 15,307$ ,  $p = .001$ ,  $F_2(1, 30) = 3.32$ ,  $MSE = 30,559$ ,  $p = .078$ . Gaze durations were also shorter in the second word A-BC condition ( $M = 553$  ms,  $SE = 24$ ) than in the first word AB-C condition ( $M = 612$  ms,  $SE = 26$ ),  $F_1(1, 27) = 9.46$ ,  $MSE = 9,791$ ,  $p = .005$ ,  $F_2(1, 30) = 9.3$ ,  $MSE = 6,510$ ,  $p = .005$ . The interaction between local segmentation and global segmentation was not significant ( $F_s < 1$ ).

It is surprising that first-fixation durations and gaze durations in the ambiguous region were all affected by global segmentation. Both measures were shorter in the second word A-BC condition than in the first word AB-C condition. Because the sentences in the two conditions were identical up to the right side of the overlapping ambiguous strings, the only explanation of this effect is the difference between texts following the ambiguous region. These results suggest that word segmentation might be affected not only by the fixated word but also by the characters (words) to the right of fixation. However, it is not clear why global segmentation would affect the reading times on the ambiguous region. It is also worth noting that, although global segmentation affected fixation times in the ambiguous region, the interaction between local segmentation and global segmentation was not significant. It is obvious that subjects cannot ensure the correct segmentation until they check the information in the disambiguating region. This suggests that the influence of the disambiguating region on first-fixation duration and gaze duration on the ambiguous region is not likely caused by the semantic processing of the disambiguating region. Otherwise, we would expect that whether the local segmentation fits with the global segmentation or not should affect first-fixation duration and gaze duration on the ambiguous region, and hence predict an interaction between the two factors. We suspect this unexpected main effect of global segmentation is caused by the properties of the materials. In some sentences, the character C in the ambiguous region could constitute a phrase with the word following it. For example, in the sentence shown in Figure 4, the

Table 2

*Eye Movement Measures in the Overlapping Ambiguous String Region and Disambiguating Region in Experiment 3*

Measure	Overlapping ambiguous string				Disambiguating region			
	High-low frequency		Low-high frequency		High-low frequency		Low-high frequency	
	segA-BC	segAB-C	segA-BC	segAB-C	segA-BC	segAB-C	segA-BC	segAB-C
First-fixation duration	265 (9)	290 (14)	293 (10)	313 (12)	273 (14)	242 (13)	233 (10)	257 (14)
Gaze duration	506 (28)	575 (28)	602 (32)	648 (31)	314 (19)	318 (19)	289 (15)	315 (19)
Second-pass reading time	694 (82)	422 (53)	447 (64)	696 (67)	327 (56)	184 (24)	151 (22)	322 (53)
Regression-in probability	.66 (.04)	.5 (.05)	.41 (.05)	.63 (.05)				
Regression-out probability					.41 (.05)	.24 (.03)	.18 (.04)	.37 (.04)

*Note.* First fixation duration, Gaze duration, and Second-pass reading time were measured in milliseconds. Standard errors are shown in parentheses.

character 装 in the low-high/AB-C condition could constitute a phrase 装货物 and the similar constructions appears in 1/3 of these sentences. It is possible that subjects tried to process the whole structure when they fixated character C, thus the fixation time on ABC in first word AB-C condition might contains additional time processing the phrase begin from character C. The results of Experiment 5 in Li et al. (2009) showed this kind of tendency.

Second-pass reading time on the ambiguous region is more informative and diagnostic. As we noted before, only the competition hypothesis predicts an interaction between the local segmentation and global segmentation manipulations. The results were consistent with the competition hypothesis. Second-pass reading times for the high-low and low-high frequency conditions were 558 and 571 ms, respectively, and were 570 and 559 ms for the second word A-BC and first word AB-C conditions. None of the main effects of local segmentation and global segmentation were significant ( $F_s < 1$ ). However, the interaction between local segmentation and global segmentation was significant,  $F_1(1, 27) = 28.79$ ,  $MSE = 63,012$ ,  $p < .001$ ,  $F_2(1, 30) = 6.34$ ,  $MSE = 164,969$ ,  $p = .017$ . In the high-low frequency condition, second-pass reading times were shorter for the first word AB-C condition than that for the second word A-BC condition,  $F_1(1, 27) = 16.14$ ,  $MSE = 64,019$ ,  $p < .001$ ,  $F_2(1, 30) = 3.34$ ,  $MSE = 164,969$ ,  $p = .077$ . In contrast, in the low-high frequency condition second-pass reading times were longer for the first word AB-C condition than that for the second word A-BC condition,  $F_1(1, 27) = 17.55$ ,  $MSE = 44,951$ ,  $p < .001$ ,  $F_2(1, 30) = 3.01$ ,  $MSE = 164,969$ ,  $p = .093$ . These results clearly show that the higher-frequency word wins the competition more often than the lower-frequency word. Once this segmentation is congruent with the sentence context, it led to less rereading or shorter second-pass reading times on this region.

Regression-in probability for the high-low frequency and low-high frequency conditions was .58 and .52, respectively, and .53 and .56 for the second word A-BC and first word AB-C conditions. None of the main effects of local segmentation and global segmentation were significant (Wald  $Z < 1.9$ ,  $ps > .05$ ). However, the interaction effect between local segmentation and global segmentation was significant,  $b = 1.584$ ,  $SE = 0.281$ , Wald  $Z = 5.62$ ,  $p < .001$ , and the pattern was similar to second-pass reading time. In the high-low frequency condition, regression-in probability was less for the first word AB-C condition than that for the second word A-BC condition,  $b = -0.683$ ,  $SE = 0.199$ , Wald  $Z = -3.42$ ,  $p < .001$ . In contrast, for the low-high frequency condition regression-in probability was greater for the first word AB-C than for the second word A-BC condition,  $b = -0.901$ ,  $SE = 0.198$ , Wald  $Z = 4.53$ ,  $p < .001$ . These results suggest that subjects needed fewer regressions for the ambiguous strings in the fit condition than in the misfit condition, which is consistent with the assumption that a higher-frequency word wins the competition more often than a lower-frequency word.

**Disambiguating region.** Detailed eye movement measures are presented in Table 2. First-fixation durations for the high-low frequency and low-high frequency condition were 257 and 245 ms, respectively, and were 253 and 250 ms for the second word A-BC and first word AB-C conditions. None of the main effects were significant ( $F_s < 1.5$ ,  $ps > .25$ ). However, the interaction between local segmentation and global segmentation was significant,  $F_1(1, 27) = 15.51$ ,  $MSE = 1,461$ ,  $p < .001$ ,  $F_2(1, 30) = 4.21$ ,  $MSE =$

3,153,  $p = .049$ . In the high-low frequency condition, first-fixation durations for the first word AB-C condition were shorter than for the second word A-BC condition,  $F_1(1, 27) = 7.67$ ,  $MSE = 1,978$ ,  $p = .010$ ,  $F_2(1, 30) = 2.7$ ,  $MSE = 3,153$ ,  $p = .111$ . In contrast, in the low-high frequency condition first-fixation durations were longer for the first word AB-C condition than for the second word A-BC condition,  $F_1(1, 27) = 5$ ,  $MSE = 1,610$ ,  $p = .034$ ,  $F_2(1, 30) = 1.58$ ,  $MSE = 3,153$ ,  $p = .218$ . These results are generally consistent with the predictions of the competition hypothesis. In the early stage, before readers' eyes saccade to the disambiguating region, the local segmentation had finished. In the fit condition, the local segmentation was congruent with the global segmentation; thus, readers needed less time to process the disambiguating region. However, in the misfit condition, in which the local segmentation was incongruent with the global segmentation, Chinese readers had to revise the outcome of the local segmentation in the disambiguating region, resulting in longer fixation times.

Gaze durations were 316 and 302 ms for the high-low frequency and low-high frequency conditions, respectively, and were 302 and 316 ms for the second word A-BC and first word AB-C conditions. None of the main effects of local segmentation and global segmentation were significant ( $F_s < 1$ ). The interaction between local segmentation and global segmentation was not significant,  $F_1(1, 27) = 2.36$ ,  $MSE = 2,619$ ,  $p = .135$ ,  $F_2 < 1$ . However, the trend was similar to that of first-fixation duration, showing shorter gaze durations in the fit condition than in the misfit condition.

Second-pass reading times for the high-low frequency and low-high frequency conditions were 256 and 236 ms, respectively, and were 239 and 253 ms for the second word A-BC and first word AB-C conditions. None of the main effects were significant ( $F_s < 1.5$ ,  $ps > .24$ ), but the interaction between local segmentation and global segmentation was significant,  $F_1(1, 27) = 10.92$ ,  $MSE = 59,896$ ,  $p = .003$ ,  $F_2(1, 30) = 6.68$ ,  $MSE = 59,170$ ,  $p = .015$ . For the high-low frequency condition, second-pass reading times for the first word AB-C condition were shorter than that for the second word A-BC condition,  $F_1(1, 27) = 7.00$ ,  $MSE = 43,848$ ,  $p = .013$ ,  $F_2(1, 30) = 2.65$ ,  $MSE = 59,170$ ,  $p = .114$ . In contrast, for the low-high frequency condition, second-pass reading times for the second word A-BC condition were shorter than that for the first word AB-C condition,  $F_1(1, 27) = 9.67$ ,  $MSE = 35,985$ ,  $p = .004$ ,  $F_2(1, 30) = 5.39$ ,  $MSE = 59,170$ ,  $p = .051$ . These results showed that second-pass reading time in the fit condition were shorter than the misfit condition.

Regression-out probability for the high-low frequency and low-high frequency conditions was .32 and .28, respectively, and .29 and .31 for the second word A-BC and first word AB-C conditions. None of the main effects of local segmentation and global segmentation were significant (Wald  $Z < 1.7$ ,  $ps > .1$ ). However, the interaction between local segmentation and global segmentation was significant,  $b = 1.696$ ,  $SE = 0.309$ , Wald  $Z = 5.49$ ,  $p < .001$ . For the high-low frequency condition, regression-out probability for the first word AB-C condition was lower than that for the second word A-BC condition,  $b = -0.753$ ,  $SE = 0.211$ , Wald  $Z = 3.57$ ,  $p < .001$ . In contrast, for the low-high frequency condition regression-out probability was higher for the first word AB-C condition than that for the second word A-BC condition,  $b = 0.942$ ,  $SE = 0.226$ , Wald  $Z = 4.17$ ,  $p < .001$ . These results

revealed that in the misfit condition, more regressions out from the disambiguating region were needed than that in the fit condition.

In sum, the results are consistent with the competition hypothesis, and suggest that word frequency affects the competition between words when processing overlapping ambiguous strings in natural sentence reading. In the ambiguous region, second-pass reading time was shorter and regression-in probability was less when the local segmentation based on word frequency was congruent with global segmentation based on sentence context. For the disambiguating region, eye movements showed a similar pattern. First-fixation durations and second-pass reading times were shorter and regression-out probability was lower when the local segmentation was congruent with the global segmentation. All of these results suggest that it is easier to process the disambiguating region when the local segmentation is congruent with the global segmentation. These results confirmed our hypothesis that a higher-frequency word wins the competition more often when processing an overlapping ambiguous string in sentence reading.

### General Discussion

In three experiments, we tested three possible mechanisms in segmenting overlapping ambiguous strings in Chinese reading. The first two characters and the last two characters in a three-character ambiguous string could both constitute a word. Previous studies showed that all of the words constituted by these characters are activated (Inhoff & Wu, 2005). We explored how these activated words compete for final representation by distinguishing three hypotheses. The left-priority hypothesis assumes that the word on the left has an advantage in the competition and the other words cannot be processed until the word on the left is recognized. The independent processing hypothesis assumes that words at different positions are processed simultaneously and independently, and that the word segmentation ambiguity cannot be settled without the help of sentence context. The competition hypothesis assumes that all of the words compete for a single winner and any word can win the competition if its activation is high enough.

The results of all three experiments are consistent with the competition hypothesis but not consistent with the left-priority hypothesis and the independent processing hypothesis. In Experiment 1, Chinese readers preferred to pronounce the middle character as it is in the high-frequency word regardless of its position (left-hand or right-hand). These results are in conflict with the prediction of the left-priority hypothesis which predicts that the middle character should always be pronounced as it is in the left word. In Experiment 2, fixation time on the first word AB was longer when the frequency of the second word was higher (in the case of BC) than when it was lower (in the case of BD). These results are in conflict with the independent processing hypothesis, which predicts that fixation duration in the AB region should not differ between the two conditions. In Experiment 3, second-pass reading time and regression-in probability were lower for the ambiguous regions when the local segmentation (based on word frequency) was congruent with the global segmentation (based on sentence context, the fit condition) than when it was incongruent (the misfit condition). These results are in conflict with the left-priority hypothesis and the independent processing hypothesis which predicts no interaction between local segmentation and global segmentation. Thus, these three experiments provided

strong evidence for the competition hypothesis in dealing with overlapping ambiguity in Chinese reading.

The Chinese word segmentation model proposed by Li et al. (2009) assumed that the characters in the perceptual span are processed in parallel. The activated character information feeds forward to the word-processing level, and all of the words associated with these activated characters are activated. These activated words compete for a single winner. However, Li et al.'s model also assumed that the word on the left has an advantage during the competition. The processing of the next word can only start when processing of the word on the left has finished (serially AB-C). However, when dealing with overlapping ambiguous strings, recognition of the first word AB was influenced by the second word BC. If the frequency of the second word is much higher than that of the first word, the second word could win the competition and change the segmentation style into A-BC. These results suggest that the left word priority assumption in Li et al.'s model should be revised. However, the competition hypothesis does not reject the notion that the word on the left will have some advantage during competition. Actually, even if the properties of activated words are all equal, the left-hand word would win the competition more often because of the constraints of visual acuity and visual attention.

In the current study, the competition hypothesis is strongly supported by all three experiments. Note that the competition hypothesis assumes that word segmentation in Chinese reading is a combination of a parallel processing component and a serial processing component. In the early stage of processing, characters in the perceptual span are processed in parallel and multiple words are activated. This is the parallel processing component. The parallel component is supported by evidence from Experiments 2 and 3. In Experiment 2, fixation times on the region AB were affected by the frequency of the word constituted by the last two characters in the string. In Experiment 3, second-pass reading times on the ambiguous string were shorter and the regression-in probability was lower when the local segmentation fits with the global segmentation than misfit. This suggests that the second word in the ambiguous string could be activated if its frequency is high. All of these pieces of evidence suggest that multiple words are activated at an early stage of word processing. However, these activated words compete with each other, and only one word can win the competition at any given round of competition. This is the serial processing component. The serial component is supported by evidence from Experiment 3. If all of the activated words are kept in memory as the independent hypothesis assumes, the second-pass reading time and regression-in probability in the ambiguous region and the fixation times in the disambiguating region should not differ between the fit condition and the misfit condition. Apparently, the predictions of the independent hypothesis were not supported. Hence, serial processing and parallel processing are not contrary to each other for this hypothesis as some researchers claim (see Schotter et al., 2012, for a review). Although the present study involved Chinese reading, the conclusions might be relevant for similar questions in other languages, such as the example of *UNLOCKABLE* in English reading. How the conclusions of this study extend to other languages requires further study.

The results of the current study are also consistent with the view that word segmentation is a two-stage process that contains word recognition and context integration. There may be an early word

segmentation stage governed by local properties of stimuli such as word frequency. Later, in the information integration stage, this segmentation may be corrected if it is not consistent with sentence context. In support of this view, we found that early measures of eye movements such as first-fixation duration and gaze duration were affected by word frequency, but not affected by the interaction of local segmentation and global segmentation. However, second-pass reading time and the regression-in probability of the ambiguous region, as well as almost all of the measures (except gaze duration) in the disambiguating region, were affected by the interaction between global segmentation and local segmentation, suggesting that the initial segmentation was revised in a later stage if it did not fit into sentence context.

The results of Experiment 3 are similar to the processing of lexical and syntactic garden paths in English reading, which refers to the phenomenon that when people process certain types of sentences, they prefer to go with one meaning that is finally proved to be incorrect and they have to regress back to earlier parts of the text (Frazier & Rayner, 1982, 1990; Staub, 2011). Garden path phenomena have been widely studied in English by chiefly observing two indices: first-pass reading time in the disambiguating region as a reflection of early processing and regression-in probability to the ambiguous region as an index of reanalysis (Altmann, 1994; Altmann, Garnham, & Dennis, 1992; Rayner & Sereno, 1994). The results of the current study suggest that the garden path phenomenon cannot only be caused by syntactic ambiguity, but it can also be caused by the character-to-word grouping of overlapping ambiguous strings in Chinese reading. An overlapping ambiguous string may be segmented depending on the relative frequency of the two words, which may not fit in the sentence context. If this is the case, it leads to a garden path phenomenon, and the processing in later stages has to correct this segmentation error. However, the important finding in the current research is not only that we found a garden path phenomenon in dealing with spatially ambiguous Chinese strings, but also this phenomenon confirmed our hypothesis that a word competition mechanism exists in Chinese reading.

As stated in the introduction, many factors may contribute to word segmentation in Chinese reading. In the current study, we have illustrated that word frequency affects word segmentation not only in processing isolated character strings but also in natural sentence reading. For segmenting ambiguous polymorphemic words, Pollatsek et al. (2010) also found that word frequency can affect the context effect for segmenting an ambiguous string such as *UNLOCKABLE*. Although the context was consistent with the left-branching structure AB-C, the lower the frequency of the left-hand word AB (such as *UNLOCK*) was, the less likely the left-branching preference AB-C (*UNLOCK-ABLE*) appeared. However, we do not think word frequency is the only factor that affects Chinese word segmentation. Word segmentation in Chinese reading is very complicated, and other information, such as context and lexical statistical cues (i.e., some characters are more likely to be the first character of a word, whereas others may be more likely to be the last character of a word), might influence this process (Rayner, Li, Juhasz, & Yan, 2005; Reilly, & Radach, 2012; Tsai, Lee, Lin, Tzeng, & Hung, 2006; Yen et al., 2012). In addition, local word plausibility might also influence this process strongly (Staub, Rayner, Pollatsek, Hyönä, & Majewski, 2007; Yang, Staub, Li, Wang, & Rayner, 2012). In Experiment 2, the high-

plausibility of the AB-C segmentation style was consistent with the sentence context, thus fixation time was much shorter than that in Experiment 3. We can infer that both word frequency and local plausibility are critical in segmenting overlapping ambiguous strings which should be emphasized in future work.

In this study, the frequency manipulation for overlapping ambiguous strings provided a window to investigate how word segmentation proceeds. In sentences without ambiguity, word recognition is simultaneous with word segmentation in Chinese (Li et al., 2009), and we cannot tease apart these two mental processes. However, for overlapping ambiguous strings, the segmentation behavior can be directly reflected in the eye movement measures. Thus, this research brings a new technique to investigate Chinese word segmentation.

In conclusion, the results of the three experiments in the current study clearly support the competition hypothesis, suggesting that multiple words constituted by the characters in the perceptual span are activated when processing overlapping ambiguous strings. These activated words compete for a single winner. Later on, Chinese readers might revise the segmentation if they find the initial segmentation does not fit into the sentence context. These results have important implications for understanding the mechanisms of word recognition and word segmentation in Chinese reading.

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