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Eye movement guidance in Chinese reading: Is there a preferred viewing location?

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Abstract

In this study, we examined eye movement guidance in Chinese reading. We embedded either a 2-character word or a 4-character word in the same sentence frame, and observed the eye movements of Chinese readers when they read these sentences. We found that when all saccades into the target words were considered that readers eyes tended to land near the beginning of the word. However, we also found that Chinese readers' eyes landed at the center of words when they made only a single fixation on a word, and that they landed at the beginning of a word when they made more than one fixation on a word. However, simulations that we carried out suggest that these findings can't be taken to unambiguously argue for word-based saccade targeting in Chinese reading. We discuss alternative accounts of eye guidance in Chinese reading and suggest that eye movement target planning for Chinese readers might involve a combination of character-based and word-based targeting contingent on word segmentation processes.

Keywords

Eye movements; reading; Chinese reading

Introduction

In English reading, eye movements are very much affected by the characteristics of the fixated word and the word to the right of fixation (Rayner, 1998, 2009). The target of the initial saccade on a word is generally assumed to be the center of the word or the optimal viewing position (OVP, O'Regan & Levy-Schoen, 1987). However, the eyes typically land short of the OVP on the preferred viewing location (PVL, Rayner, 1979), which is halfway between the beginning and the middle of a word (McConkie, Kerr, Reddix, & Zola, 1988;

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McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Radach & Kempe, 1993; Rayner, Sereno, & Raney, 1996; Vitu, O'Regan, & Mittau, 1990). Thus, while the OVP represents the location in a word where performance should be optimal, the PVL represents where the eyes actually land. In English reading, eye movement guidance is aided by the spaces between words since they help to demarcate the boundary of the words before the eyes fixate on them (Rayner, Fisher, & Pollatsek, 1998). However, not all writing systems have spaces between words. In particular, for example, text written in Chinese is formed by strings of equally spaced boxlike symbols called *characters*. Importantly, there are no spaces in the text to separate words. Without spaces, how do Chinese readers determine where to send their eyes? There are at least three options: (1) saccade targeting is word-based, so that some specific position (either at the beginning or at the center) of a word is selected as the target of next saccade; (2) saccade targeting is character-based, so that Chinese readers identify as many characters as possible on each fixation and select somewhere to the right of the identified characters as the saccade target; and (3) some kind of constant distance strategy is used in which the eyes move a set distance on each saccade (but with some variability).

Chinese reading differs from English reading in many dimensions. First, there are more than 5000 Chinese characters (Hoosain, 1991) in contrast to 26 letters in English; and the information density in each Chinese character is much higher than English letters (Hoosain, 1991). Second, word length is shorter in Chinese; among the 56,008 words that are included in one published source (*Lexicon of common words in contemporary Chinese*, 2009), 6% are single-character words, 72% are 2-character words, 12% are 3-character words, and 10% are 4-character words. Less than 0.3% of Chinese words are longer than 4 characters. Third, as noted above, there are no spaces in Chinese text to separate words. Text written in Chinese is formed by strings of equally spaced box-like symbols called characters. Chinese readers thus have to depend on lexical knowledge to segment characters into words (Li, Rayner, & Cave, 2009). Because of these differences, findings from English can't be directly extended to Chinese reading.

Previous studies have demonstrated that words have psychological reality and are processed as a unit in Chinese. First, similar to English, Chinese characters are identified more efficiently in a word than in a string of characters that do not constitute a word (Cheng, 1981). Second, Li et al. (2009) found a word boundary effect, wherein character recognition accuracy dropped at the word boundary when Chinese readers were briefly presented Chinese characters consisting of either two 2-character words or a 4-character word. Third, Li and Logan (2008) demonstrated that Chinese characters belonging to a word could be perceived as an object and affect attentional deployment. Fourth, Bai, Yan, Liversedge, Zang, and Rayner (2008) found that while inserting spaces between words did not facilitate reading, inserting spaces between characters interfered with reading.

Other eye movement studies demonstrated that properties of Chinese words affect fixation durations during reading. First, word predictability and word frequency both influence fixation durations of Chinese readers: high-frequency words are fixated for less time than low-frequency words (Yan, Tian, Bai, & Rayner, 2006) and high-predictable words are fixated for less time than low-predictable words (Rayner, Li, Juhasz, & Yan, 2005). Second, Rayner, Li, and Pollatsek (2007) extended the E–Z Reader model of eye movement control in English reading (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003) to Chinese. The model accounted for fixation durations and word skipping rates (Rayner et al., 2005) during Chinese reading quite well, suggesting that words are an important factor in eye movement control for Chinese readers. However, there is evidence to suggest that the planning of when and where to move the eyes are independent when programming eye movements (Aslin & Shea, 1987; Becker & Jürgens, 1979; Rayner & McConkie, 1976; Rayner & Pollatsek, 1981). Hence, even though word properties affect fixation duration, it does not necessarily mean that they also affect the decision of where to move the eyes.

Compared with English reading, eye movement patterns in Chinese reading are not well understood. An important question is where Chinese readers send their eyes during reading. The initial eye movement studies of Chinese reading dealing with a PVL effect did not find a PVL within a word. Yang and McConkie (1999) and Tsai and McConkie (2003) found that the initial fixations on a word were distributed equally on all of the characters, resulting in a flat PVL curve (PVL curves plot the frequency of the initial fixations across the letters of words). However, more recently, Yan, Kliegl, Richter, Nuthmann, and Shu (2010) reported some conflicting results relative to the initial studies. First, they found that the initial fixation on a word was more likely to fall on the characters at the beginning of a word, resulting in a PVL curve peaked at the beginning of a word when more than one fixation is made on a word (for similar results, see Shu, Zhou, Yan, & Kliegl, 2011). This pattern is consistent with findings from unspaced English reading (Rayner et al., 1998) and findings from Japanese reading (Kajii, Nazir, & Osaka, 2001). Second, Yan et al. found that when only one fixation is made on a word, the landing position is more likely to be at the center of a word. This result is similar to that found in English (Rayner, 1979; Rayner, Sereno, & Raney, 1996). Third, Yan et al. simulated a constant distance strategy and found that this model can generate skipping, single fixation duration, and refixation curves as a function of word length and word frequency that look quantitatively similar to the empirically observed ones. Nevertheless, on the basis of additional evidence, they concluded that this strategy does not adequately account for the overall data pattern with respect to eye movement guidance in Chinese reading.

Yan et al. interpreted their results as suggesting that there are two different mechanisms to guide eye movements in Chinese reading. First, if the word boundary can be determined via parafoveal vision, the saccade will be targeted to the center of the word. Second, when the boundary can’t be determined via parafoveal vision, the saccade will be targeted to the beginning of the word. While this interpretation is a reasonable way to account for the observed data, there is an alternative explanation. Specifically, given that words are processed more efficiently if the eyes fixate at the center of the word (O’Regan, 1981; O’Regan & Levy-Schoen, 1987), it is possible that all of the characters in a Chinese word are processed when a fixation is at the center of the word, so the next saccade does not need to target the other characters belonging to the same word. To put it another way, it is not necessary that readers know the boundary of the word to saccade to the center of that word. It is possible that because the eyes fixated at the center of the word (by chance), another fixation on the same word is not necessary. Hence, the difference in the data pattern for the PVL curves between single fixations and initial of multiple fixations does not necessarily support the claim that Chinese readers can sometimes determine the boundary of a word parafoveally and send their eyes to the center of the word in such cases. In summary then, it is not clear whether word properties affect target selection during saccade planning in Chinese reading.

In the present study, we examined how word properties affect where the eyes are deployed in Chinese reading. However, we approached the problem in a different way from previous studies. Virtually all of the previous studies (Tsai & McConkie, 2003; Yan et al., 2010; Yang & McConkie, 1999) on this issue mainly followed the methods used in the studies with readers of English (Rayner, 1979), hoping to find the same kind of PVL curve as that in English reading. In these studies, the saccade landing locations on all of the words in single sentences or in passages were averaged when calculating the PVL curve. In the present study, we took a different approach. We embedded target words of different lengths in the same set of sentence frames and then examined the PVL curve on these target words. The target words were carefully chosen so that most Chinese readers would agree that they are words. We were especially interested in whether there was any tendency for Chinese readers to fixate at the center or the beginning of a word. Thus, either a 2-character target word or a 4-character target word was embedded in the same sentence frame with the sentences being identical up to the target word. Hence, any differences in the landing position on the target word would be due to the properties of the target word. If Chinese readers have a tendency to look at the center of a word, we expected an inverted U shape PVL curve such as that which has been observed in English reading. More importantly, when comparing the PVL curves of the two conditions, the peak of the PVL curve should shift right for longer target words (4-character condition) compared with short target words (2-character condition). In addition, if eye guidance is character-based in Chinese, we anticipated evidence that readers' fixations would tend to fall near the beginning of words.

Methods

Subjects

Thirty-two native Chinese speakers, who were students at universities in Beijing near the Institute of Psychology, Chinese Academy of Sciences, were paid to participate in the experiment. All of them had normal or corrected-to-normal vision, and all were naive regarding the purpose of the experiment.

Apparatus

Eye movements were recorded by an SR EyeLink II tracker, which has a resolution of approximately 30′ of arc. Subjects read the target sentences (which were printed horizontally from left to right) on a 19-in. CRT monitor connected to a DELL PC. They wore a lightweight helmet that is part of the eye-tracking system. The eye-tracking system samples at the rate of 250 Hz and provides eye movement data for further analysis via another PC. Although the Eyelink II system is able to compensate for head movements, the subjects rested their heads on a chinrest to minimize head movements during the experimental trials. Viewing was binocular, but eye movement data were collected only from the right eye. The subjects were seated 70 cm from the video monitor; at this distance, one character subtended .8° of visual angle.

Materials

The materials consisted of 100 sentence frames (or 200 sentences in total). Initially, 200 sentences, ranging from 18 characters to 33 characters, were obtained from an online corpus1. One word in the middle of the sentence (not within the first 5 or last 5 characters of a sentence) was replaced with a blank. Five subjects (who did not participate in the eye movement experiment) filled in the word that they thought was most suitable in the sentence. They were asked to provide at least two words, one 2-character word and one 4-character word. By this procedure, we chose 143 sentence frames, each with two target words, one 2-character word and one 4-character word. For these sentences, at least two subjects filled in the chosen 2-character word and the chosen 4-character word in the sentence. Twenty additional subjects were recruited to rate how well the target word fit into 286 sentences (the selected 143 sentence frames with either the 2-character or 4-character word). Each subject only saw one version of the sentence frame. A rating of 7 meant that the target word fit very well into the sentence, and a rating of 1 meant that the target word did not fit in the sentence. From these ratings, we chose the 100 sentence frames with the highest average score (average = 5.1, see Figure 1 for an example). The chosen 2-character

[1]Center for Chinese Linguistics PKU, http://ccl.pku.edu.cn:8080/ccl_corpus/index.jsp?dir=xiandai

target words were confirmed to be a word and not to be part of other words by two native Chinese speakers and by checking a Chinese lexicon (*Lexicon of common words in contemporary Chinese*, 2009). Hence, the 2-character target word in the 2-character condition did not combine with the following two characters to constitute a 4-character word. As noted earlier, in Chinese, 72% of the words are 2-character words, and 10% are 4-character words (Lexicon of common words in contemporary Chinese, 2009). Hence, choosing 2-character and 4-character words as the target word is representative of Chinese text.

Procedure

When subjects arrived for the experiment, they were given instructions for the experiment and a description of the apparatus. The eye tracker was calibrated at the beginning of the experiment and the calibration was validated as needed. For calibration and validation, subjects looked at a dot that was presented at various locations in a 3 × 3 grid in a random order. Then each subject read 10 sentences for practice and the 100 experimental sentences in a different random order, but with appropriate counterbalancing procedures to ensure that an equal number of each type of target word was read. The subjects were told to read silently, and that they would periodically be asked to answer questions about the sentences. These questions were asked after about one third of the 110 sentences that were read; the subjects were correct over 90% of the time.

Each trial started with a fixation box (1° × 1° in size) at the location of the first character of the sentence. The sentence was shown after subjects successfully fixated on the box. After reading a sentence, the subject pressed a response button on a button box to start next trial.

Data analysis

Across all of the trials, approximately 3% of the data were lost due to a track loss. In some trials, subjects moved back to the beginning of a sentence when they had looked through the sentence. Since we were interested in the landing position on the target words, all of the fixations after the return sweep were discarded.

Results and Discussion

We report the results in three steps. First, we report the following eye movement measures averaged across the whole sentence: (1) number of fixations, (2) average saccade length, and (3) average fixation duration. Second, we report the following measures on the target word: (1) first-fixation duration (the duration of the first fixation on a word independent of the number of fixations on the word), (2) gaze duration (the sum of all fixations on a word prior to the reader’s moving to another word), (3) total fixation time (the sum of all fixations on a word, including regressions), (4) number of fixations, and (5) the probability that the reader skipped the target word. Third, we report the landing positions on the target word. Since the text was identical for the two conditions up to the target word, any difference in landing position must be caused by the properties of the target word. An ANOVA or t-test was carried out on each of the sets of data, using subjects ($F1$ or $t1$) and items ($F2$ or $t2$) as random effects. After reporting the results, we present some simulations similar to those reported by Yan et al. (2010) designed to shed further light on the issues.

Global measures

Across the entire sentence, there were fewer fixations (9.6 fixations, SEM = .4) in the 2-character condition than in the 4-character condition (10.0 fixations, SEM = .4), $t1(31)$ = 5.05, $p < .01$; $t2(99)=3.54$, $p < .001$), the average saccade length was slightly longer in the 4-character condition (3.19 characters, SEM = .13) than in the 2-character condition (3.10

characters, *SEM* = .13), $t1(31) = 1.97$, $p < .1$, $t2(99) = 2.24$, $p < .05$, and there was no difference in average fixation duration across these two conditions (both were 237ms, *t*s < 1). The saccade length and fixation duration data are generally comparable to those reported in previous studies on Chinese reading (Rayner et al., 2005; Yan et al., 2006).

Eye movement measures on the target word

The length of the target word was obviously different for the two conditions (2 characters in the 2-character condition, but 4 characters in the 4-character condition). Previous studies showed that word length affected fixation duration and the skipping rate in English and other alphabetic writing systems; long words are fixated longer (as measured by gaze duration) and are less likely to be skipped than short words (Brysbaert & Vitu, 1998; Just & Carpenter, 1980; Rayner; 1979; Rayner & McConkie, 1976; Rayner et al., 1996). We expected the same pattern for Chinese reading. Table 1 shows the eye movement measures associated with the target word.

First fixation durations did not differ across the two conditions (2-character condition: *M* = 250ms, *SEM* = 4 ms; 4-character condition: *M* = 249 ms, *SEM* = 5ms; *t*s < 1). However, gaze duration for the 2-character condition (266ms, *SEM* = 5ms) was shorter than that in the 4-character condition (355ms, *SEM* = 16ms), $t1(31) = 7.04$, $p < .001$, $t2(99) = 15.95$, $p < .001$. Total time was also shorter in the 2-character condition (296ms, *SEM* = 7ms) than in the 4-character condition (403ms, *SEM* = 18ms), $t1(31) = 7.15$, $p < .001$, $t2(99) = 13.64$, $p < .001$. One possible reason that we did not find a difference in first fixation duration is that the word boundary information was not acquired early enough to affect the first fixation duration[2].

There were fewer fixations on the target word in the 2-character condition (.73, *SEM* = .04) than in the 4-character condition (1.41, *SEM* = .07), $t1(31) = 17.47$, $p < .001$; $t2(99) = 28.78$, $p < .001$. Not surprisingly, the target word was more likely to be skipped in the 2-character condition (33% of the time, *SEM* = .03) than in the 4-character condition (6%, *SEM* = .01), $t1(31) = 11.82$, $p < .001$; $t2(99) = 18.54$, $p < .001$. The differences in eye movement patterns between the two conditions were similar to the word length effects that have been found in English reading (Rayner, 1998, 2009).

In the 2-character condition, the target word was fixated only once on 61% of the trails and was fixated two or more times on 6% of the trials. In the 4-character condition, the target word was fixated only once on 54% of the trails and was fixated two or more times on 40% of the trials. For the 4-character condition, where there was enough data to examine the fixation durations when 2 or more fixations were made, we conducted a further analysis. Specifically, fixations on the target word were categorized into three categories: (1) single fixations, (2) first fixations when two or more fixations were made, and (3) second fixations when two or more fixations were made. Fixation duration was shorter for second fixations (219ms, *SEM* = 5ms) than single fixations (246ms, *SEM* = 6ms) or first fixations (251ms, *SEM* = 5ms). This observation was confirmed via a main effect in a one-way ANOVA, $F1(2,62) = 20.72$, $\eta_p^2 = .40$, $p < .001$, $MSE = 450$; $F2(2,198) = 31.54$, $\eta_p^2 = .24$, $p < .001$, $MSE = 1174$. Planned contrasts showed that the difference between single fixations and second fixations was significant, $F1(1,31) = 19.90$, $\eta_p^2 = .39$, $MSE = 1151$, $p < .001$; $F2(1,99) = 43.58$, $\eta_p^2 = .31$, $MSE = 2738$, $p < .001$, as was the difference between first fixations and second fixations, $F1(1,31) = 66.29$, $\eta_p^2 = .39$, $MSE = 487$, $p < .001$; $F2(1,99) = 69.10$, $\eta_p^2 = .41$, $MSE = 1480$, $p < .001$. The difference between single fixations and first

[2]Differences in first fixation duration in alphabetic writing systems often do not appear (Rayner, 1998, 2009). The length effect is typical in gaze duration because as word length increases, the probability of making additional fixations also increases thus inflating the gaze duration.

fixations was not significant (*F*s<1). This latter finding is at variance with Yan et al. (2010) as they reported that first fixations in two-fixation cases were longer than single fixations.

In summary, gaze durations on the target word were shorter in the 2-character condition than in the 4-character condition. The general pattern of findings presented above is consistent with the findings of English reading and those of Chinese reading (Rayner et al., 2005; Yan et al., 2006). If word properties play no role in determining the fixation duration on a word, we would expect that fixation duration should not differ whether the fixation is the first fixation or the second fixation on a word. However, for the 4-character condition, we found that second fixations on the word were shorter than first fixations. This is consistent with the view that word properties play an important role in Chinese reading when determining the duration of a fixation.

Does word length affect the landing position on words?

In English reading, the PVL curve is at maximum somewhere between the beginning and the center of a word (Rayner, 1979). This has generally been taken as evidence that the reader aims a saccade to the center of the next word, but often undershoots the target (McConkie et al., 1988). If the center of Chinese words is also the target of saccades in Chinese reading, we expected a similar pattern for the PVL curve. To make the measurements more comparable in the two conditions, we examined a region of interest (ROI) with a length of 4 characters. The ROI included all four characters of the target word in the 4-character condition, and included the 2 characters of the target word and the following two characters in the 2-character condition. Hence, only one word was included in this ROI in the 4-character condition, but two or three words were included in the 2-character condition. If there is a PVL at the middle of a word for Chinese, we expected an inverted U shape PVL curve for the 4-character condition. But, would the PVL curve be different for the two conditions?

Initial landing position—Figure 2 shows the proportion of initial fixations that landed on different characters in the ROI. The initial fixations were more likely to fall on the first character and the proportions dropped from left to right. On the surface, this appears to be consistent with a character-based model of saccade targeting as the PVL curve peaked at the beginning of a word. If saccades were more likely to target the center of a word as in English reading, we would have expected that the peak of the PVL curve in the 4-character condition should shift right in comparison to the 2-character condition. This was not what we observed. As shown in Figure 2, the two PVL curves are almost identical. The average landing position (measured from the left side of the 4-character ROI) was not different between the 2-character condition (.98 characters) and the 4-character condition (.99 characters). A Bayes factor calculation (Rouder, Speckman, Sun, Morey, & Iverson, 2009) revealed that the null hypothesis of no difference between the two conditions was 5.45 times more likely than the alternative hypothesis of a word length effect.

Forward saccade landing positions—The PVL curve of Chinese readers peaked at the beginning of a word. Does this mean that Chinese readers targeted the beginning of a word? When calculating the PVL curve, only the initial fixations on a word were included. Hence, only the fixations as a result of saccades launched from the characters to the left of that ROI were counted, but refixations on the ROI were not. As a result, all of the forward fixations were counted when calculating the number of fixations for the first character, but only a proportion of the fixations (fixations resulting from long saccades) were counted for the other characters. Thus, the proportion of included fixations decreased from left to right. Hence, in some sense it may not be appropriate to compare the number of fixations falling on the character at the beginning of a word (since all fixations falling on that character are included) to the other characters at the end of a word (where fewer fixations are included). To make the comparisons more comparable for all of the characters in a word, we analyzed all of the forward fixations on a word (including intraword refixations). If Chinese readers target the beginning of a word, we would expect that the probability of the landing position of all forward saccades (including intraword forward refixations) should also peak at the beginning of a word. Otherwise, if the PVL curve of initial fixations peaking at the beginning of a word is caused by the method used to compute the PVL curves, we would expect that the proportion of fixations as a result of all of the forward saccades should be equal at all of the characters in the word.

As shown in Figure 3, the proportion of fixations (following forward saccades) that landed on a character was almost equal for all of the 4 positions in the ROI (and was close to 25% in all cases). Thus, when all fixations were included, the distribution of fixations landing on the word was comparable across the 4 character ROI.

Landing positions of the first of multiple fixations versus single fixations— Yan et al. (2010) computed the PVL curves separately for the cases when there was only one fixation on a word and when there were multiple fixations. To compare our results with those of Yan et al., we computed similar analyses on the target words. As shown in Figure 4, our results generally replicated their results: the PVL curve peaked at the beginning of a word for the first of multiple fixations (Figure 4A), and it peaked at the center of a word for single fixations (Figure 4B). However, these results do not necessarily support the argument that Chinese readers target their eyes to the center of a word when they can determine the right boundary of a word, and target the beginning of a word when they can not. We will return to this point later.

Refixation probability—Refixation probability (the probability of fixation on a character belonging to the same word) also replicated Yan et al.'s (2010) results. Since the refixation rate was very low in the 2-character condition, we only analyzed the refixation results in the 4-character condition. As shown in Figure 5, refixation probability decreased gradually from the beginning to the end of a word. These results are consistent with the assumption that another fixation is needed when the initial fixation falls on a character at the beginning of a word, but is not needed when the initial fixation falls on a character at the center or end of a word. These results are different from those in alphabetic languages, where the refixation probability is lowest when the initial fixation is at the center of a word, and higher when the initial fixation is at either end of a word (McConkie et al., 1989; Rayner et al., 1996). The difference is probably due to the absence of inter-word spaces between Chinese words.

Saccade Length into and out of the Target Word—Since the text was identical for the two conditions before the target word, we expected that the launch sites would be similar for saccades into the target word in the 2-character and 4-character conditions. Indeed, the launch site was fairly similar for the two conditions (roughly 2.65 characters from the beginning of the target word). We analyzed the saccade length into the 4-character ROI (which, as noted previously, included the 4 characters of the target word in the 4-character condition and the 2 characters of the target word and 2 characters following it in the 2-character condition). Saccade length into the 4-character ROI was similar across the two conditions: (2-character condition = 3.46 characters, 4-character condition = 3.50 characters, $ts < 1$). We then examined the saccade size into the 2-character and 4-character target words and found that the incoming saccade length for the first of multiple fixations was 2.7 for the 2-char condition, and 2.9 for the 4-character condition, $ts < 1$. However, when only one fixation was made, the incoming saccade length was 3.05 for the 2-char condition and 3.85 for 4-character condition, $t1(31) = 5.06$, $p < .001$, $t2(99) = 10.53$, $p < .001$.

The text was also identical for the two conditions after the target word. Hence, we also analyzed the length of saccades launched from the 4-character ROI (aligned to the end of the target word). The 4-character condition ROI included the target word, while for the 2-character condition the ROI included the target word and two characters to the left of it. The average length of the saccades launched from the 4 character ROI was longer for the 4-character condition (3.29 characters, *SEM* = .13 characters) than the 2-character condition (3.01 characters, *SEM* = .12 characters, $t1(31) = 6.06$, $p < .001$; $t2(99) = 2.69$, $p <. 001$). This analysis confirmed that Chinese readers do not saccade a constant distance during reading. Furthermore, the results clearly indicate that the properties of the fixated word can affect saccades leaving it.

Simulations

The PVL curves of the current study generally replicated those of Yan et al. (2010). Specifically, the PVL curves for the first of multiple fixations peaked at the beginning of a word and decreased gradually from left to right. In the case of single fixations on a word, the PVL curve peaked at the center of a word. However, this pattern can’t be used to unequivocally argue that readers target the center of a word when Chinese readers can determine the right boundary of a word, and target the beginning when they cannot. As we argued in the Introduction, it is possible that because the eyes fixated at the center of the word (by chance), another fixation on the same word was not necessary. To demonstrate this point, we carried out a simulation to show that even if words play no role in eye movement guidance, a similar PVL curve can be expected. Figure 6 illustrates this. To generate this figure, we assumed (see Reilly & O’Regan, 1998, and Yan et al., 2010 for similar assumptions in their simulations) that saccades travel a constant distance (with some variance) regardless of where the word boundaries are. We also assumed that launch sites were equally distributed across all characters close to the start of the word. As the PVL curve of all of the forward fixations showed, this is a reasonable assumption. Then we computed a PVL curve on a 4-character ROI, which had nothing to do with word boundaries. As shown in Figure 6.F, the PVL peaked at the beginning of the ROI, and decreased from left to right. This simulation shows that a PVL curve that peaks at the beginning of a word does not necessarily mean that Chinese readers always target (and send their eyes to) the beginning of a word. The simple simulation fit the observed PVL curve of initial fixations on a word very well (the best fit to the observed data was a normal distribution with a mean of 2.6 characters, and a SD of .7). We assumed that the saccade length from any character is a random variable of normal distribution. We then calculated the number of initial fixations on a 4-character ROI. We simulated all of the saccades launched from the ten characters to the left of the ROI, and then we calculated the proportion of initial fixations on each character in this 4-character ROI. As shown in Figure 6, the simulated data fit the observed data very well.

The simple constant distance saccade simulation can predict similar PVL curves for the obtained data when computed separately for single fixations and the first of multiple fixations. We then conducted similar analyses on the simulated data (with the same constant distance assumption as reported above) using the same method that Yan et al. used. We computed PVL curves separately for single fixations and the first of multiple fixations. As shown in Figure 7, although the simulation did not assume that saccades target the beginning of a ROI, nor did it assume that the saccades target the center of a word, it generated similar PVL curves as the results shown in Figure 4 and Yan et al. (2010). The PVL curve of single fixations peaked at the center of a word, and the PVL curve of the first of multiple fixations peaked at the beginning of the ROI. This simulation shows that the results of Yan et al. (2010) are subject to alternative explanations, and hence they can’t be used to ambiguously argue for a word-based target selection.

Yan et al. (2010) also reported a simulation showing that the observed data for different predictability classes was outside the 95% confidence interval predicted by the constant model. Most importantly, the skipping probability predicted by the constant distance simulation did not account for the finding that skipping probability varies as a function of predictability (Rayner et al., 2005; Rayner et al., 2007). On the basis of this and other evidence, they rejected the constant distance account. Based on the PVL curves and the simulation that falsified the constant distance account, Yan et al. concluded that the target selection of Chinese readers is word based. Saccades target the center of the word if Chinese readers can identify the word boundary before the saccade, and target the beginning when they can not. This conclusion implicitly assumes that the constant distance account and the word based account are the only two alternatives that can explain the PVL curves in Chinese reading (Figure 2 and Figure 4). However, other models which assume that the distribution of fixations as a result of saccades launched from a specific character is a Gaussian shape can generate similar PVL curves as well even if they do not assume that saccades travel a constant distance. To give an example, in another simulation we assumed that the mean distance the eyes travel in each saccade is not constant in each saccade, but a random variable with a square distribution (ranging from 2.1–3.1 characters). The other aspects of the simulation were identical to the simulation reported above 3. The simulation generated similar PVL curves as shown in Figure 6F and Figure 7. Hence, falsifying the constant distance account does not warrant assuming the word based account. Note that although the simulations provided an alternative explanation for the observed PVL curve, it is not sufficient to use them to argue that Chinese readers move their eyes ahead in some constant fashion. Actually, as we will discuss in more detail below in the Discussion, as per Yan et al. (2010), we do not think the eye movements of Chinese readers reflect a constant distance strategy of eye movement control.

One important reason that led Yan et al. (2010) to reject the constant distance account was, as noted above, that it can't explain the skipping effect as a function of predictability4. However, the argument may not be fully convincing. As Yan et al. (2010) noted, Rayner, Binder, Ashby, and Pollatsek (2001) found that the initial landing positions in words were not affected by the predictability of that word. Rayner et al. (2001) suggested that skipping and target selection may use different mechanisms. Hence, showing that the constant model can not explain the predictability effect on skipping does not guarantee that saccade target selection is word based. Indeed, a modified version of the constant distance model can explain both the observed PVL curves and the skipping probability as a function of predictability. For example, one way to explain the predictability effect on skipping rate is to assume that the identification of the characters belonging to a high predictable word is easier, and hence the saccade length is longer if the word to the right of the fixation is a high predictable word. To demonstrate this we did another simulation with the method we described in the last section except that we assumed that saccade length is longer when the next word is more predictable (2.8 characters) than when it is less predictable (2.4 characters). The simulation results showed that the skipping rate for the 2-character word was 42.9% for predictable words, and was 27.9% for less predictable words. For this simulation, the PVL curves had the same pattern as that shown in Figure 7. In this simulation, we did not assume that saccades went to any specific position of a word, but the

[3]We did an additional simulation and obtained similar results. In that simulation, we assumed that the mean distance the eyes travel in each saccade is not constant, but a random variable with a Gaussian distribution (mean: 3 characters, std = 0.5).
[4]Yan et al. (2010) argued that the observed data were outside the 95% confidence interval predicted by the constant distance model, but they did not report the details of how they selected the parameters in their simulation. However, the parameters could greatly influence the 95% confidence interval. Hence, we do not consider the fact that the observed data were outside the predicted 95% confidence interval as strong evidence against the constant distance account.

simulation predicted both the skip rate data as a function of predictability and the PVL curves.

General Discussion

The question of the basis for eye guidance in Chinese reading is very important for modeling eye movement behavior in Chinese reading. Most models of English reading assume that eye movement guidance is word-based. If eye movement guidance in Chinese reading is similarly word-based, then some of these models could be used directly to explain the eye movement behavior of Chinese readers, including our extension of the E–Z Reader model to Chinese (Rayner et al., 2007). On the other hand, if eye movement guidance for Chinese readers is not word based, some special assumptions would have to be made to model the eye movement behavior of Chinese readers.

In this study, we examined the relation between word properties and eye guidance in Chinese reading using a combination of empirical data and simulations. The results of our experimental study, and specifically our initial analyses, suggest that Chinese readers do not target the center of a word for their next saccade. We embedded either a 2-character word or a 4-character word in the same sentence frame in two conditions, and examined Chinese readers' eye movements as they read these sentences. The initial fixations on a word were not more likely to land at the center of a word as has been found in English reading. Instead, the peak of the PVL curve was at the beginning of the target word. Most importantly, the PVL curve was not different for the two conditions. If saccades were more likely to target the center of a word, we would have expected that the PVL curve in the 4-character condition should shift rightwards compared with the 2-character condition. However, the PVL curves in these two conditions were almost identical. The results of the experiment are also ambiguous regarding the claim that Chinese readers are more likely to send their eyes to the beginning of a word. Although the PVL curve for the 4 character words (which only included the initial fixation on a word) peaked at the beginning of a word, a curve plotting the landing positions of all of the forward saccades (including refixations within a word) was flat.

In subsequent analyses, we followed up on previous research by Yan et al. (2010). They reported that the PVL curve of Chinese readers peaked at the beginning of a word for the first of multiple fixations on a word and peaked at the center of a word for single fixations on a word. Based on these findings, Yan et al. argued that Chinese readers send their eyes to the center of the word when they can determine the right boundary of the word in parafoveal vision, but send their eyes to the beginning of a word when they can not. In either case, saccade target selection is word based. The results of the current study generally replicated these results. However, our simulations suggest that Yan et al.'s interpretation of their data should be viewed with some caution. First, our simulations showed that a constant distance model could predict a PVL curve peaked at the beginning of a word for the first of multiple fixations, and also predict a PVL curve peaked at the center of a word for single fixations. These results were similar to those reported by Yan et al., even though the simulation assumed that the saccade target selection had nothing to do with word boundaries at all. Thus, researchers need to be careful when dividing the data based on the number of fixations on a word, and then drawing conclusions based on each part of the data. Second, the same simulations showed that a constant distance model could predict a PVL curve which peaked at the beginning of a ROI even though saccade target selection had nothing to do with word boundaries. Other simulations which did not assume a constant distance strategy, a character-based strategy, or a word-based strategy generated similar PVL curves as that observed in the experimental study. These simulations suggest that a PVL curve peaked at the beginning of a word should not be considered as exclusive evidence that Chinese readers target their eyes to the beginning of a word. To summarize, the present results seem to provide little clear evidence that Chinese readers target either the beginning or the middle of the word. As noted above, it is not surprising that we did not find a PVL like that in English with Chinese. In Chinese text, there are no inter-word spaces, which can be perceived in parafoveal vision in English reading (Rayner et al., 1998). Hence, we assume that Chinese readers can't easily acquire word boundary information via parafoveal vision.

Like Yan et al., we tend to think that a constant distance strategy can't fully explain eye guidance since there is clear evidence that word properties have psychological reality for Chinese readers. In addition, Yan et al. (2010) provided some evidence that the constant distance strategy can't adequately account for eye guidance in Chinese reading. Overall, the results of the current study provided further evidence against the constant distance strategy. The saccade length out of the target word was longer in the 4-character condition than the 2-character condition, suggesting that the properties of the fixated word affect the saccade leaving it.

As described in the Introduction, there is an important difference between our study and that of Yan et al. (2010). In Yan et al. (2010), the saccade landing locations on all of the words in their sentences were averaged when calculating the PVL curve. In contrast, we embedded target words of different lengths in the same set of sentence frames and then examined the PVL curve on these target words. Yan et al. (2010) thus had more observations per subject). We used 100 sentence frames and with 100 2-character target words and 100 4-character target words (with each subject reading 50 2-character target words and 50 4-character target words). Hence, compared to Yan et al. (2010), we had fewer observations for 2-character words. However, the target word manipulation that we used in this study had some advantages. Words of different length were embedded in the same sentence frame, so the effects of other factors were controlled so that any difference between the two conditions should be largely caused by the difference between the word lengths of the two conditions. One might argue that the power of our study is not big enough. However, we suspect that the power of our study is sufficient for our purposes. In the crucial analysis of average landing position, a Bayes factor calculation revealed that the null hypothesis of no difference between the two conditions was 5.45 times more likely than the alternative hypothesis of a word length effect. We did not utilize 1- and 3-character words in our study. Since our primary interest is with saccade landing positions, 1-character words would not be very informative. In future research, it might be interesting to explore landing position effects with 3-character words.

At this point, we think that it is not clear if saccade target planning in Chinese reading is word based or character based, and the issue of saccade target selection in Chinese reading is thus still an open question. Here we propose another candidate for eye guidance in Chinese reading. According to this account, eye movement target planning for Chinese readers might involve a combination of character-based and word-based targeting contingent on word segmentation processes. We suggest that saccades in Chinese reading do not target any specific position within a word, but the word properties of the fixated word can affect eye movement patterns following it. Since there are no extra spaces between words, Chinese readers might often not know the word boundary before fixating on a word. On a given fixation, Chinese readers may try (unconsciously) to identify as many characters as possible to the right of fixation, and then move their eyes beyond the identified characters. Hence saccade length will be longer if the characters around the fixated positions are simpler to recognize and be shorter for the characters that are harder to recognize. And, it is likely that characters forming words are easier to identify to the right of fixation (Li et al., 2009). Also, efficiency in identifying characters undoubtedly drops dramatically to the right of fixation due to limitations of visual acuity and of cognitive load.

Still another possibility for Chinese eye movement guidance is that readers might target the first two characters of a word no matter whether the word is 2-characters long or longer. In the above discussion, we assumed that words are clearly defined in Chinese reading. However, given that there are no spaces between words in Chinese reading, word boundaries are sometimes ambiguous. Some of our 4-character Chinese words were ambiguous in that the first 2 characters could also constitute a word; and some cases, the first 2 characters could constitute other words when combined with other characters. Indeed, the first two characters of 19 out of our 100 4-character target words constituted a word[5]. We analyzed the results when these ambiguous target words were not included. The results were virtually identical to those reported in the Results section (see Appendix), suggesting that including these words did not affect the results too much. Even so, the first two characters might be important for the perception of the whole word. Thus, it is possible that Chinese readers look at the first two characters when the first two characters constitute a meaningful unit no matter whether they are part of a 4-character word or not. Distinguishing all of these possibilities needs further research.

While the results of the present study and those of Yan et al. (2010) provide important data concerning eye guidance and saccade targeting in Chinese reading, an important issue is when is word boundary information in Chinese reading determined? The Chinese word segmentation model presented by Li et al. (2009) provides some insight into this question. The model assumes that all of the Chinese characters in the visual field are processed in parallel, with the efficiency of character processing being affected by acuity and visual attention. The model followed the interactive account of word processing (McClelland & Rumelhart, 1981) and assumed that the information in the character recognition level feeds forward to the word processing level, which activates the related words. All of the activated words compete for a single winner. Meanwhile, the activity in the word processing level feeds back to the character recognition level and affects the efficiency of character recognition. More activated words provide more feedback to the character processing level and the characters belonging to those words are processed more efficiently than others. Only when the competition is complete is the word recognized and the word boundary determined. Hence, Chinese word segmentation and word recognition is a unified process. According to the Li et al. model, Chinese readers segment (and recognize) words online. But this segmentation process usually happens when the eyes fixate on the word, so it does not affect the target selection on that word. However, since word processing can affect character recognition efficiency, word properties affect when to move the eyes.

In the present study, we found some additional evidence that word properties affect fixation durations of Chinese readers. Consistent with research on English (Rayner et al., 1996), the second fixation on a word was shorter than the first fixation or a single fixation. Along with previous findings that word frequency and word predictability affect fixation durations on a word (Yan et al., 2006; Rayner et al., 2005), these results suggest that when to move the eyes in Chinese reading is influenced by lexical processing.

In summary, our experimental study in combination with the simulations suggests that previous findings cannot be used to argue unambiguously for word-based or character-based target selection in Chinese reading. We have also suggested that eye movement target planning for Chinese readers might involve a combination of character-based and word-based targeting contingent on word segmentation processes (Li et al., 2009). Finally, it seems fairly clear that the decision of when to move the eyes in Chinese reading is influenced by word properties.

[5]We thank an anonymous reviewer for noting this.

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Appendix

Since there are no spaces between words in Chinese texts, word boundaries sometimes are ambiguous. The first two characters of some of the 4-character words could also constitute a word by themselves. Among the 100 4-character target words, 19 items had this problem. In these 19 items, the first two characters of the 4-character target word matched a word in the lexicon (Lexicon of common words in contemporary Chinese research team, 2009). To examine how much these words affected the results, we did the analyses again on those that did not have these problems. In addition, 18 of the 200 target words were used more than once. Although the effect of these repeated words should be minimal since words are repeated quite often in reading, we removed these items from the analyses to exclude possible influence of these repeated words. All together, 63 items were included in the additional analyses. The results were quite similar to the results reported in the Result section of the main text. The PVL curves for the initial fixations and for all of the forward fixations were also similar to Figure 2 and Figure 3.

	All 100 trials			**63 trials**		
	2-char	**4-char**	**Statistics**	**2-char**	**4-char**	**statistics**
First fixation duration	250	249	*ts* < 1	249	252	*ts* < 1
Gaze duration	266	355	$t1(31) = 7.04$, $p < .001$, $t2(99) = 15.95$, $p < .001$.	264	357	$t1(31) = 7.46$, $p < .001$, $t2(62) = 12.62$, $p < .001$.
Total time	296	403	$t1(31) = 7.15$, $p < .001$, $t2(99) = 13.64$, $p < .001$.	291	406	$t1(31) = 7.51$, $p < .001$, $t2(62) = 11.30$, $p < .001$.
Number of fixations	.73	1.41	$t1(31) = 17.47$, $p < .001$; $t2(99) = 28.78$, $p < .001$	.73	1.41	$t1(31) = 17.48$, $p < .001$; $t2(62) = 20.96$, $p < .001$
First pass skip rate	33%	6%	$t1(31) = 11.82$, $p < .001$; $t2(99) = 18.54$, $p < .001$	33%	6%	$t1(31) = 9.54$, $p < .001$; $t2(62) = 13.85$, $p < .001$
Duration of first of multiple fixations		251	First vs second fixation $F1(1,31) = 66.29$, $\eta_p^2 = .39$, $MSE = 487$, $p < .001$; $F2(1,99) = 69.10$, $\eta_p^2 = .41$, $MSE = 1480$, $p < .001$.		256	First vs second fixation $F1(1,31) = 26.98$, $\eta_p^2 = .47$, $MSE = 724$, $p < .001$; $F2(1,62) = 54.78$, $\eta_p^2 = .47$, $MSE = 750$, $p < .001$.
Duration of second of multiple fixations		219	One way ANOVA $F1(2,62) = 20.72$, $\eta_p^2 = .40$, $p < .001$, $MSE = 450$; $F2(2,198) = 31.54$, $\eta_p^2 = 0.24$, $p < .001$, $MSE = 1174$.		221	One way ANOVA $F1(2,62) = 14.09$, $\eta_p^2 = .31$, $p < .001$, $MSE = 782$; $F2(2,124) = 34.70$, $\eta_p^2 = 0.36$, $p < .001$, $MSE = 691$.
Duration of single fixation		246	Single vs second fixation $F1(1,31) = 19.90$, $\eta_p^2 = .39$, $MSE = 1151$, $p < .001$; $F2(1,99) = 43.58$, $\eta_p^2 = 0.31$, $MSE = 2738$, $p < .001$,		249	Single vs second fixation $F1(1,31) = 18.78$, $\eta_p^2 = .38$, $MSE = 683$, $p < .001$; $F2(1,62) = 49.29$, $\eta_p^2 = 0.45$, $MSE = 608$, $p < .001$,
Saccade length into target word	3.46	3.50	ts<1	3.50	3.55	ts<1
Saccade length out of target word	3.01	3.29	$t1(31) = 6.06$, $p < .001$; $t2(99) = 2.69$, $p <. 001$	3.00	3.25	$t1(31) = 4.24$, $p < .001$; $t2(62) = 2.33$, $p <. 05$

2-character condition

我们要尽可能弄清楚这个问题的原因和它同其他问题错综复杂的关系。

We have to try our best to understand the reason for the problem and its complex relation with other problems.

4-character condition

我们要尽可能弄清楚这个问题的来龙去脉和它同其他问题错综复杂的关系。

We have to try our best to understand the causing for the problem and its complex relation with other problems.

Figure 1.

An example of the stimuli. The target word is underlined in the example (but not during the experiment).

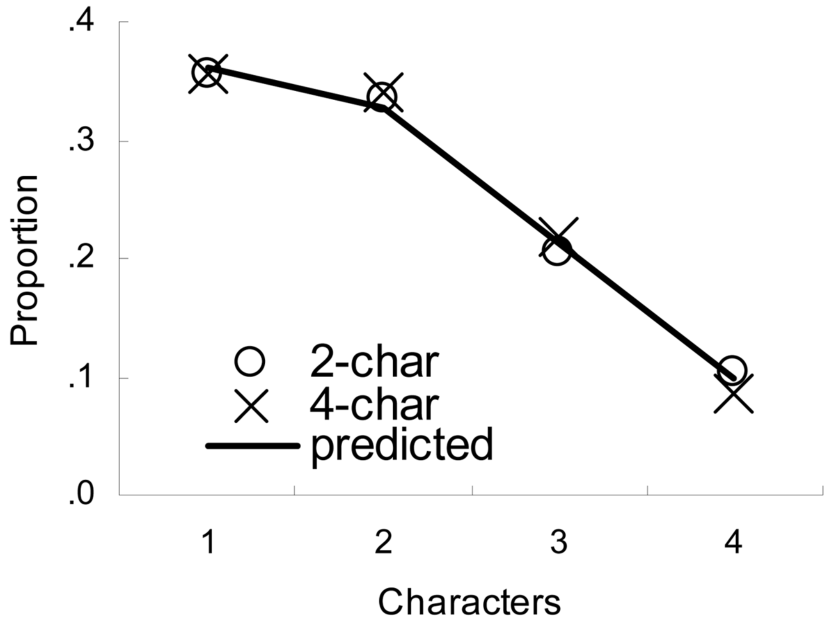

Figure 2.
Proportion of initial fixations at different character positions on a 4-character ROI aligned to the beginning of the target word. The solid line represents the values predicted by a constant-distance saccade model.

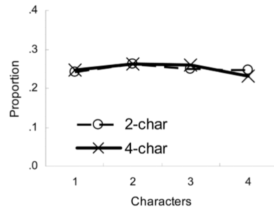

Figure 3.

Proportion of all forward fixations at different character positions on a 4-character ROI aligned to the beginning of the target word.

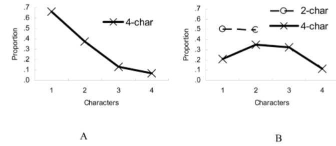

Figure 4.
PVL curves drawn separately for the first of multiple fixations (A), and single fixations (B). For the first of multiple fixations, only the 4-character condition was included since there were not enough trials for the 2-character condition.

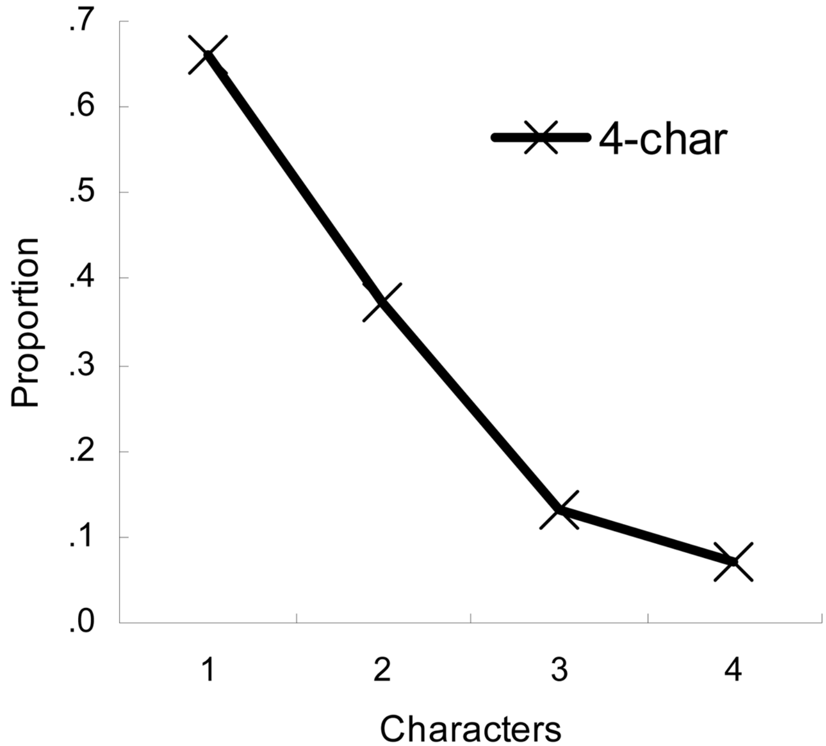

Figure 5.
Refixation probabilities as a function of initial landing position. Only the 4-character condition was included since there were not enough trials for the 2-character condition.

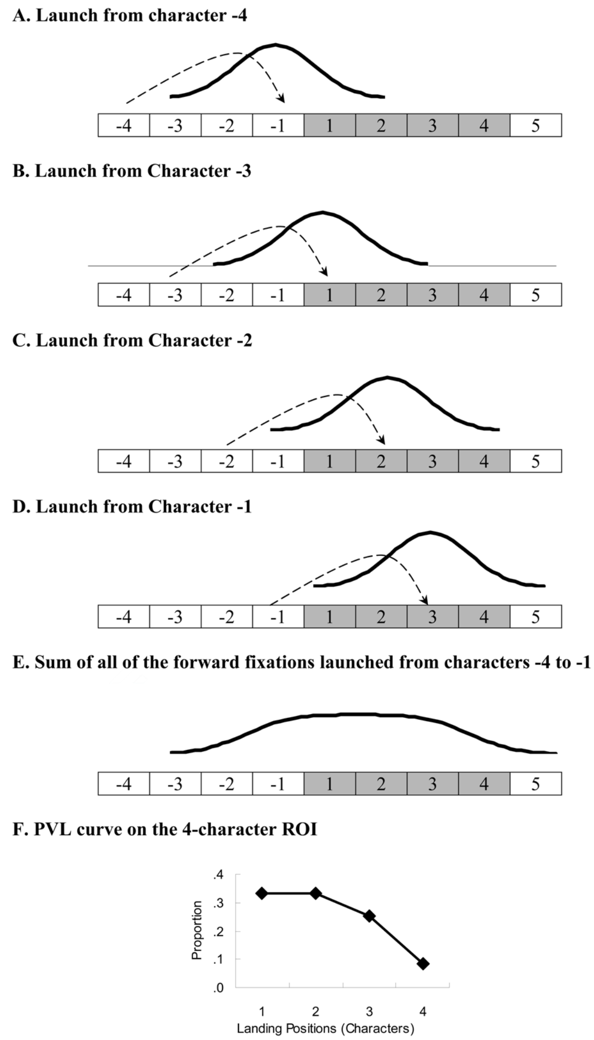

Figure 6.

A Hypothetical landing site distribution for Chinese words as a function of the launch site. Panels A–D represent the landing site distribution when saccades were launched from 4, 3, 2 or 1 characters to the left of the RO). The landing site distributions are approximately Gaussian in shape (with a mean of 2.6 characters and a standard deviation of 0.7 characters). The ROI is shaded in the boxes. Panel E represents the landing site distribution of all of the forward saccades launched from the four characters to the left of the ROI. Panel F is the PVL curve calculated from the landing site distribution shown in Panel E. The unit in the horizontal axis is based on characters, and all of the fixations landing on a character were counted. Note that the data in this figure are from a simulation.

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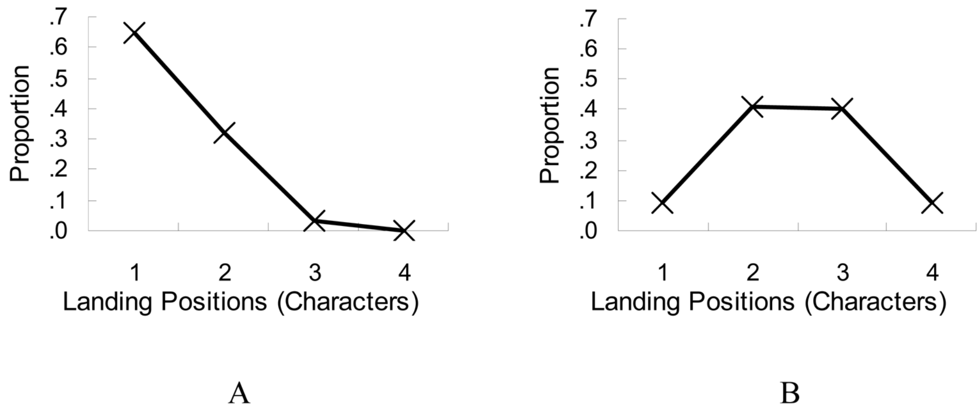

Figure 7.
Hypothetical landing site distribution for Chinese words drawn separately for first of multiple fixations (Panel A) and single fixations (Panel B).

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Table 1

Eye movement measures for the target word. The unit for all of the time measures is ms.

	2-character condition		4-character condition	
	Mean	**Standard error**	**mean**	**Standard error**
First fixation duration	250	4	249	5
Gaze duration	266	5	355	16
Total time	296	7	403	18
Number of fixations	0.73	0.04	1.41	0.07
First pass skip rate	0.34	0.03	0.07	0.01