Flexible Saccade-Target Selection in Chinese Reading

Ming Yan (1, 2, 3), Reinhold Kliegl (2), Eike Richter (2),

Antje Nuthmann (4), & Hua Shu (1)

(1) Beijing Normal University, China, (2) University of Potsdam, Germany,

(3) Peking University, China, & (4) University of Edinburgh, Scotland

Running head: Saccade Programs in Chinese Reading

Address for correspondence:

Reinhold Kliegl

Department of Psychology, University of Potsdam

Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany

Email: kliegl@uni-potsdam.de

Tel.: +493319772868, fax: +493319772793

Abstract

As Chinese is written without orthographical word boundaries (i.e., spaces), it is unclear whether saccade targets are selected on the basis of characters or words and whether saccades are aimed at the beginning or the center of words. Here, we report an experiment where 30 Chinese readers read 150 sentences while their eye movements were monitored. They exhibited a strong tendency to fixate at the word center in single-fixation cases and at the word beginning in multiple-fixation cases. Different from spaced alphabetic script, initial fixations falling at the end of words were no more likely to be followed by a refixation than initial fixations at word center. Further, single fixations were shorter than first fixations in two-fixation cases, which is opposite to what is found in Roman script. We propose that Chinese readers dynamically select the beginning or center of words as saccade targets depending on failure or success with segmentation of parafoveal word boundaries.

Flexible Saccade-Target Selection in Chinese Reading

The joys of reading are experienced under a remarkably large cultural diversity, ranging from alphabetic Western languages to the primarily character-based languages of Asia. This diversity not withstanding, all reading of written script starts with movements of the eyes, requires the extraction of visual, lexical, and semantic information, while respecting constraints of visual acuity and oculomotor control, before it arrives at propositions representing the meaning of the text. On the surface, this task appears to be a bit easier for alphabetic languages where clearly delineated words normally serve as convenient targets for mostly sequential inspection. So how do Chinese readers select their saccade targets given that this language uses a character-based script without spaces between words and with much ambiguity about word boundaries?

Research on eye-movement control in reading of alphabetic languages has yielded a key set of observations about where in a word we fixate and how fixation durations depend on this location. For alphabetic languages, there is the widely held assumption that saccade targeting is word-based: Each saccade intends to move the eyes to a specific word (cf., Radach & Kennedy, 2004). Therefore, the spatial component of eye-movement control in reading can be analyzed in a hierarchical way (McConkie, Kerr, & Dyre, 1994): First, which word is selected as the target of the next saccade, and second, where do the eyes actually land given the selection? The second question refers to the distribution of fixation positions in words. Fixation locations are most frequently slightly left of word center (i.e., the so-called preferred viewing location, PVL, Rayner, 1979). Actually, finding such a PVL is the most cited piece of evidence in support of word-based eye guidance in reading of alphabetic script (see Yang & Vitu, 2007, for discussion). Commonly held explanations for the characteristics of the PVL (McConkie, Kerr, Reddix, & Zola, 1988) rely on the assumption that the word center as the optimal viewing position is specified as the goal of saccade programs (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989).

Obviously, this strategy of saccade-target selection requires knowledge of the beginning and the end of the target word. The spaces between words provide exactly this information in alphabetic scripts. Indeed, if spaces are removed from English texts, reading efficiency suffers strongly (Malt & Seamon, 1978; Rayner, Fischer, & Pollatsek, 1998). More importantly for the present context, the PVL curve no longer follows a Gaussian shape, but decreases sharply and linearly from the beginning to the end of the word (Rayner et al., 1998; Rayner & Pollatsek, 1996; in response to Epelboim, Booth, Ashkenazy, Taleghani, & Steinman, 1997; Epelboim, Booth, & Steinman, 1994, who had claimed that they did not find a PVL effect). Kajii, Nazir, and Osaka (2001) and Saino, Hyönä, Bingushi, and Bertram (2007) also reported such a linear PVL curve for reading of Japanese, a script using a mixture of ideographic characters (Kanji) and syllabic characters (Hiragana, Katakana) and written without spaces. These results suggest that, in the absence of clear word boundaries, readers simply send their eyes to the beginning of the next word. Indeed, when Saino et al. inserted spaces between words in a pure Hiragana script, the linear “unspaced” PVL curve started to resemble the quadratic “spaced” PVL curve observed for alphabetic scripts.

In this article, we ask how readers select saccade targets in Chinese reading, a character-based script written from left to right without spaces. On the basis of the research just described one might expect the “unspaced” PVL curve, but the empirical evidence suggests a different pattern. Yang and McConkie (1999) and Tsai and McConkie (2003) obtained flat PVL curves and concluded that, unlike other languages, target selection is not word based in reading Chinese. Our evaluation of this claim requires a brief review of the Chinese writing system. Moreover, in addition to the PVL curve, we need to introduce other indicators of saccade-target selection (i.e., the optimal viewing position [OVP] curve based on refixation probabilities and the so-called Inverted Optimal Viewing Position [IOVP] effect referring to the observation that fixation durations in reading are longer for within-word fixation positions close to word center than for positions near word boundaries, Vitu, McConkie, Kerr, & O’Regan, 2001). We demonstrate that native readers of Chinese dynamically switch between the linear “unspaced” and the Gaussian “spaced” PVL curves. The choice between the two alternative strategies for target selection is probably linked to success or failure of parafoveal word segmentation.

The Chinese writing system

Chinese uses a non-alphabetic, character-based script with square-shaped forms of different levels of visual complexity (i.e., roughly the number of strokes) as basic writing units. There are two sets of modern Chinese writing systems, Simplified and Traditional Chinese (see Figure 1). Mainland of China reduced visual complexity of many characters in the 1950s, and thus uses the Simplified Chinese characters. The Traditional Chinese is mainly used in Taiwan and Hong Kong.

These characters take the same amount of horizontal extent in a passage of text, irrespective of their visual complexity. Words serve as targets for saccades in alphabetic scripts; spaces provide highly visible demarcations between them. Therefore, spaces actually introduce a theoretically relevant confound between the *conceptual* word (also known as the lexical item) which is defined by meaning and knowledge and the *orthographic* word which is defined by white spaces. The *concept of a word* also exists in Chinese. It is defined as a string of one to rarely longer than four characters; most words are two characters long. There are at least four differences hampering comparisons of words between Chinese and alphabetic scripts: (1) lack of explicit word boundaries, (2) semantic ambiguity of word boundaries, (3) differences in distribution of word length, and, according to current knowledge, (4) flat PVL curves.

Lack of explicit word boundaries. As shown in Figure 1, Chinese written text is a serial string of characters with punctuation but without spaces to tell readers where a word begins or ends. Thus, aside from punctuations, there are no explicit word boundaries in Chinese orthography. There are a few studies that focused on the consequences of lacking word boundaries. Readers did not benefit from the insertion of inter-word spaces for normal sentences (Liu, Yeh, Wang & Chang, 1974), but a benefit was observed for ambiguous (Hsu & Huang, 2000a) and difficult (Hsu & Huang, 2000b) sentences. Recently, Bai, Yan, Liversedge, Zang, and Rayner (2008) showed that texts with spaces inserted between words or with words highlighted were read as efficiently as visually familiar unspaced text according to global and local measures of fixation probabilities and fixation durations. Furthermore, when spaces were inserted between every character or when the inserted spaces generated nonwords, reading was slowed in comparison to normal script. The authors concluded that words and not individual characters are the unit of primary importance in Chinese reading. They did leave it open, however, whether this information is available early enough to be used for target selection in saccade programming.

Word-boundary disagreement and semantic ambiguity. Chinese readers very often disagree on word boundaries for the same text (Hoosain, 1992; Miller, Chen, & Zhang, 2007). For example, Miller et al. (2004) report an example of a 7-character string that was parsed in six different ways, ranging from a single to five words. In most cases, such word-boundary disagreement does not imply a difference in meaning. For example the string of characters “重要的” can be segmented into a word which is translated as “important”, or “重要 的” translated as “of importance”. This is similar to English, where “ice cream” can also be written as “icecream”. Sometimes, however, word-boundary disagreement leads to different meanings. This semantic ambiguity is best illustrated with a string of characters (e.g., “花生长” in Chinese), where it is not clear without context whether the word boundary within the string could be parsed as “花 生长” (flower growth) or “花生 长” (peanut growth). There are rare examples of this kind also for English. If written without space, the string of letters “busheater” could mean “bus heater” or “bush eater”. Inhoff and Wu (2005) examined how a sequence of 4 Chinese characters with word-segmentation ambiguity is parsed into words. They found evidence for parallel activation of all possible meanings in the perceptual span with subsequent inhibition of inappropriate candidates. They interpreted their results as evidence against a strictly serial assignment of characters to words. Wu, Slattery, Pollatsek, and Rayner (2008), however, failed to replicate this result with a preview-boundary manipulation and suggest that Inhoff and Wu's results might emerge rather late in processing and, therefore, do not conclusively rule out serial assignment. Given our interest in word-based PVL, OVP, and IOVP-curves, we used only sentences where independent raters agreed on semantic word boundaries. This way we also avoided interindividual differences in parafoveal word segmentation of the same sentences.

Perceptual span and distribution of word lengths. Irrespective of language, eye-movement control in reading is fundamentally constrained by the perceptual span, that is the region of effective vision from which useful information can be obtained during a fixation. The perceptual span comprises about 3-5 letters to the left and 12-15 letters to the right of the current fixation location in alphabetic languages (McConkie & Rayner, 1975). In terms of degrees of visual angle, Tsai and McConkie (2003) assumed that two-character Chinese words are equivalent to seven-letter English words. Similar to reading of alphabetic script, the perceptual span of Chinese readers is asymmetric, extending 1 character to the left of the current fixation location and 2 to 3 characters to its right (Tsai & McConkie, 1995; Inhoff & Liu, 1997; 1998). In most cases this area corresponds roughly to two words. Indeed, the large majority (i.e., 70% to 80%) of conceptually defined words in Simplified Chinese are two characters long (1 character: ~ 3%; 3 character: ~ 16%; 4 character and longer: 1% of words, Yu, Zhang, Jing, Peng, Zhang, & Simon, 1985). Thus, in terms of visual acuity, Chinese readers obviously could use word-based processing of a series of characters. Indeed, Tsai and McConkie showed that low frequency of word(s) at the next two character positions to the fixated one significantly increased the odds that the word was selected as the next saccade target. They also reported significant, but weaker effects of visual complexity (i.e., number of strokes) for the three characters to the right.

Flat PVL curves. As already mentioned above, given the flat PVL curves for these data, however, Tsai and McConkie (2003; see also Yang & McConkie, 1999) claimed that Chinese readers definitely do not select words as targets. They left it open whether characters can be used to this end or whether readers simply deploy saccades of fixed amplitude, granting some oculomotor error. For two reasons, we do not consider these results as conclusive. First, as reviewed above, there is already other research clearly indicative of word-based processing during reading Chinese, although it is not clear so far whether this word-based information is already available for target selection. Second and more importantly, Yang and McConkie (1999) and Tsai and McConkie (2003) did not control word-boundary ambiguity and this lack of control might have obscured word-based effects. Compared to reading with spaces between words, reading Chinese without control for word-boundary segmentation is like reading texts with different visual properties for different subjects. Consequently, landing positions derived from such material may contain too much noise because they represent a mixture of words with different visual properties for different subjects.

Target selection in reading of alphabetic script

The primary indicator of saccade target selection is the PVL curve. There are, however, other indicators that will prove useful to isolate differences in saccade targeting in Chinese reading. In reading of alphabetic scripts, properties of the process of target selection are not only inferred from the distribution of landing positions of fixations, but also from the probability of refixations as a function of landing position, and from fixation durations associated with landing positions. Moreover, differences between single-fixation and multiple-fixation cases need to be taken into account.

Preferred viewing location (PVL). PVL curves plot the frequency of fixations across the letters of words. They are typically normal distributions truncated at word boundaries, with a peak slightly to the left of word centers (McConkie *et al.* 1988; Nuthmann, Engbert, & Kliegl, 2005, 2007; Rayner, 1979). Peak and variance of PVL curves also depend on the distance of the previous fixation location to the beginning of the current word (i.e., the launch-site distance, McConkie et al., 1988): The PVL peak shifts towards the beginning and the end of the word for close and far launch sites, respectively, and the variance of the PVL curve increases with launch site. Apparently, primarily low-level processing rather than high-level word variables, affect landing positions. Some recent studies report very small linguistic influences on landing position (e.g., White & Liversedge, 2004) while other studies found no effects

(Radach & Kempe, 1993; Radach & McConkie, 1998; see Engbert & Nuthmann, 2008, for a review). Also, although readers tend to skip more often or fixate shorter on more predictable words, predictability has little influence on initial landing positions in words (Rayner, Binder, Ashby, & Pollatsek, 2001). Finally, in a recent “mindless” reading study in which subjects were asked to scan z-strings, landing position distributions were remarkably similar to those of normal reading (Nuthmann et al., 2007).

Optimal viewing position (OVP). OVP curves represent the refixation probability of a word as a function of initial fixation position. They are typically u-shaped with a clear minimum near the word center; that is, subjects are more likely to refixate a word if they initially land on the beginning or end of the word as compared to the center of the word (e.g., McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; O'Regan, Lévy-Schoen, & Pynte, 1984; Nuthmann *et al.*, 2005). Refixation probability is typically higher for fixations at word beginnings in comparison to word ends. Refixations are “costly” in terms of reading speed. Therefore, locations close to word center are presumably optimal for word processing. Refixations in alphabetic scripts are postulated to occur as a consequence of suboptimal initial landing positions (McConkie *et al.*, 1989).

PVL and OVP form the basis for the widely held assumption of word-based saccade targeting (e.g., Radach & Kennedy, 2004; see Vitu, 2003, for a different perspective). Accordingly, eye movements to a selected target word are directed to a functional target location at or near the center of that word, the location at which refixations are the least frequent (McConkie et al., 1989). Systematic and random oculomotor error causes the eyes to deviate from that location, giving rise to the PVL (McConkie et al., 1988). These assumptions on saccade targeting are implemented in current computational models of eye-movement control in reading (SWIFT: Engbert et al., 2002, 2005; E-Z Reader: Reichle et al., 1999, 2003).

Inverted optimal viewing position (IOVP). Somewhat paradoxically, fixation durations at the word center, that is at the optimal viewing position, are longer than those at the beginning and at the end of words, leading to an inverted u-shaped function of fixation duration over fixation position (Vitu et al., 2001). The IOVP effect holds both for single and first of multiple fixations but generally single fixations are longer than those of multiple-fixation cases (e.g., Kliegl, Nuthmann, & Engbert, 2006; Schilling, Rayner, & Chumbley, 1998). Nuthmann et al. (2005) linked this IOVP effect to mislocated fixations as a consequence of oculomotor errors (see section on PVL curves above); that is, fixations on unintended words. They claim that a new saccade program is started instantaneously if the intended target word is missed. On average, this will lead to decreased durations after mislocated fixations. Finally, because mislocated fixations are most likely at the beginning and end of words, the proposed mechanism generates the inverted u-shape for fixation durations when computed as a function of landing position. This account is implemented in the SWIFT model of eye-movement control during reading (Engbert, Nuthmann, Richter, & Kliegl, 2005; for alternative explanations see also McDonald *et al.*, 2005; Pollatsek, Reichle, & Rayner, 2006; Vitu, Lancelin, & d'Unienville, 2007).

In summary, there is quite some variance related to PVL curves across languages. For spaced alphabetic scripts, the PVL is quadratic with a peak in the word center. For unspaced alphabetic and Japanese script the PVL is linear with a peak at the word beginning. Finally, for unspaced Chinese script, the PVL appears to be flat. To our knowledge, there is no comprehensive report about PVL, OVP, and IOVP for Chinese or other character-based reading. Saino et al. (2007) reported a few post-hoc OVP and IOVP analyses for Japanese reading, but did not distinguish between single and multiple-fixation cases. Moreover, although we consider, for example, Bai et al.'s (2008) results as strong evidence for word-based processing during Chinese reading, we do not yet know whether locations in words are actually used as saccade targets. We expected that PVL, OVP, and IOVP curves differ between alphabetic and character-based scripts. If saccade targeting in Chinese reading is word-based, there should be a preference for a certain location within words as in alphabetic languages. In other words, we expect a quadratic "spaced" PVL with a peak close to the center of the conceptual word. Given that Chinese is written without spaces, however, we might also find the linear "unspaced" PVL with a peak at the beginning of the word, as suggested by reading of unfamiliar unspaced English (Rayner *et al.*, 1998) or familiar unspaced Japanese texts (Kajii *et al.,* 2001; Saino et al., 2007). Either PVL would not only constitute evidence against the proposition that target selection in Chinese reading is character-based or globally controlled, but is also likely to shed new light on the general mechanism of target selection during saccade programming when obvious markers such as spaces between words are missing.

Method

Subjects

Thirty students from the Beijing Normal University with normal or corrected to normal vision, who were native speakers of Chinese, participated in the eye-tracking experiment. The sessions lasted 30 to 40 minutes. Subjects received Yuan 10 for their participation. Another group of 20 students participated in a check of word-boundary agreement; they were paid Yuan 5 for their participation.

Material

Subjects read the Beijing Sentence Corpus (BSC) comprising 150 sentences. The sentences were selected from *People's Daily*, which is a newspaper with Simplified Chinese characters. Some of the sentences were slightly edited. The selection and edition of sentences aimed at removing possible semantic ambiguities and word boundaries disagreement. Sentences are 15 to 25 characters in length (M=21.0, SD=2.5), corresponding to 7 to 15 words (M=11.2, SD=1.6). Summed across sentences, the BSC comprises 1686 tokens of 936 words (types); 5.4%, 75.3%, 15.9%, and 3.3% of the words (types) are one to four characters long, respectively. This word-length distribution is representative for Chinese sentences (Yu *et al.*, 1985). The number of strokes per word, which is a rough index of its visual complexity, varies form 2 to 42 (M=15.6, SD=5.5); the percentages of number of strokes in the range of 1 to 10, 11 to 20, and above 20 are 16%, 68%, and 16%, respectively. Word frequencies were taken from the *Modern Chinese Word Frequency Dictionary* (Beijing Language Institute Publisher, 1986) based on 1.2

million words. They vary from 1 to 64,100 (M=403, SD=2454). The percentages of words with frequencies in the range of 0 to 10, 11 to 100, 101 to 1000, and above 1000 per million words are 21%, 40%, 33%, and 6%, respectively.

The reading material was selected with as little word-boundary ambiguity as possible. Agreement on word boundaries was tested in a pretest of word-boundary judgment. Each subject coded 75 sentences into word units. The percentage of agreements was calculated relative to the experimenter's word segmentation on boundary/non-boundary out of an N-character-sentence with N-1 boundary candidates. The average agreement was 97% (ranging from 80% to 99.5%). The coding method is described in detail in the Appendix.

Apparatus

Eye movements were calibrated and recorded binocularly with an EyeLink II system (500 Hz). Single sentences were presented on the one third vertical position from the top of the screen of a 19-inch ViewSonic G90f Monitor (1024 x 768 resolution; frame rate 100 Hz; font: Song 32) controlled by a P4 computer running at 2.8 GHz under a Windows XP environment. Subjects were seated 43 cm in front of the monitor with the head positioned on a chin rest.

Procedure

Subjects were calibrated with a standard nine-point grid for both eyes. After validation of calibration accuracy, a fixation point appeared on the left side of the monitor. If the eye tracker identified a fixation on the fixation spot, the fixation point disappeared and a sentence was presented such that the center of the first character in the sentence appeared at the fixation point position.

Subjects were instructed to read the sentences for comprehension, then fixate a dot in the lower right corner of the monitor, and finally press a button on a joystick to signal the completion of a trial. The sentence was replaced by an easy yes-no question pertaining to the current sentence on 28% of the trials, which the participant answered with two different joystick buttons. These questions served primarily to ensure reading for comprehension. All participants correctly answered at least 80% of them. Subsequent to the response, a fixation spot indicating the beginning of the next trial was presented. Fixation of the fixation point initiated presentation of the next sentence or a drift correction. The experimenter carried out an extra calibration if the tracker did not detect both eyes within a pre-defined window around at the initial fixation point.

Data analysis

Data were reduced to a fixation format using an algorithm for the binocular detection of saccades (Engbert & Kliegl, 2003). Reading saccades were defined as saccades with amplitudes of at least half a character space (0.4 deg). Further analyses were based on software developed for the analysis of the Potsdam Sentence Corpus reading data (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Kliegl et al., 2006; Nuthmann et al. 2005). Sentences containing a blink or loss of measurement were deleted. Analyses were based on fixations measured in the right eye. Fixations were horizontally allocated to zones representing 50% of a character corresponding to a zone width of 16 pixels. For example, a Chinese two-character word comprises 4 zones, numbered from 1 to 4 sequentially. Fixation durations shorter than 75 ms or longer than 1000 ms were excluded from analyses, thus retaining 98% of all fixations.

Results

Results are presented in four sections. We report inferential statistics for several landing-position phenomena: (a) PVL curves (i.e., landing position distributions) for different types of fixations, (b) OVP functions (i.e., refixation probabilities as a function of landing position), (c) incoming amplitudes and launch sites analysis, and (d) the dependence of fixation durations on fixation position for single and first-of-two fixations (i.e., the IOVP effect, Vitu *et al.*, 2001; Nuthmann *et al.*, 2005).

First fixation landing position distributions

In Figure 2 shows the distribution of landing positions (McConkie *et al.*, 1988; Vitu *et al.*, 2001; McDonald & Shillcock, 2004) for initial fixations (i.e., first fixations irrespective of the number of fixations on that word) separately for words ranging in length from one to four characters. In an analysis of variance of fixation probabilities, we specified half-character fixation zone as nested within word length, leaving out the final zone to avoid singularity due to the probabilities summing to 1.0. For each word length the probability of fixations differed between character zones $F(2,58)=2.9$, $p<.1$; $F(4,116)=21.9$, $p<.001$; $F(6,174)=22.5$, $p<.001$), for words of two to four characters, respectively. Thus, different from Tsai and McConkie (2003), fixation probabilities vary by landing positions.

Polynomial trends of fixation probabilities over position inform about the shape of the PVL curve. Negative linear trends indicate a significant preference for targeting the beginning over the end of words and negative quadratic trends (i.e., convex curvature) indicate a preference for the center of words. The linear trend was significant for 3- and 4-character words [3: $F(1,29) = 45.4$, $p<.001$; 4: $F(1,29) = 124.0$, $p<.001$]; similar non-significant numerical trends are also visible for 1- and 2-character words. These results are similar to results reported by Rayner *et al.* (1998) for reading unspaced English text, and Kajii *et al.* (2001) for reading Japanese. The significant quadratic trends for 2-, 3-, and 4-character words capture the convex shape indicative of a preference for targeting the word center [2: $F(1,29) = 4.6$, $p<.05$); 3: $F(1,29) = 34.8$, $p<.001$; 4: $F(1,29) = 4.6$, $p<.05$]. These additive effects generate the asymmetric curvatures shown for 2-, 3-, and 4-character words in Figure 2. Convex PVL curves have been observed during reading of spaced scripts (McConkie *et al.*, 1988; McDonald & Shillcock, 2004; Vitu *et al.*, 2001), but the present ones are broader and much less peaked than those.

The differences between the relative weights associated with selecting the center or the beginning of words as saccade target are striking when PVLs are plotted for different word lengths (2-4 characters) and launch site distances (1-3 characters; also displaying half characters) as shown in Figure 3 (McConkie et al., 1988), again displaying initial fixations (i.e., first fixations irrespective of the number of fixations on that word). Solid lines are best-fitting normal curves, and vertical dotted lines represent the means of the fitted curves. The canonical interpretation of these curves is the following: The eyes target the word center, because it represents the OVP. For far launch sites this OVP is undershot, while for very close launch site the OVP is overshot. This interpretation is plausible for alphabetic languages where we almost always observe convex PVLs. The Chinese-reading PVLs of Figure 3 suggest an alternative interpretation: When the launch distance is smaller than two characters, the word center dominates as the saccade target (like in alphabetic languages), but for longer launch distances the word beginning is the dominant saccade target. The latter pattern (exceptional in alphabetic languages) was observed for lauch-sites of 7 letters for 4-letter words in German, that is only for the shortest word length and the maximum launch site examined (Nuthmann et al., 2005).

The negative linear and quadratic trends may reflect different strategies in aiming for words with and without a clear orthographical word boundary. First fixations represent a mixture of single-fixation and first-of-several fixation cases. Possibly, these cases are preferentially linked to the linear and quadratic PVL curves. Therefore, in the following analyses, we consider single-fixation cases and two-fixation cases separately. Means and standard deviations of landing positions for first, single and first-of-two fixations is also provided in Table 1.

Landing position distribution in single-fixation cases

For single-fixation cases, reading data from alphabetic languages typically show a mean landing position which is close to word center (McDonald & Shillcock, 2004; Kliegl *et al.*, 2006) suggesting that reading saccades target the center of the word. Therefore, finding preferred viewing locations for single fixations in Chinese (i.e., in the absence of clear word boundaries) would clearly indicate word-based eye-movement control. In Figure 4-A, data are plotted separately for words of two, three, and four characters (see also Table 1). An analysis of variance on fixation probabilities (normalized to sum to one for each word length within each reader and leaving out the final zone to avoid singularity) indicates that single-fixation landing position differs significantly among character-zones in the word ($F(2,58) = 15.8$, $p<.001$; $F(4,116) = 20.4$, $p<.001$; $F(6,174) = 7.4$, $p<.001$). For words of two and three characters, both linear and quadratic trends are reliable (linear trends: $F(1,29) = 16.7$, $p<.001$; $F(1,29) = 6.4$, $p<.05$; quadratic trends: $F(1,29) = 14.4$, $p<.01$; $F(1,29) = 63.1$, $p<.001$, for words of two and three characters, respectively). For words of four characters, the quadratic trend is significant ($F(1,29) = 62.1$, $p<.001$) while the linear trend is marginally significant ($F(1,29) = 3.7$, $p<.1$).

Thus, in general, the polynomial trends replicate the mixture of the two word-targeting strategies reported above for all first-fixation cases. As evident from Figure 4A, for single fixations the weight has visibly shifted toward the convex quadratic trend indicative of a higher preference for targeting the center of words. The landing position distributions of single-fixation cases are similar to the ones observed in English (Rayner, 1979; McDonald & Shillcock, 2004). Thus, at least to some extent, Chinese readers separate character strings into word units with parafoveal preprocessing, and then select the word center as saccade target, where processing is known to be the most efficient.

Landing position distribution of first fixation in two-fixation cases

Figure 4B shows the distributions for first fixations in 2-fixation cases. Data are plotted separately for words of two to four characters (see also Table 1). Analysis of variance indicates that first fixation landing position in 2-fixation cases differs significantly among character-zones in the word ($F(2,58) = 102.8$, $p<.001$; $F(4,116) = 43.2$, $p<.001$; $F(6,174) = 23.9$, $p<.001$). For words of two characters, both negative linear and positive quadratic trends are reliable ($F(1,29) = 122.2$, $p<.001$; $F = 31.8$, $p<.001$, respectively). For words of three and four characters, only the linear trend is significant ($F(1,29) = 163.2$, $p<.001$; $F(1,29)= 283.7$, $p<.001$) but not the quadratic trend ($F(1,29) = 2.0$, $p>.1$; $F(1,29)= 2.8$, $p>.1$). Note that quadratic trends indicate concave PVL for first-of-two fixation cases rather than convex PVL curves for single-fixation cases.

In summary, when a word is read with two successive fixations, the first fixation most frequently lands at the very beginning of that word. Thus, compared to single fixations we observe a pronounced shift of the PVL from word center to the word beginning. This overall pattern is in agreement with what has been observed for alphabetic languages (Nuthmann, 2006; see also McDonald & Shillcock, 2004), but the dissociation appears to be stronger in Chinese. The observed range of fixation probabilities is about twice as large for first-of-two than for single fixations (see y-axes of Figures 4A and 4B). In general, the results suggest that there is an overall stronger tendency for targeting the beginning of words in Chinese than in alphabetic languages.

Refixation probability

In alphabetic languages, OVP curves show an asymmetric u-shaped form (e.g., McConkie et al., 1989). As for the Chinese data, Figure 5 presents refixation probability (i.e., the probability of making at least one additional fixation on the word before leaving it), as a function of the position of the first fixation for words ranging from 2 to 4 characters in lengths. If the first fixation is placed at the very beginning of the word, there is an increased likelihood that the word will receive an immediate refixation. This is true for all word length and qualitatively agrees with what has been observed for alphabetic languages. However, across within-word fixation positions, Chinese readers produce monotonically decreasing rather than quadratic refixation probability functions. Thus, in contrast to alphabetic languages, there is no increase in refixation probability if the first fixation is close to the end of the word. Basically, Chinese readers appear to have very little need for intra-word regressions directed from the end to the beginning of the word.

Launch site distance and word length

Table 2 shows the mean incoming saccade amplitudes and launch sites for single fixations and first of multiple fixations for 2- to 4-character words. Launch site is defined as the location of the last fixation, while launch site distance is the number of characters from the launch site to the beginning of the fixated word. ANOVAs for all word lengths clearly indicate that saccades leading to single fixations are always launched closer to the word boundary than first fixations ($F(1,29)=30.0$, $p<.001$; $F(1,29)=21.7$, $p<.001$; $F(1,29)=25.7$, $p<.001$, for 2- to 4-character words, respectively) and that at the same time saccade amplitudes are significantly longer than those leading to a first of multiple fixations ($F(1,29)=10.0$, $p<.01$; $F(1,29)=31.1$, $p<.001$;

$F(1,29)=24.0$, $p<.001$, for 2- to 4-character words, respectively).

The results thus show an interesting dissociation: As compared to first fixations, single fixations are preceded by fixations nearer to the current word (i.e., shorter launch site distance) and are aimed at with longer saccades (longer incoming saccade amplitudes, Table 2). This suggests that a fixation closer to the following word makes it more likely to obtain information about its borders, thus enabling the oculomotor system to aim at the PVL with longer saccades. In contrast, a fixation far from the following word makes it less likely to obtain information about its borders, and hence prevents the oculomotor system from aiming at the PVL. It seems that in such cases word beginnings are the aim of most saccades.

Fixation durations as a function of landing position

Figure 6 displays single-fixation and first-of-two fixation durations for words of two characters in length as a function of initial landing positions. Means and standard deviations of single-fixation duration, gaze duration, first-fixation duration and refixation duration in two-fixation cases for words of two characters in length are listed in Table 3. The restriction to two-character words is due to the high percentage of words of this length in the BSC and in Chinese texts in general. The results replicate the well-known IOVP effect (Vitu *et al.*, 2001; Nuthmann *et al.*, 2005; McDonald, Carpenter, & Shillcock, 2005), but the effect is much weaker for reading Chinese than for reading alphabetic languages.

For single fixation durations, in an ANOVA with four levels of character zone, there was a significant quadratic trend $F(1,29) = 7.8$, $p<.01$. Further, the data reported in Table 3 suggest a trend towards a tradeoff between durations of first fixation and refixation in 2-fixation cases: The duration of first fixation is longest when the initial fixation is at the center of a word while the duration of the second fixation shows the mirrored pattern (Vitu *et al.*, 2001; Nuthmann *et al.*, 2005; McDonald, Carpenter, & Shillcock, 2005). It appears that the longer the eyes remain at the initial location, the less processing will be required from the second location, and the shorter will be the second fixation duration. In the ANOVA, however, only refixation durations differed reliably between the four positions ($F(3, 81) = 3.2$, $p<.05$) while only the linear trend was significant ($F(1,27) = 4.6$, $p<.05$), but not the quadratic trend ($F(1,27) = 1.5$, $p>.1$). For first fixation durations, neither the quadratic trend nor the linear trend was significant (all Fs<1, see also Figure 6). Taken together, we find a weak, but statistically reliable IOVP effect for single-fixation duration, but no reliable effect for the first-fixation duration in two-fixation cases.

Somewhat surprisingly, first-fixation durations in two-fixation cases are longer than single-fixation durations (Table 3, Figure 6). For statistical inference, we employed a repeated-measure ANOVA on fixation duration with fixation type (single fixation vs. first fixation in two-fixation cases) and half-character zone (1 to 4) as factors. There was only a significant main effect of fixation type ($F(1,27) = 16.4$, $p<.001$), while neither the main effect of half-character zone ($F(3, 81) = .8$, $p>.1$) nor the interaction were significant ($F(3, 81) = .4$, $p >.1$).

The difference between first-fixation duration in two-fixation cases and single-fixation duration that we observed in Chinese reading is clearly different from reading in alphabetic languages. In these languages single fixations are longer than the first fixation in two-fixation cases (Kliegl *et al.*, 2006; Schilling et al.,1998).

Word-based targeting vs. simulation of fixed-amplitude strategy

In the final results section, we test one specific saccade targeting assumption based on both empirical and simulated data. About 80% of written Chinese words are 2 characters words. Yang and McConkie (2004; see also Yang & Vitu, 2007) argue that early saccades (i.e., those preceded by fixation durations of less than ~150 ms) are generated without explicit target specification; visual or lexical properties of upcoming units only influence target specification when fixations durations are long enough. Following such reasoning and given the dominance of two-character words in Chinese, one might want to argue that Chinese readers always use a fixed-amplitude strategy, that is, saccades are always programmed to be of constant length with a certain distribution of random errors. In other words, given the high predictability of the word-length environment during reading Chinese, it may be more efficient to go with a fixed-amplitude strategy and completely switch off parafoveal word segmentation for the purpose of saccade-target selection.

As a test of the fixed-amplitude strategy, the data were reprocessed in the following way: For each reader and sentence, the original sequence of saccade lengths was destroyed by random permutation while the word order and thus sequence of word lengths was preserved (Kliegl, 1981; MacDonald & Shillcock, 2005). The randomization altered the assignment of fixations to words in a sentence, providing a random baseline measure. Taken together, this procedure simulates fixed saccade amplitudes which are subject to random error, while we derive the distribution of the random error component from the empirical saccade-length distribution. To obtain confidence intervals, we repeatedly shuffled the sequence of amplitudes from the same empirical distribution (Figure 7).

The differences between the observed empirical data and the random-baseline simulations allows us to tease apart word-based targeting and the fixed-amplitude strategy. First, the fixed-amplitude strategy (i.e., the simulation) cannot explain that skipping probability is affected by word predictability. As shown by the lines in Figure 8A, we find that skipping probability increases with word predictability for words ranging from 1 to 4 characters (see also Rayner et al., 2005, 2007). As expected, the observed values clearly fall outside the 95% confidence intervals of a simple simulation of the fixed-amplitude strategy.

Second, the fixed-amplitude strategy does not adequately recover how various fixation probabilities depend on word length and word frequency. As shown in Figure 8B, the probability of single fixations is strongly underestimated and the probability of skipping is strongly overestimated for words longer than one character and for low frequency words. Refixation probabilities are in reasonable agreement with the fixed-amplitude strategy but this result does not carry much weight given the evidence against it.

Finally, contrary to the prediction from fixed-amplitude strategy, we already know that the average incoming saccade amplitude for single fixations was significantly longer compared to those leading to first fixations (see Table 2). Taken together, the simulation of the fixed-amplitude strategy suggests that, in general, skilled Chinese readers do not use a fixed-amplitude strategy, which is in agreement with what has been demonstrated for alphabetic script (e.g., McConkie et al., 1988; Reilly & O'Regan, 1998). Nevertheless, Chinese is different and this account might still be valid under some circumstances, for example, for beginning readers of Chinese. Beginning readers make much shorter saccades and consequently show character-by-character reading (Feng et al., 2005). For them, a fixed-amplitude strategy might be the optimal way to read. If so, then at some point in development there must be a transition to word-based targeting. Of course, this prediction needs empirical confirmation.

General Discussion

With the current study we aimed to consolidate previous experimental evidence for a word-based targeting strategy in reading of Chinese sentences. For example, Bai et al. (2008) showed that with spaces inserted at word boundaries reading is as efficient as it is for normal script, but if inserted spaces generate nonwords, reading is slowed. One open question has been whether words rather than characters are specified as targets in saccade programs. To address this question, we examined PVL, OVP, and IOVP curves and identified significant differences between reading of alphabetic and Chinese character-based scripts. First, single fixations are generally shorter than first fixations in two-fixation cases of two-character words. In contrast, in alphabetic scripts single fixations typically last longer than first fixations (e.g., Kliegl et al., 2006; Schilling et al., 1998). Second, differences in landing positions (PVL) for first fixations as opposed to single fixations appear to be more pronounced in Chinese: For single fixations, in both writing systems fixation locations are clustered around the center of the word. For the first fixation in two-fixation cases, however, we observe a shift in PVL towards the beginning of the word, while this shift is more pronounced in Chinese as compared to alphabetic script. Third, only initial fixations at the beginning of the word, but not at the end of the word, trigger refixations. Thus, there is no evidence for the u-shaped OVP curve typical for alphabetic script. Finally, the fixation-duration IOVP effect is only observed for single fixations, but not for the first fixation in two-fixation cases. Given the similarity between Chinese and alphabetic reading in the sensitivity of fixation durations to variables such as word frequency and predictability (Rayner, Li, Juhasz, & Yan, 2005; Tsai & McConkie, 2003; Yan, Tian, Bai, & Rayner, 2006), the qualitative differences at the level of saccade targeting reported here are quite striking.

The basic saccade target in Chinese reading

In most models of isolated word recognition in Chinese (Perfetti, Liu, & Tan, 2005), the character or radical (i.e., a component of a compound character) is assumed to be the basic unit. However, these units may not represent the target for saccade programs in continuous reading of Chinese. There are currently two conflicting theoretical proposals with good arguments for each of them.

On the one hand, given that characters are the basic unit and that they take the same horizontal space irrespective of visual complexity, the character-based targeting account suggests that these units serve as saccade targets during reading, that is the eyes are directed to selected characters. McConkie and colleagues (Yang & McConkie, 1999; Tsai & McConkie, 2003) took their results as evidence to support the idea that characters may be the basic reading unit in Chinese.

On the other hand, although most characters have a meaning of their own, this meaning can be strongly qualified or completely different if the same character occurs in the context of another word or is actually part of another word. For example, the character *打* means *make* in the word 打电话 (make a phone call), *play* in 打篮球 (play basketball), and *take* in 打车 (take a taxi). Thus, word meaning is more important than the individual characters that make up the word.

Word segmentation in the parafovea

Why are there two types of reading patterns in Chinese reading? For alphabetic scripts, readers presumably estimate/compute the position(s) of the upcoming word(s) in the parafovea and program a saccade to the center of the selected word (see Reilly & O'Regan, 1998, for computer simulations of several saccade targeting strategies). This assumption is also implemented in most eye-movement control models, such as SWIFT (Engbert *et al.*, 2005) and E-Z Reader (Reichle, Rayner, & Pollatsek, 2003; Pollatsek, Reichle, & Rayner, 2006) and was used in an extension of this model to Chinese reading (Rayner, Li, & Pollatsek, 2007). This process assumes clear orthographical word boundaries (i.e., low spatial frequency information).

If saccade targeting in Chinese reading is word-based, as suggested by the analysis of single fixations, the story is similar to alphabetic reading. For single fixations, landing positions were distributed with a preference near word center, similar to findings from alphabetic reading (McDonald & Shillcock, 2004; Nuthmann & Kliegl, in press; Rayner, 1979). Chinese readers may simply use other information than spaces to accomplish word segmentation in the parafovea (e.g., differences in frequency of characters at the end and the beginning of words or meaning of the first character of the upcoming word). Once they choose the saccade target, word processing and saccade generation proceed as in alphabetic scripts. However, the differences between single-fixation and two-fixation cases clearly suggest a second strategy during reading Chinese.

For two-fixation cases, the PVL peak shifted to the word beginning, similar to what was reported for reading of unspaced English text (Rayner *et al.*, 1998) and unspaced Japanese text (Kajii *et al.,* 2001; Saino et al., 2007). Obviously, readers pay more attention to the beginning part of a word once there are difficulties in word segmentation (Rayner *et al.*, 1998). Despite the differences in PVL peak between single-fixation and first-of-two fixation cases, these results are also compatible with word-based targeting. Only a flat PVL could be interpreted as support for character-based targeting or some form of global control.

As a tentative proposal we suggest that the two Chinese PVL curves reflect differences in processing demands related to parafoveal word segmentation. In other words, we suggest a two-stage process during Chinese reading: If parafoveal word segmentation is successful within the usual time limit for target selection, saccades are aimed at the word center to process the information of the to-be-fixated word in a single fixation. If not, readers aim for the beginning of the next word with a focus on word segmentation and an increased likelihood for a forward refixation.

Traditionally, a shift in first-fixation PVL toward word beginnings is explained as a consequence of a longer launch-site distance combined with a general undershoot tendency of the oculomotor system (McConkie et al., 1988; Nuthmann et al., 2005). Therefore, we plotted the landing position distributions as a function of launch site for various word lengths (Figure 3). Indeed, as for alphabetic scripts, the PVL peak shifts towards the word beginning with increases in launch site. There is a major difference however: In alphabetic scripts, the peak of the fitted Gaussian curve is always on the target word (e.g., Figure 6 in Nuthmann et al., 2005). In the Chinese data, the peak is estimated to occur *befor*e the target word in 10 of 18 PVL curves. Moreover, compared to single fixations, first fixations were not only characterized by a longer mean launch site distance, but also by shorter incoming saccade lengths. Such an adjustment in saccade amplitude is consistent with the proposal that those saccades indeed aim at the beginning of the word. Therefore, different from the traditional explanation, we propose that the PVL curves result from a superposition of two PVLs, one for the word center and one for the word beginning. Conclusive tests, however, will require a larger data base than the one presently available.

The hypothesis that readers first fixate at the word beginning in two-fixation cases to accumulate more information about word segmentation is also supported by the difference between single-fixation durations and first-fixation durations in two-fixation cases. In English and German reading, first fixations in two-fixation cases are typically shorter than single fixations (Kliegl *et al.*, 2006; Schilling *et al.*, 1998) whereas in Chinese reading they are longer. These increased first-fixation durations are strongly suggestive of problems with word segmentation. Low frequency, low contextual predictability, and high visual complexity may contribute to these problems. In other words, readers spend extra time with fixations landing at word beginnings in order to gather information about where the currently fixated word ends. Note that Saino et al. (2007) also reported long gaze durations for PVL at the beginning of words in Japanese script.

Finally, refixations in alphabetic scripts are postulated as a consequence of suboptimal initial landing positions (McConkie *et al.*, 1989; but see McDonald & Shillcock, 2004, arguing that first-fixation positions close to word beginnings are a consequence of refixation pre-planning). If two-fixation cases in Chinese, as in Western languages, were to reflect only oculomotor errors, we would expect a similar probability of refixations at both ends of the fixated word (Epelboim *et al.*, 1994; McConkie *et al.*, 1989; Nuthmann *et al.*, 2005; Rayner *et al.*, 1996; Vitu *et al.*, 1990; Vitu *et al.*, 2001). However, this is not the case in Chinese reading where first fixations at the beginning of words are much more likely to be followed by refixations than fixations at the end of words.

Our analyses are moot about what factors determine the success/failure of parafoveal word segmentation. For a review of word properties available early enough in alphabetic scripts to this end we refer to a recent article by Juhasz, White, Liversedge, and Rayner (2008). Reasonably, the saliency of visual and morphological properties will also be used by Chinese readers. Also, unlike for alphabetic scripts, parafoveal semantic information of non-compound characters is available very early (Yan, Richter, Shu, & Kliegl, in press). We suspect that visual complexity will be an additional important factor. Tsai & McConkie (2003) reported an increased likelihood for fixating visuall complex characters in position 1 to 3 next to fixated one. Kajii et al. (2001) reported that the linear PVL curve for Japanese script was observed for words composed of pure Kanjii words or mixed Kanji-Hiragana word with Kanji-initial characters. The linear PVL, however, was also observed during reading of pure Hiragana script (Saino et al., 2007).

In conclusion, reading unspaced text challenges the assumption that word centers are always the target of saccade programs. The analyses of PVL, OVP, and IOVP in reading Chinese sentences revealed a remarkable flexibility in this respect. Readers appear to go for the word center when words are read with single fixations and for the word beginning when more than one fixation is needed. The latter is likely to be tied to problems of parafoveal word segmentation. Interestingly, this strategy was also reported for unpracticed reading of unspaced English text (Rayner, Fischer, & Pollatsek, 1998). Thus, it is likely that both types of targeting are available to all readers independent of the specific language or cultural context.

References

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

Engbert, R., & Kliegl, R. (2003). Microsaccades uncover the orientation of covert attention. *Vision Research, 43*, 1035-1045.

Engbert, R., & Nuthmann, A. (2008). Self-consistent estimation of mislocated fixations during reading. *PLoS ONE, 3*, e1534.

Engbert, R., Nuthmann, A., Richter, E., & Kliegl, R. (2005). SWIFT: A dynamical model of saccade generation during reading. *Psychological Review, 112*, 777-813.

Epelboim, J., Booth, J. R., Ashkenazy, R., Taleghani, A., & Steinman, R. M. (1997). Fillers and spaces in text: The importance of word recognition during reading. *Vision Research, 37*, 2899-2914.

Epelboim, J., Booth, J. R., & Steinman, R. M. (1994). Reading unspaced text: Implications for theories of reading eye movements. *Vision Research, 34*, 1735-1766.

Feng, G., Miller, K. F., Shu, H., & Zhang, H. C. (2005). Orthography and the Development of Reading Processes: An Eye Movement Study of Chinese and English. Paper submitted to *Cognition*.

Hoosain, R. (1992). Psychological reality of the word in Chinese. In H. C. Chen & O. J. L. Tzeng (Eds.), *Language processing in Chinese* (pp. 111-130). Elsevier.

Hsu, S-H. & Huang, K.-C. (2000a). Interword spacing in Chinese text layout. *Perceptual and Motor Skills, 91*, 355-365.

Hsu, S-H. & Huang, K.-C. (2000b). Effects of word spacing on reading Chinese text from a video display terminal. *Perceptual and Motor Skills,* 90, 81-92.

Inhoff, A. W., & Liu, W. (1997). The perceptual span during the reading of Chinese text. In H. C. Chen (Ed.), *Cognitive processing of Chinese and related Asian Languages* (pp. 243-266): The Chinese University of Hong Kong Press.

Inhoff, A. W., & Liu, W. (1998). The perceptual span and oculomotor activity during the reading of Chinese sentences. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 20-34.

Inhoff, A.W., & Wu, C. (2005). Eye movements and the identification of spatially ambiguous words. *Memory & Cognition, 33*, 1345-1356.

Juhasz, B.J., White, S.J., Liversedge, S.P., & Rayner, K. (2008). Eye movements and the use of parafoveal word length information in reading. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 1560-1579

Kajii, N., Nazir, T. A., & Osaka, N. (2001). Eye movement control in reading unspaced text: the case of the Japanese script. *Vision Research, 41*, 2503-2510.

Kliegl, R.(1981). *Eye movements in reading: An attempt to separate perceptual and psycholinguistic factors.* MA Thesis. University of Colorado.

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General, 135*, 12-35.

Kohsom, C., & Gobet, F. (1997). Adding spaces to Thai and English: Effects on reading. *Proceedings of the Cognitive Science Society, 19,* 388-393.

Liu, I.M., Yeh, J.S., Wang, L.H., & Chang, Y.H. (1974). Effects of arranging Chinese words as units on reading efficiency. *Chinese Journal of Psychology,* 16, 25-32.

Malt, B.C., & Seamon, J.G., (1978). Peripheral and cognitive components of eye guidance in filled-space reading. *Perception & Psychophysics, 23,* 399-402.

McConkie, G. W., Kerr, P. W., & Dyre, B. P. (1994). What are “normal” eye movements during reading: Toward a mathematical description. In J. Ygge & G. Lennerstrand (Eds.), *Eye movements in reading* (pp. 315-328). Oxford: Pergamon Press.

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations on words. *Vision Research, 28*, 245-253.

McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception & Psychophysics, 46*, 245-253.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception and Psychophysics, 17*, 578-586.

McDonald, S. A., Carpenter, R. H. S., & Shillcock, R. C. (2005). An anatomically-constrained, stochastic model of eye movement control in reading. *Psychological Review, 112*, 814-840.

McDonald, S. A., & Shillcock, R. C. (2004). The potential contribution of preplanned refixations to the preferred viewing location. *Perception & Psychophysics, 66*, 1033-1044.

McDonald, S. A., & Shillcock, R. C. (2005). Toward an appropriate baseline for measures of eye movement behavior during reading. *Journal of Experimental Psychology: Human*

Perception and Performance, 31, 584-591.

Miller, K. F., Chen, S. Y., & Zhang, H. C. (2007). *Where the words are: Judgments of words, syllables, and phrases by English and Chinese speakers*. Unpublished manuscript, University of Michigan.

Nuthmann, A. (2006). *The "Where" and "When" of Eye Fixations in Reading.* Doctoral Dissertation. University of Potsdam. URN:http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-7931.

Nuthmann, A., Engbert, R., & Kliegl, R. (2005). Mislocated fixations during reading and the inverted optimal viewing position effect. *Vision Research, 45*, 2201-2217.

Nuthmann, A., Engbert, R., & Kliegl, R. (2007). The IOVP effect in mindless reading: Experiment and modeling. *Vision Research, 47*, 990-1002.

Nuthmann, A., & Kliegl, R. (in press). Preferred viewing locations: a validation and an extension. *Perception*.

O'Regan, J. K., & Lévy-Schoen, A. (1987). Eye movement strategy and tactics in word recognition and reading. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 363-383). Hillsdale, NJ: Erlbaum.

O'Regan, J. K., Lévy-Schoen, A., & Pynte, J. (1984). Convenient fixation location within isolated words of different length and structure. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 250-257.

Pollatsek, A., Reichle, E. D., & Rayner, K. (2006). Tests of the E-Z Reader Model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology, 52*, 1-56.

Perfetti, C.A., Liu, Y., & Tan, L.H. (2005). The lexical constituency model: Some implications of research on Chinese for general theories of reading. *Psychological Review,* 112 , 43-59.

Radach, R., & Kempe, V. (1993). An individual analysis of initial fixation positions in reading. In G. d'Ydewalle & J. Van Rensbergen (Eds.), *Perception and cognition: Advances in eye movement research* (pp. 213-226). Amsterdam: North-Holland.

Radach, R., & Kennedy, A. (2004). Theoretical perspectives on eye movements in reading: Past controversies, current issues and an agenda for future research. *European Journal of Cognitive Psychology, 16*, 3-26.

Radach, R., & McConkie, G. W. (1998). Determinants of fixation positions in words during reading. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 77-100). Oxford: Elsevier.

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception & Psychophysics, 8*, 21-30.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research, 38*, 1129-1144.

Rayner, K., Li, X. S., Juhasz, B. J., & Yan, G. (2005). The effect of word predictability on the eye movements of Chinese readers. *Psychonomic Bulletin & Review, 12*, 1089-1096.

Rayner, K., Li, X. S., & & Pollatsek, A. (2007). Extending the E-Z Reader model of eye movement control to Chinese readers. *Cognitive Science, 31,* 1021-1033.

Rayner, K., & Pollatsek, A. (1996). Reading unspaced text is not easy: Comments on the implications of Epelboim et al.'s (1994) study for models of eye movement control in reading. *Vision Research, 36*, 461-465.

Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 1188-1200.

Reichle, E. D., Rayner, K., & Pollatsek, A. (1999). Eye movement control in reading: accounting for initial fixation locations and refixations within the E-Z Reader model. *Vision Research, 39*, 4403-4411.

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye-movement control in reading: Comparisons to other models. *Behavioral and Brain Sciences, 26*, 445-526.

Reilly, R. G., & O'Regan, J. K. (1998). Eye movement control during reading: A simulation of some word-targeting strategies. *Vision Research, 38*, 303-317.

Reilly, R. G., & Radach, R. (2006). Some empirical tests of an interactive activation model of eye movement control in reading. *Cognitive Systems Research, 7*, 34-55.

Sainio, M., Hyönä, J., Bingushi, K., & Bertram, R. (2007). The role of interword spacing in reading Japanese: An eye movement study. *Vision Research, 47,* 2575-2584

Schilling, H. E. H., Rayner, K., & Chumbley, J. I. (1998). Comparing naming, lexical decision, and eye fixation times: Word frequency effects and individual differences. *Memory and Cognition, 26*, 1270-1281.

Tsai, C. H., & McConkie, G. W. (1995). *The perceptual span in reading Chinese text: A moving window study.* Paper presented at the Seventh International Conference on the Cognitive Processing of Chinese and Other Asian Languages, Hong Kong.

Tsai, J. L., & McConkie, G. W. (2003). Where do Chinese readers send their eyes? In J. Hyönä, R. Radach & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 159-176). Oxford: Elsevier.

Vitu, F. (2003). The basic assumptions of E-Z Reader are not well-founded. *Behavioral and Brain Sciences, 26*, 506-507.

Vitu, F., Lancelin, D., & d'Unienville, V.M. (2007). A perceptual-economy account for the inverted-optimal viewing position effect. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 1220-1249.

Vitu, F., McConkie, G. W., Kerr, P., & O'Regan, J. K. (2001). Fixation location effects on fixation durations during reading: an inverted optimal viewing position effect. *Vision Research, 41*, 3513-3533.

Vitu, F., O'Regan, J. K., & Mittau, M. (1990). Optimal landing position in reading isolated words and continuous texts. *Perception & Psychophysics, 47*, 583-600.

Wu, J., Slattery, T.J., Pollatsek, A., & Rayner, K. (2008). Word segmentation in Chinese reading. In K. Rayner, D. Shen, X. Bai, & G. Yan (Eds.) *Cognitive and cultural influences on eye movements (*pp. 260-269). Tianjin: Tianjin People's Publishing House/Psychology Press..

Yan, G., Tian, H., Bai, X., & Rayner, K. (2006). The effect of word and character frequency on the eye movements of Chinese readers. *British Journal of Psychology, 97*, 259-268.

Yan, M., Richter, E.M., Shu, H., & Kliegl, R. (in press). Readers of Chinese extract semantic information from parafoveal words. *Psychonomic Bulletin & Review.*

Yang, H.-M., & McConkie, G. W. (1999). Reading Chinese: Some basic eye-movement characteristics. In H.-C. Chen (Ed.), *Reading Chinese script: A cognitive analysis* (pp. 207-222). Mahwah, NJ: Lawrence Erlbaum.

Yang, S.-N., & McConkie, G. W. (2004). Saccade generation during reading: Are words necessary? *European Journal of Cognitive Psychology, 16*, 226-261.

Yang, S.-N., & Vitu, F. (2007). Dynamic coding of saccade length in reading. In R.P.G. van Gompel, M.H. Fischer, W.S. Murray, & R.L. Hill (eds.), *Eye movements: A window on mind and brain* (pp.293-317). Amsterdam: Elsevier Ltd.

Yu, B., Zhang, W., Jing, Q., Peng, R., Zhang, G., & Simon, H. A. (1985). STM capacity for Chinese and English language materials. *Memory & Cognition, 13*, 202-207.

Acknowledgements

This research was supported by grant from the Natural Science Foundation of China (30870758, 60534080) to Hua Shu and, by a grant from Deutsche Forschungsgemeinschaft KL 655/8 to Reinhold Kliegl and Ralf Engbert, and by a grant from China Postdoctoral Science Foundation (20080440008) to Ming Yan. Material from the Beijing Sentence Corpus is available upon request. The authors would like to thank Kevin Miller and Shiouyuan Chen for comments on and suggestion of a mathematically tractable way to report average word boundary agreement. We also thank Erik Reichle and a reviewer for helpful comments.

Table 1. Mean (standard deviations) of landing positions for 2- to 4-character words and first fixations (irrespective of number of fixations), single fixations, and first fixations in two fixation cases.

Word length	Word center	Fixation type		
		First	Single	First-of-two
2-character	2.5	2.40 (0.12)	2.50 (0.11)	1.81 (0.33)
3-character	3.5	2.93 (0.32)	3.40 (0.31)	2.17 (0.47)
4-character	4.5	3.07 (0.52)	4.06 (0.70)	2.28 (0.54)

Note. Units for means, standard deviations, and word centers are half-character zones, computed across subjects' means.

Table 2. Means (standard deviations) of incoming saccade amplitudes and launch site distances relative to the beginning of the word for single fixations and first of multiple fixations and 2- to 4-character words.

	Word length					
	Incoming saccade amplitude			Launch site distance		
	2	3	4	2	3	4
Single fixations	2.49 (0.36)	2.67 (0.42)	3.07 (0.58)	1.52 (0.35)	1.27 (0.36)	1.22 (0.46)
First fixations	2.35 (0.52)	2.33 (0.45)	2.56 (0.55)	1.74 (0.40)	1.59 (0.40)	1.73 (0.59)

Note. Units are characters. Means and standard deviations are computed across subjects' means.

Table 3. Means (standard deviations) of single fixation duration (SFD), gaze duration (GD), first fixation and refixation duration in two-fixation cases (FFD and RFD) for four half-character zones for 2-character words

	Half-character zones of 2-character words			
	1	2	3	4
SFD	213 (26)	217 (25)	218 (25)	214 (27)
GD	270 (44)	243 (34)	231 (31)	229 (32)
FFD	234 (36)	234 (37)	243 (74)	225 (49)
RFD	207 (29)	204 (44)	182 (37)	195 (55)

Figure Captions

Figure 1. A set of example Chinese sentences translated as '*It is possible that the US athletes will win the men's ski competition again*'. Chinese is a non-alphabetic language system whose basic writing units are Chinese characters. There are currently Simplified Chinese (a, mainland of China) and Traditional Chinese (b, mostly used in Hong Kong and Taiwan). Both scripts are written from left to right as strings of characters without word boundary, but they can be decomposed into words (c).

Figure 2. Preferred viewing locations of initial fixations (i.e., first fixations irrespective of number of fixations): proportions at half-character positions in Chinese words ranging from 1-4 characters.

Figure 3. Landing position distributions for initial fixations (i.e., first fixations irrespective of number of fixations) for different word lengths (2-4 characters) and launch site distances (1-3 characters; also displaying half characters). Lines are best-fitting normal curve for each distribution. Vertical lines represent the means of the fitted curves.

Figure 4. Preferred viewing locations in Chinese words ranging from 2- 4 characters (*A*: proportions for single fixations; *B*: proportions for first fixation of two-fixation cases).

Figure 5 Refixation probabilities as a function of initial landing position for Chinese words ranging from 2- 4 characters.

Figure 6. Single-fixation durations (sfd) and first-fixation durations in 2-fixation cases (ffd) as a function of initial landing position.

Figure 7. Distribution of amplitudes pooled over sentences and subjects. Each bin spans a tenth of a character.

Figure 8. A: Skipping probabilities as functions of word predictability for different word lengths. Lines denote data and gray areas denote 95% confidence intervals for the respective functions generated by simulations of the fixed amplitude strategy. B: Probabilities of skipping (circle), single fixation (square), and refixation (triangle) for different word lengths (left panel) and different log frequency classes (right panel). We can compare the empirical data (dashed lines) with the simulated data (solid lines).

Figure 1

a) Simplified Chinese

美国选手在男子滑雪比赛中有望蝉联冠军

b) Traditional Chinese

美國選手在男子滑雪比賽中有望蟬聯冠軍

c) Simplified Chinese with word space

美国 选手 在 男子 滑雪 比赛 中 有望 蝉联 冠军

Figure 2

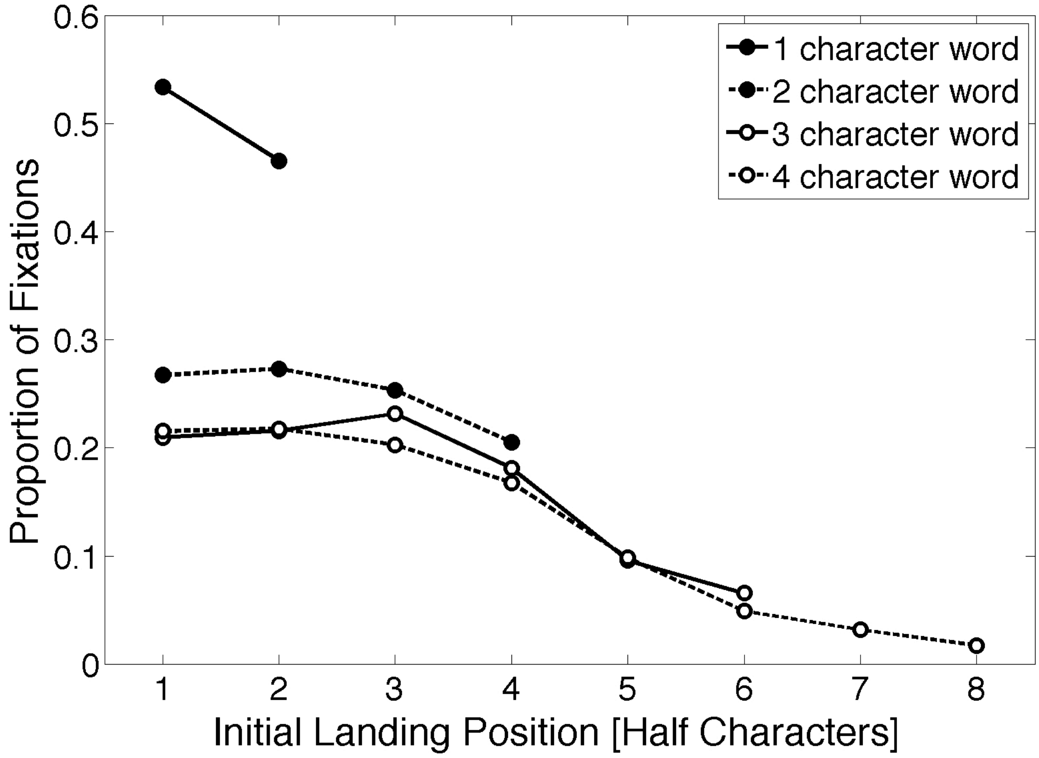

0.6
0.5
0.4
0.3
0.2
0.1
0
Proportion of Fixations
1
2
3
4
5
6
7
8
Initial Landing Position [Half Characters]
1 character word
2 character word
3 character word
4 character word

Figure 3

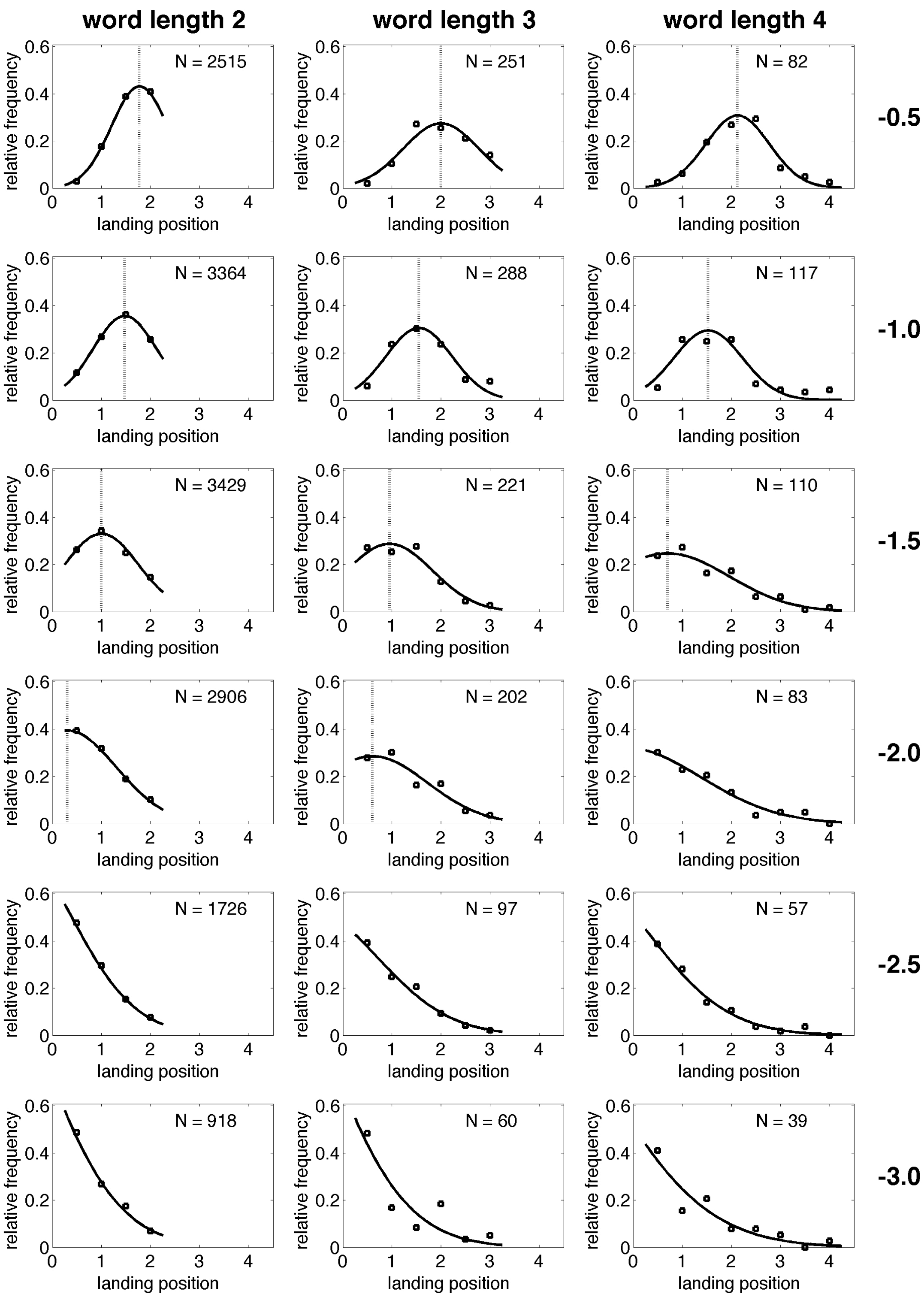

word length 2
word length 3
word length 4
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
N = 2515
N = 251
N = 82
N = 3364
N = 288
N = 117
N = 3429
N = 221
N = 110
N = 2906
N = 202
N = 83
N = 1726
N = 97
N = 57
N = 918
N = 60
N = 39
relative frequency
landing position

Figure 4

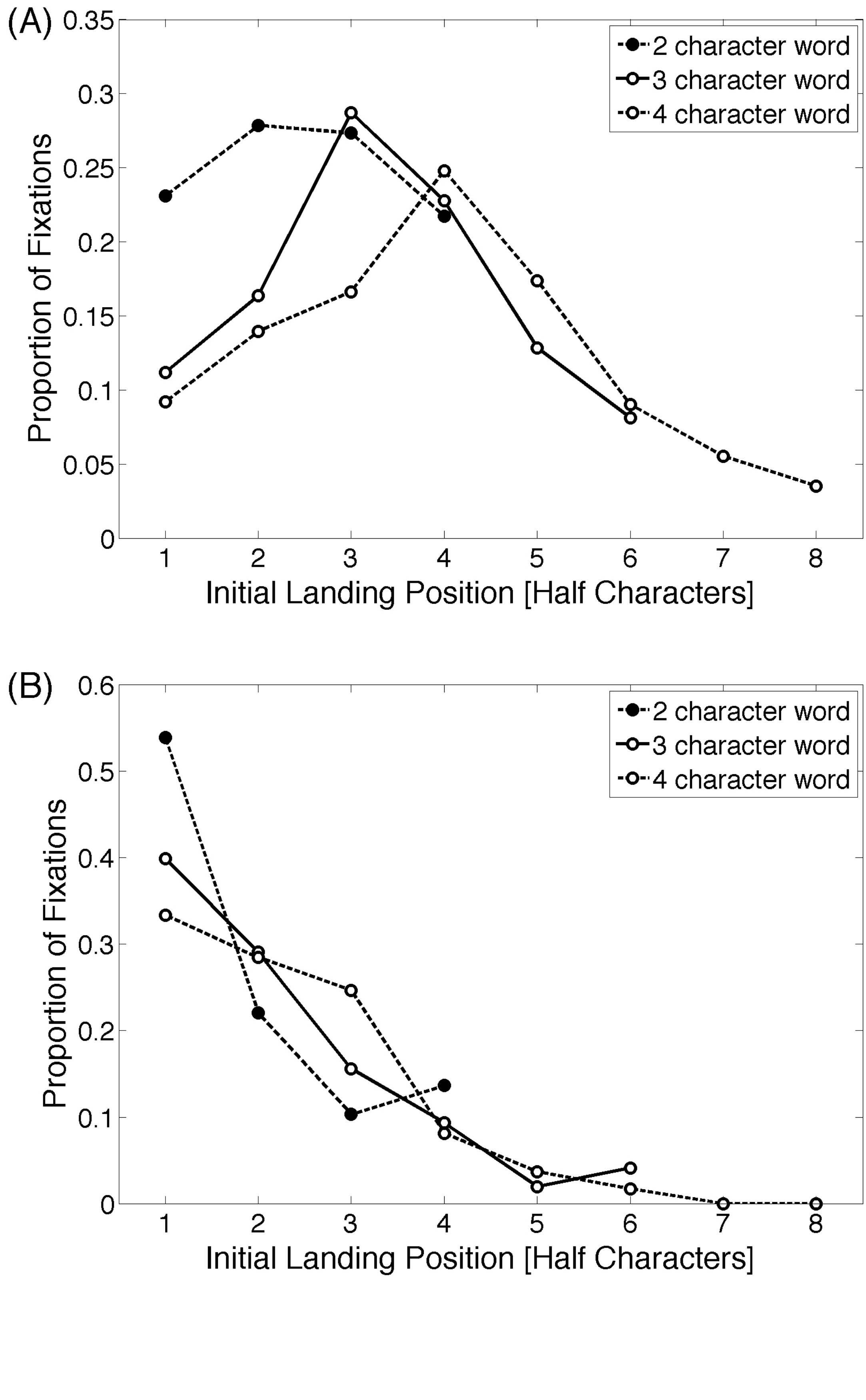
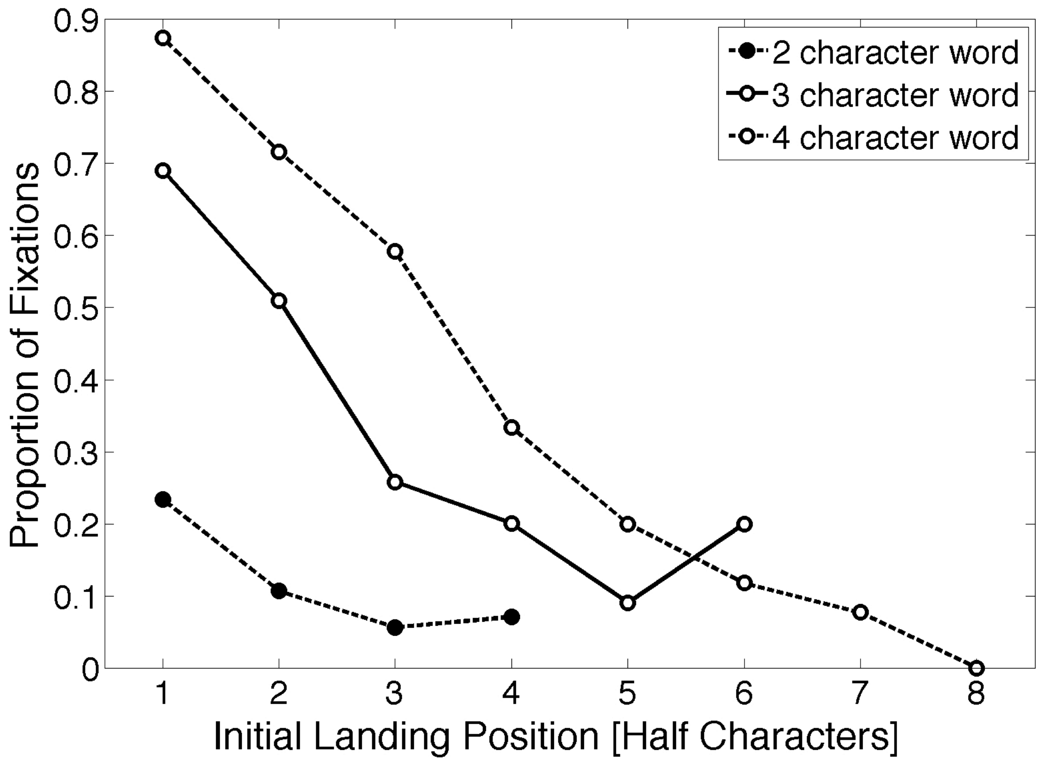

(A)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Proportion of Fixations
1 2 3 4 5 6 7 8
Initial Landing Position [Half Characters]
2 character word
3 character word
4 character word
(B)
0.6
0.5
0.4
0.3
0.2
0.1
0
Proportion of Fixations
1 2 3 4 5 6 7 8
Initial Landing Position [Half Characters]
2 character word
3 character word
4 character word

Figure 5



2 character word
3 character word
4 character word
Proportion of Fixations
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
Initial Landing Position [Half Characters]

Figure 6

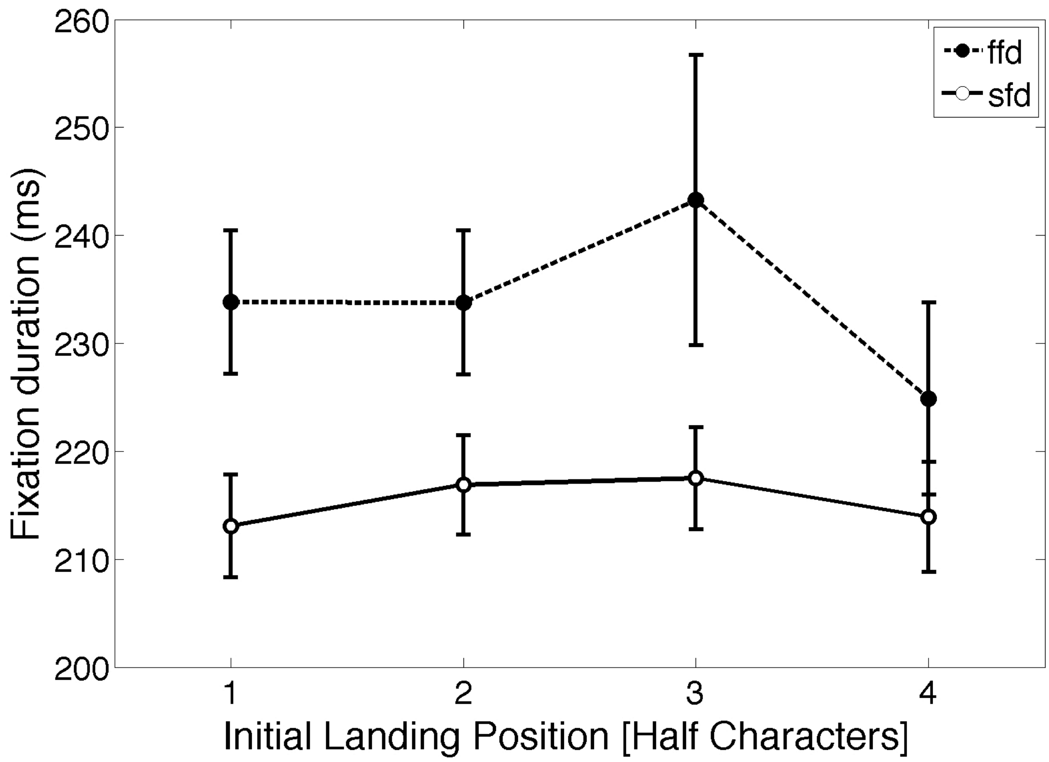

ffd
sfd
260
250
240
230
220
210
200
Fixation duration (ms)
1
2
3
4
Initial Landing Position [Half Characters]

Figure 7

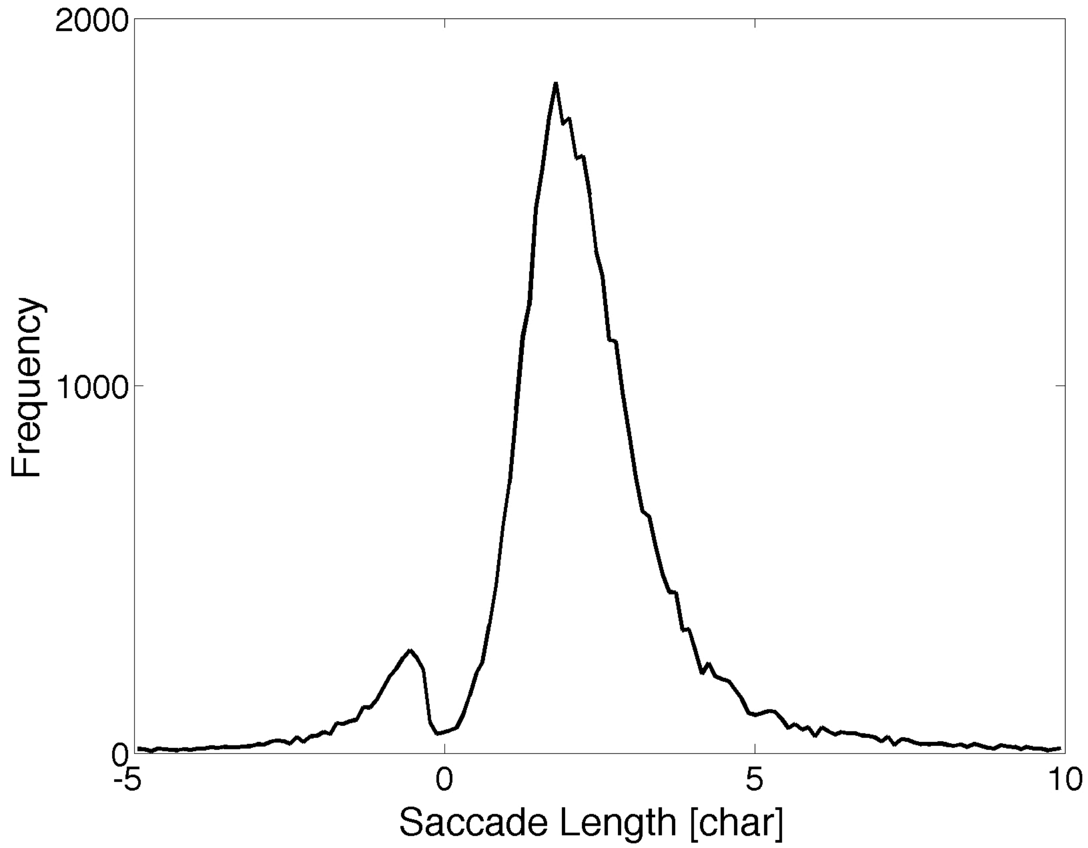
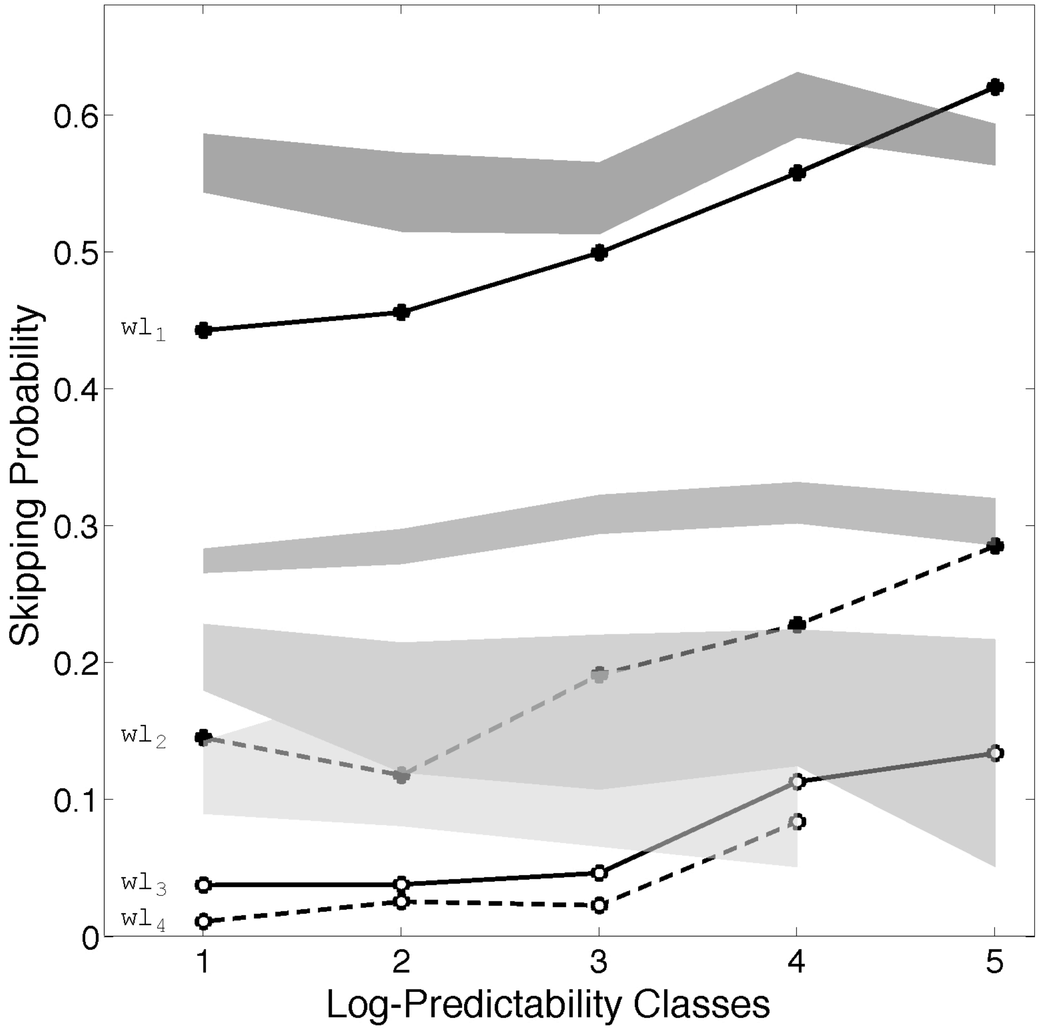
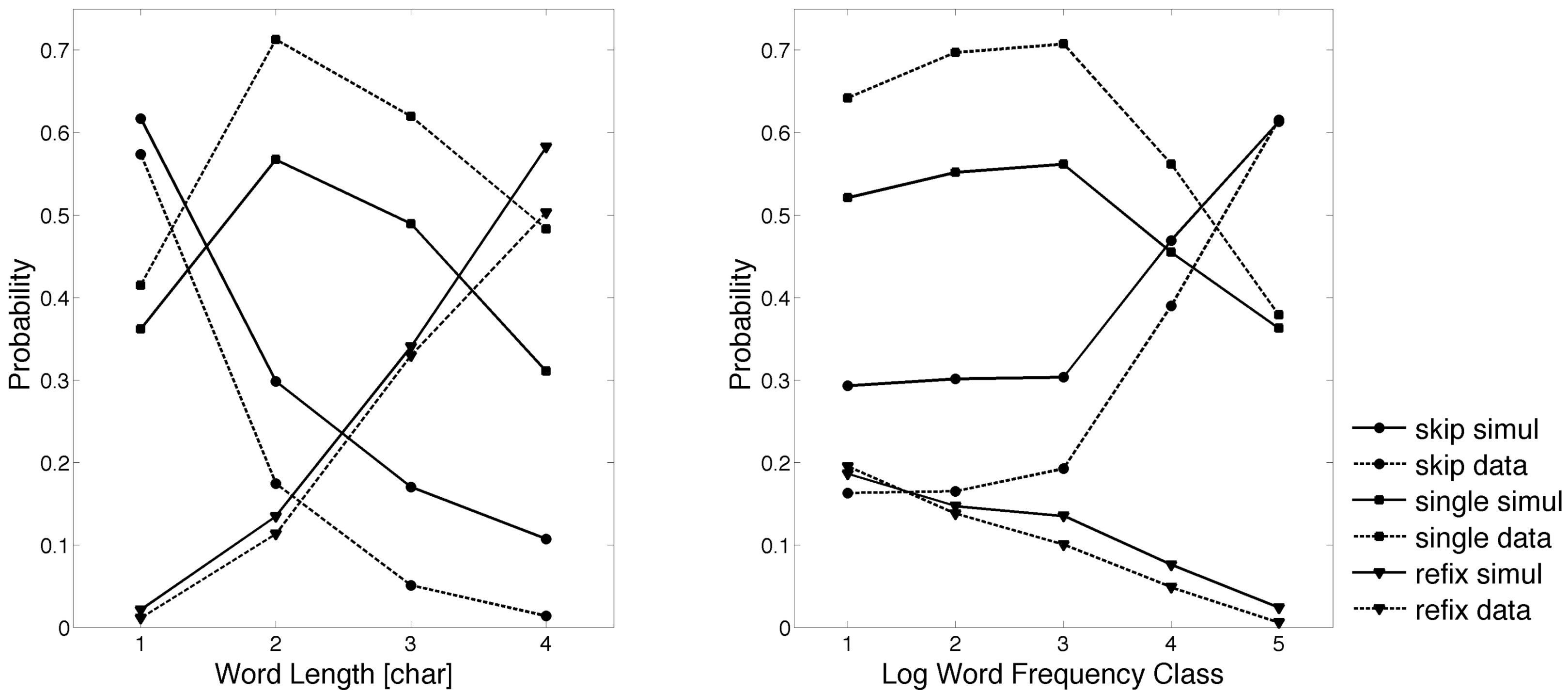


Figure 8A



Skipping Probability
0.6
0.5
0.4
0.3
0.2
0.1
0
wl1
wl2
wl3
wl4
1
2
3
4
5
Log-Predictability Classes

Figure 8B



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Probability
1
2
3
4
Word Length [char]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Probability
1
2
3
4
5
Log Word Frequency Class
skip simul
skip data
single simul
single data
refix simul
refix data

Appendix: Illustration of coding of word-boundary agreement

BSC sentence:

美国选手在男子滑雪比赛中有望蝉联冠军

(It’s possible that the US athletes will win the men’s ski competition again)

There are 18 characters and 17 word boundary candidates.

Experimenter’s word segmentation, i.e., the word segmentation for data analysis) with ‘/’ indicating a word boundary:

美国/ 选手/ 在/ 男子/ 滑雪/ 比赛/ 中/ 有望/ 蝉联/ 冠军

This can be further coded into a string of ‘0’s and ‘1’s, in which 0 indicates “not followed by a boundary” and 1 indicates “followed by a boundary”:

01011010101101010

Subject’s answer:

美国选手/ 在/ 男子/ 滑雪/ 比赛/ 中/ 有望/ 蝉联/ 冠军

00011010101101010

Thus, the agreement between subject and experimenter on this item is 16/17.