

Saccade-Target Selection of Dyslexic Children When Reading Chinese

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Abstract

This study investigates the eye movements of dyslexic children and their age-matched controls when reading Chinese. Dyslexic children exhibited more and longer fixations than age-matched control children, and an increase of word length resulted in a greater increase in the number of fixations and gaze durations for the dyslexic than for the control readers. The report focuses on the finding that there was a significant difference between the two groups in the first-fixation landing position as a function of word length in single-fixation cases, while there was no such difference in the initial fixation of multi-fixation cases. We also found that both groups had longer incoming saccade amplitudes while the launch sites were closer to the word in single fixation cases than in multi-fixation cases. Our results suggest that dyslexic children's inefficient lexical processing, in combination with the absence of orthographic word boundaries in Chinese, leads them to select saccade targets at the beginning of words conservatively. These findings provide further evidence for parafoveal word segmentation during reading of Chinese sentences.

Keywords: Chinese, dyslexic children, eye movements, saccade-target selection, reading

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1. Introduction

While reading, readers move their eyes to different positions across the text to gain information. Most former studies on alphabetic scripts agree that saccade-target selection is word-based (see Radach & Kennedy, 2013 for a review) and that the center of the word serves as the primary intended landing position, since it is assumed to be the optimal viewing position (OVP; O'Regan, & Lévy-Schoen, 1987). To this end, low spatial frequency information (i.e., the spaces between words) serves as the major cue for determining the beginning and end of parafoveal words, and this information allows the reader to determine where to fixate next even when the parafoveal word has not yet been recognized (McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Rayner, Fischer, & Pollatsek, 1998).

For unspaced scripts like Chinese, in which word boundaries are not explicitly marked by spaces between them, previous studies have suggested that skilled readers of these writing systems still target the word center in single-fixation cases (Li, Liu, & Rayner, 2011; Yan, Kliegl, Richter, Nuthmann, & Shu, 2010). More critically, Yan et al. (2010) demonstrated that word-based saccade-target selection in Chinese may depend on whether the parafoveal word that is going to be fixated has been successfully segmented during the previous fixations. Specifically, if such a parafoveal segmentation process fails, readers target the beginning of the word (i.e., the first character of the unrecognized word) instead. The present study aims to provide evidence for this parafoveal word segmentation hypothesis on the basis of

saccade-target selection by Chinese dyslexic readers.

There is considerable evidence showing that “low-level” (i.e., non-linguistic) factors such as word length are primary sources of information that readers use to determine where in the next word the eyes should land first when reading spaced alphabetic writing systems (see Rayner, 2009 for a review). Due to random oculomotor control error and the saccadic range effect (McConkie, Kerr, Reddix, & Zola, 1988) or errors that occur at the perceptual level (Engbert & Krügel, 2010), first-fixation landing positions (FLPs; i.e., the initially fixated location on a word after making a first-pass saccade into that word) form a Gaussian distribution with a peak slightly to the left of word centers (*preferred viewing location*, PVL; Rayner, 1979). Obviously, such PVL curves require knowledge about word lengths, which is provided by spaces. When spaces are removed, the PVL shifts to the beginning of the word and the curve falls linearly from word beginning towards the end of the word (Rayner et al., 1998; Rayner & Pollatsek, 1996). On the other hand, some studies suggest that, together with word length, higher-level linguistic processing can also be used to program saccades. For example, Rayner, Reichle, Stroud, Williams, and Pollatsek (2006) found that readers landed further into high frequency words than low frequency words. Hyönä and Pollatsek (1998) found that when reading compound words, readers landed further into words when the initial morphemes of the compounds were of high frequency than when they were less frequent. Probably the most convincing evidence for high-level guidance of eye movements was reported by Yan et al. (2013a) during the reading of Uighur script, in which words have rich

suffixes attached to the end that serve various functions. In two experiments implementing statistical and experimental control approaches, they reported that, in addition to word length having a major influence, FLPs are closer to word beginnings when the words are morphologically more complex (i.e., have more suffixes).

Taken together, the results reviewed above are difficult to explain solely by low-level guidance of eye movements and indicate that low-level visual information and high-level lexical information may jointly influence saccade programming. Influences of high-level information on saccade-target selection can also be shown during the reading of unspaced writing systems; however, it would be interesting to know how readers target their eyes in scripts in which spaces are not available if saccade-target selection is influenced only by low-level variables. Chinese offers such an opportunity: The basic writing units, characters, are square-shaped forms with varying levels of visual complexity as indicated by the number of strokes. While spaces are used in alphabetic scripts as cues of word positions, Chinese characters are evenly spaced in the text and no low frequency cues are given to separate words. This leads to word-boundary disagreements (Hsu & Huang, 2000; Inhoff & Liu, 2005) that result in different meanings. For example, the character string “花生长” can be parsed as either “花/生长” (flower growth) or “花生/长” (peanut growth) in different contexts; an equivalent example in English might be *fangear*, which can be parsed as *fang ear* or *fan gear* (see Libben, 1994, for more examples of ambiguous compounds). Given that the perceptual span extends between one character to the left and up to four characters to the right of the current fixation point in skilled readers of Chinese

(Inhoff & Liu, 1998; Yan, Zhou, Shu, & Kliegl, 2013b), and that most Chinese words are single-character or two-character words, skilled readers of Chinese should be able to segment character strings into word units in the parafovea in most cases; however, the lack of explicit word boundaries might impose parafoveal word segmentation difficulties for developing and dyslexic readers, who typically have smaller perceptual spans in both alphabetic (e.g., Rayner, 1986) and Chinese scripts (Yan, Pan, Laubrock, Kliegl, & Shu, 2013c).

How do skilled readers of Chinese choose words as their saccade-targets? The absence of orthographic word boundaries requires that readers roughly process the lexical information of a word in the parafovea. Yan et al. (2010) proposed a two-stage process model of reading Chinese, suggesting that saccade-target selection depends on whether the upcoming word has been segmented from the sentence. If the word length information can be obtained easily, readers target the center of the word. This is supported by the evidence that the FLP distributions in single-fixation cases are similar to those observed in English (McDonald & Shillock, 2004; Rayner, 1979), and suggests that skilled readers of Chinese separate a string of characters into words in parafoveal vision and select the word center as the saccade target. However, when parafoveal word segmentation fails, readers more often target the beginning of the word with a focus on word segmentation. Evidence for this comes from the shift of FLPs from the center to the beginning of the word in multi-fixation cases; the probabilities decreased linearly from the beginning to the end of the word. Taken together, FLPs in single-fixation and multi-fixation in reading Chinese are considered

indicators of success or failure in parafoveal word segmentation. Further evidence for this model of word segmentation comes from the fact that, unlike in reading of alphabetic writing systems, first-fixation durations (FFDs; i.e., the duration of the first fixation on a word) in two-fixation cases in Chinese were no shorter than single-fixation durations (SFDs; i.e., the fixation duration of words that receive only one fixation), which suggests that first fixations in two-fixation cases are not due to oculomotor error and that readers may instead need to do foveal word segmentation. This parafoveal word segmentation hypothesis is also supported by Yang, Wang, Xu, and Rayner (2009), who reported that Chinese readers acquire more parafoveal information from character N+1 if it is part of word N+1 than if it is part of word N+2.

Summing up, the studies reviewed above indicate that FLPs can be indicators of linguistic processing for skilled readers. What about typically developing readers and readers with dyslexia? Examining adults and children between seven and eleven years old reading English, Joseph, Liversedge, Blythe, White, and Rayner (2009) found no difference in FLPs on four-, six-, or eight-letter words between children and adults, suggesting that readers of spaced alphabetic scripts are able to process word length information to guide their saccades from very early on (McConkie, Zola, Grimes, Kerr, Bryant, & Wolff, 1991). However, first fixations of poor readers and dyslexic readers tend to land at word beginnings (Hawelka, Gagl, & Wimmer, 2010; Kuperman & Van Dyke, 2011). In alphabetic languages, researchers interpreted this as a consequence of relying on sublexical processing to identify words (Hawelka et al.,

2010). It is not clear, however, whether the FLPs of poor readers could be affected by high-level linguistic processing in the parafovea.

An unspaced nonalphabetic script like Chinese imposes a larger parafoveal processing load for the identification of word boundaries. In the present study, we aim to provide evidence that the FLP acts as an indicator of parafoveal word segmentation from a reading development and impairment perspective. Given the smaller perceptual span of Chinese dyslexic children (Yan et al., 2013c), if they are more affected by the absence of word boundaries, we expect a larger difference in saccade-targeting of first-fixation landing positions between dyslexic readers and control readers in single-fixation cases than in multi-fixation cases.

Participants were asked to read aloud, since Hyönä and Olson (1995) suggested that eye movements are more closely linked with word recognition processes in oral reading than in silent reading and that oral reading might bring about more pronounced effects of word properties (e.g., word length and word frequency) than silent reading.

2. Method

2.1 Participants

The sample consisted of 33 fifth-graders (18 boys and 15 girls) with dyslexia and an age-matched control group of 29 children (13 boys and 16 girls) from the same grade. The dyslexic children had normal IQ (above 85 on the Wechsler Intelligence Scale for Children, Chinese revision [C-WISC, Gong & Cai, 1993]) with two exceptions (83 and 84 on C-WISC) and an average score of 96 ($SD=8$). As shown in

Table 1, the two groups were equivalent in nonverbal IQ (based on Picture Completion in C-WISC). All participants were native Mandarin speakers in Beijing and had normal or corrected-to-normal visual acuity. Parents approved the participation of their children before testing.

The diagnosis of dyslexia was based on criteria previously established in studies in mainland China (e.g., Pan, Yan, Laubrock, Shu & Kliegl, 2013; Yan et al., 2013c). Because Chinese is an extremely opaque orthography, we evaluated each child's literacy skill level by measuring their reading accuracy using a standard character recognition test with 150 characters that are expected to be learned by grade 6 (Shu, Chen, Anderson, Wu & Xuan, 2003) ordered by difficulty. Children were asked to orally name the characters, and the test was aborted when they failed 15 successive items. One point was awarded for each correctly named character. In this test, the dyslexic children scored at least 1.5 *SDs* below their corresponding age means. The performance in the character recognition task of both groups is provided in Table 1.

2.2 Material

Participants were asked to read aloud 60 sentences from a computer screen. These sentences contained 40 age-appropriate sentences chosen and edited from textbooks used in grade 5. Another 20 sentences were chosen from the Beijing Sentence Corpus (Yan et al., 2010). Sentences were 15-23 characters in length ($M = 18.0$, $SD = 2.0$), corresponding to between 7 and 13 words ($M = 9.5$, $SD = 1.3$). The sentences comprised 572 tokens (440 word types). Word length varied from 1 to 4 characters, with 38 one-character words, 372 two-character words, 22 three-character

words, and 8 four-character words. The number of strokes per word, which is a rough index of its visual complexity, varied from 2 to 43 ($M = 15.2$, $SD = 5.7$). Word frequencies were taken from the Modern Chinese Word Frequency Dictionary (Beijing Language Institute Publisher, 1986). The mean frequency was 681 ($SD = 3501$) per million words. Words longer than three characters in length were not included in the analyses, because they constitute only a very small proportion of all Chinese words.

2.3 Apparatus

Eye movements were recorded with an EyeLink 2K system (sampling at 1000 Hz). Single sentences were presented on a line below the top third of a 19-inch ViewSonic G90f monitor (resolution: 1280 by 1024 pixels; frame rate: 85 Hz). The font Song 35 was used, with one character being equivalent to approximately 1.1 degrees of visual angle. Subjects were seated 57 cm from the monitor with their head positioned on a forehead rest. All recordings and calibrations were done monocularly based on the right eye, and viewing was binocular.

2.4 Procedure

At the beginning of the task, participants were calibrated with a standard nine-point grid. After validation of calibration accuracy, a fixation point appeared on the left side of the monitor, where the first character of the sentence would appear when the eye tracker identified a fixation on the fixation point. Participants were instructed to read the sentence aloud; for the characters they could not recognize, they were instructed to continue to the next character until the end of the sentence and then

to fixate on a point in the lower right corner of the screen, and to press a joystick button to indicate completion of reading the sentence. A randomly selected third of the sentences were followed by a yes or no question, which participants were to answer using two different buttons on the joystick. 10 trials of practice sentences were given before the experimental trials.

2.5 Data Treatment and Analyses

Data analyses were based on first-pass fixations from 61 participants.¹ We excluded from analyses sentences in which the participant blinked, unless the blink occurred on the first and/or the last word of a sentence (23% of all trials). We were mainly interested in how reading ability affects FLPs of children. In addition, we also analyzed four commonly used eye-movement measures: number of fixations per word (NFs), log-transformed gaze durations (GDs; i.e., the time spent on a word before it is left for the first time), incoming saccade amplitude (SA), and launch site (LS; i.e., the location from which a saccade is initiated based on the beginning of the fixated word).

Data filter. FFDs and GDs with extreme values ($FFD < 60$ ms or > 800 ms; $GD < 60$ ms or > 2000 ms) were excluded from analyses (2% of all valid fixations). We also excluded words that received the first or the last fixation on one trial, and fixations on the first and the last words in a sentence. A total of 18769 observations contributed to each of the analyses. For analyses of the number of fixations, we focused on fixated words, and we reduced the range from 1 to 4 by adding words that received more than 4 fixations (1% of valid observations) to the 4-fixation category. This manipulation did not change the pattern of results. The analyses of SA and LS

were based on fixations on 2-character words (13569 observations) with launch sites smaller than 2 characters (98% of fixations on 2-character words).

Model specification. Statistical inferences are based on linear mixed models (LMMs) using the *lmer* program of the *lme4* package (Bates, Maechler, Bolker, & Walker, 2013) in the R environment for statistical computing and graphics (R Core Team, 2013). For NFs and GDs, we specified models including the fixed effects for participant group, word length and word frequency, and interactions between these variables. We also estimated model parameters of variance components for means of participants, sentences, and words (i.e., varying intercepts) as well as for effects of word frequency and word length for participants (i.e., varying slopes); correlation parameters between intercept and slopes were estimated for participants. We used centered log-transformed continuous frequency values; word length was centered on 2-character words.

For FLP, the LMM also included fixation type (i.e., single-fixation vs. multi-fixation) and four three-way interactions between these variables (i.e., between group, frequency, and word length; between group, frequency, and fixation type; between group, word length, and fixation type; and between frequency, word length, and fixation type). Fixation type and its correlations with intercept, length, and frequency were also included in the random-effects part of the LMM.

For LS and SA, we estimated fixed effects for group, fixation type and their interaction. In addition, we allowed for varying intercepts for participants, sentences, and words, and for varying effects of fixation type for participants (variance

components). Finally, we also estimated a correlation parameter intercepts and effects of fixation type for participants.

3. Results

3.1 Descriptive Statistics

Table 2 shows the group differences for several standard measures of eye movement. In general, as expected, dyslexic children generated fewer single fixations and skipped less often than control children. Of the words that were fixated, dyslexic children fixated more often on a word and for longer durations than control children did. Dyslexic readers' single fixations landed significantly closer to the word beginning, but there was no significant difference between the groups in FLP for the first fixation in multi-fixation cases. The control group generally had longer incoming saccade amplitudes than the dyslexic group. The two groups did not differ in their launch sites in single-fixation cases, but the control group's launch sites were further away from the word to be fixated in multi-fixation cases.

Overall, words read with a single fixation ($M = 6.00$, $SD = 2.82$ for log-transformed word frequency; $M = 1.67$, $SD = .50$ for word length) and words read with multiple fixations ($M = 4.36$, $SD = 2.08$ for log-transformed word frequency, $M = 2.02$, $SD = .34$ for word length) differed significantly in word frequency ($t = 55.27$, $p < .001$) and in word length ($t = -44.93$, $p < .001$).

3.2 First-Fixation Landing Position

For FLP, the main effects of word length and fixation type were significant ($b = .202$, $SE = .035$, $t = 5.81$, 95% confidence interval (CI) from .134 to .270 for word

length; $b = .343$, $SE = .035$, $t = 9.74$, CI from .274 to .412 for fixation type). Saccades landed further into long words than short words, and further into words that were fixated only once than into words that received multiple fixations. The main effects of group and word frequency were not significant. However, we did observe a significant interaction between word length, fixation type, and group ($b = -.132$, $SE = .038$, $t = -3.46$, CI from -.207 to -.057).

In post hoc LMMs, we further examined the interaction between group and word length for each fixation type, including word frequency as a covariate in the LMMs. As shown in the left panel of Figure 1, for FLP in multi-fixation cases (9969 observations), the main effect of word length was significant ($b = .128$, $SE = .017$, $t = 7.75$, CI from .096 to .161), while the group effect was not significant ($b = -.005$, $SE = .016$, $t = -.35$, CI from -.036 to .025), and the interaction between these two variables did not reach significance ($b = -.044$, $SE = .025$, $t = -1.75$, CI from -.094 to .005). For FLP in single-fixation cases (8800 observations), there were significant main effects of group ($b = -.205$, $SE = .026$, $t = -7.80$, CI from -.257 to -.154) and word length ($b = .244$, $SE = .026$, $t = 9.45$, CI from .193 to .294). More importantly, we also observed significant interaction between them ($b = -.205$, $SE = .035$, $t = -5.81$, CI from -.274 to -.136). As shown in the right panel of Figure 1, control children tended to land on the middle of the word, while dyslexic children “undershot” the word centers of 2-character and 3-character words. In addition, we also observed a significant main effect of word frequency ($b = .016$, $SE = .004$, $t = 3.74$, CI from .008 to .024).

3.3 Number of Fixations and Gaze Duration

The LMMs suggest similar patterns of influence of reading ability, word frequency, and word length on NFs and GDs. The main effect of group ($b = .390$, $SE = .065$, $t = 6.00$, CI from .262 to .517 for NFs; $b = .263$, $SE = .034$, $t = 7.67$, CI from .195 to .328 for GDs) was significant, suggesting that dyslexic children fixated more often and, by implication, fixated longer to process words. The main effects of word frequency and word length were significant for NFs ($b = -.028$, $SE = .007$, $t = -4.16$, CI from -.042 to -.015 for word frequency; $b = .585$, $SE = .041$, $t = 14.37$, CI from .505 to .665 for word length) and GDs ($b = -.021$, $SE = .005$, $t = -4.03$, CI from -.032 to -.011 for word frequency; $b = .296$, $SE = .031$, $t = 9.43$, CI from .235 to .358 for word length). We also observed significant interactions between group and word length in both analyses ($b = .214$, $SE = .050$, $t = 4.26$, CI from .116 to .313 for NFs; $b = .089$, $SE = .034$, $t = 2.62$, CI from .022 to .156 for GDs): The word length effects on both NFs and GDs were more pronounced for dyslexic children than for control children.

3.4 Incoming Saccade Amplitude and Launch Site

We found main effects of group ($b = -.096$, $SE = .033$, $t = -2.88$, CI from -.161 to -.031 for LS; $b = -.219$, $SE = .045$, $t = -4.83$, CI from -.308 to -.130 for SA), and of fixation type ($b = -.195$, $SE = .014$, $t = -14.04$, CI from -.222 to -.168 for LS; $b = .098$, $SE = .009$, $t = 11.36$, CI from .081 to .115). The interaction between group and fixation type was significant for LS ($b = .186$, $SE = .027$, $t = 6.72$, CI from .132 to .234). Figure 2 demonstrates that single fixations are associated with shorter launch

sites (left panel); arguably, this is because a fixation closer to the word that is to be fixated makes obtaining information about the word's ending more likely. Under this circumstance, readers are able to target the word centers with longer saccades (right panel).

4. Discussion

The present study examined the eye movements of dyslexic and age-matched control children when reading Chinese. In general, words that are difficult to recognize (long words and low frequency words) received more fixations and longer gaze durations. Extending previous findings in alphabetic scripts (Hawelka et al., 2010; Hutzler & Wimmer, 2004), we found that the word-length effects on NFs and GDs were also more pronounced among the Chinese dyslexic children than the control children. In alphabetic scripts, these effects are associated with inefficient word processing and reliance on serial sublexical processing of words, since grapheme-to-phoneme correspondences are rather reliable in these orthographies. It is fair to point out that the spaces between words probably make word-based saccade-target selection easier on average for alphabetic dyslexics, as Hawelka et al. (2010) reported a relatively large proportion of single fixations (55%). Given the specific properties of the Chinese language, it is reasonable to explain the results of the present study under the framework of parafoveal word segmentation hypothesis proposed by Yan et al. (2010) instead. The present study also contributes to a growing body of evidence that saccade-target selection can be affected by higher level linguistic processing in addition to low level visual/orthographic processing (see Yan

et al., 2013a, for a review).

Former studies on saccade-target selection basically suggest that FLPs are primarily determined using low-level information such as word length. However, for scripts without explicit word boundaries such as Chinese, readers process word length information by parafoveal word segmentation (Yan et al., 2010; Yang et al., 2009). This may not be very difficult for skilled readers, as perceptual span extends up to four characters to the right of a fixation (Inhoff & Liu, 1998; Yan et al., 2013b) whereas most Chinese words are shorter than three characters. Experimental evidence and computational simulation suggest that in Chinese, word boundary information can be generated online on the basis of simple statistical information such as word frequency and co-occurrence frequency (Richter, Yan, Engbert & Kliegl, 2010; Yen, Radach, Tzeng & Tsai, 2011). For developing readers, parafoveal word segmentation demands more resources and is more difficult. Compared to Yan et al. (2010), the average saccade amplitude in the present study was shorter, and there were more refixations. These results are in agreement with Shu, Zhou, Yan and Kliegl (2011), who reported that saccade amplitude decreased and number of fixations at word beginnings increased significantly when parafoveal word length information was difficult to obtain. Nevertheless, our results suggest that saccade-target selection is still based on words for Chinese children, even though to a smaller extent. This is in accordance with findings that young Chinese readers (2nd to 6th graders) adopt a word-based processing strategy (Chen & Ko, 2011).

The critical finding in the present study is the three-way interaction between

fixation type, word length, and subject group (Figure 1), which strongly suggests that the two groups program their saccades differently. The control group segmented those words that were easily identified (i.e., of short length and high frequency) in the parafoveal vision, targeted a position slightly to the left of the word center, and processed the word with a single fixation. As demonstrated by the solid line in the right panel of Figure 1, the mean FLPs in single-fixation cases are in nice agreement with those of McConkie et al. (1988). When they encountered difficulties in preprocessing of the word in the parafovea as indicated by multi-fixation cases, the control group targeted the word beginning (i.e., the first character) irrespective of word length. In other words, the control group has virtually the same saccade-targeting mechanism as skilled readers (Yan et al., 2010).

For the dyslexic children, on the other hand, our data suggest that they do not segment the word as efficiently. Compared to the control group, the dyslexic readers undershot the PVL in single-fixation cases. We argue that this is because of their uncertainty regarding word boundaries, presumably due to their limited perceptual span; given that word boundaries can be locally ambiguous in Chinese, with a small perceptual span it is difficult for the dyslexics to parse character strings far enough to obtain a clear word ending position. For example, if one encounters the word “科学” (science) in the parafovea and does not know the subsequent character, it is difficult to decide on the word boundary, because the two characters could be followed by the character “家” (specialist), resulting in the 3-character word “科学家” (scientists). They may have tended to be more careful not to overshoot the word center, leading to

undershooting the PVL in single-fixation cases for 2-character and 3-character words (Figure 1, right panel). In principle, this is in agreement with an unexpected but reasonable finding reported by Yan et al. (2013b): Readers of Chinese had longer saccades and more distant landing positions when they were given a gaze-contingent moving window of four characters to the right of the current fixation than when they were given the full line, which runs counter to a traditional view that predicts that limiting the amount of parafoveal information will result in a reduction in reading performance. The window created a low co-occurrence frequency at the window border (i.e., the last character within the window and the first character following the window), which probably served as a useful cue for word-boundary detection, leading to easier segmentation and facilitated parafoveal processing. Taken together, our results suggest that the dyslexic children may have processed the parafoveal word to some extent and accordingly targeted as far into the word as they could.

Recently, a random saccade-targeting model was proposed by Li et al. (2011). According to their model, single fixations are made on words randomly; if the fixation occurs near the center of the fixated word, this word is processed more quickly (due to the OVP effect), and the next saccade is directed at the next unprocessed region. The length of the next word is not necessarily used for targeting the next fixation. If word segmentation (i.e., determining the length of the parafoveal word) occurs at all, it does not occur before the word is fixated. Although many results of the present study can be explained by either word-based or random models, these two hypotheses can be teased apart. As we discussed above, the three-way interaction indicates that dyslexics

are less skillful in word segmentation, presumably due to their smaller perceptual span (Yan et al., 2013c), and thus the result is neatly in accordance with the word-based saccade-target hypothesis (Yan et al., 2010). We fail to see how this can be accounted for by the random model.

In addition, the analyses of saccade amplitude and launch site further supported our parafoveal segmentation hypothesis. In the random model proposed by Li et al. (2011), single fixations and initial fixations in multi-fixation cases are generated according to the same principle. The only difference is that the peak of the FLP distribution for multiple fixations is close to the word beginning, while for single fixations it is close to the word center. Thus the average saccade amplitude of these two types of fixations should not differ. However, Li et al. (2011) argued that the distinction between these two types of fixations, which was borrowed from previous studies on alphabetic scripts, is not appropriate, since it requires arbitrarily defining word boundaries that are not present in Chinese script. In their view, these arbitrarily defined word boundaries cut the landing position distribution into two separate parts when it peaks around word beginnings. Thus the FLP distribution of multiple fixation cases represents the right branch of a Gaussian distribution. This argument translates into a prediction that a saccade leading to the first of multiple fixations on a word should be longer than that which leads to a single fixation, because the right branch of the distribution is contributed by longer saccades. In either case, the random saccade model predicts that saccades to the initial fixation in multi-fixation cases should *not* be shorter. In the present study, however, first fixations in multi-fixation cases were

associated with more distant launch sites and smaller incoming saccade amplitudes, suggesting that when the eyes are far from the word that is to be fixated, it is less likely that the reader can successfully recognize the word boundary and thus he/she aims at the word beginning. Both groups were capable of longer saccade amplitudes into word centers in single-fixation cases, provided that readers were close enough to the parafoveal words.

Previous studies on saccade-target selection used silent reading tasks for the most part. In a longitudinal study, Huestegge, Radach, Corbic, and Huestegge (2009) demonstrated a shift of the FLP from the word beginning towards the word center in second-graders to fourth-graders reading aloud. On the other hand, beginning readers can select the word center as FLP as early as first grade in primary school during silent reading (McConkie et al., 1991). Taken together, these results are in agreement with a recent finding that the perceptual span is smaller in oral reading than in silent reading (Ashby, Yang, Evans & Rayner, 2012). Given this background information, we suspect that parafoveal word segmentation in Chinese should be more difficult in oral reading, because fewer attentional resources are available for parafoveal processing than in silent reading.

In summary, the present study describes eye movement characteristics of dyslexic readers of a nonalphabetic script. We extended the findings of dyslexic readers in alphabetic languages by showing that Chinese dyslexic children exhibited more fixations and longer durations in word processing. Dyslexic children landed closer to word beginnings than control readers only in single-fixation cases except

when the word was refixated, which indicates that parafoveal preprocessing at a linguistic level influences landing position, at least in nonalphabetic scripts. Given their lower efficiency in word processing, Chinese dyslexic children may adopt a more careful strategy of saccade-target selection in the absence of orthographic word boundaries.

AUTHOR NOTES

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FOOTNOTES

1. One girl from the dyslexic group who incorrectly answered more than 40% of the questions was excluded from data analyses.

Table 1.

Means (standard deviations) and group comparisons of reading and cognitive measures.

Measures	Control (<i>N</i> =29)	Dyslexic (<i>N</i> =33)	<i>t</i> -value	<i>p</i>
Age (year)	10.6 (.3)	10.7 (.4)	1.24	.221
Character recognition	128 (10)	85 (10)	-17.33	.000
Picture completion (Performance scale in C-WISC)	10.6 (2.6)	9.8 (2.8)	-1.18	.242

Table 2.

Means (standard deviations) of eye movement measures and *t*-values of the group comparisons.

Measures	Control (<i>N</i> =29)	Dyslexic (<i>N</i> =32)	<i>t</i> -value	<i>p</i>
Global measures				
Gaze durations (ms)	452 (49)	591 (72)	8.67	.000
Fixations per word (<i>N</i>) ^a	1.56 (.22)	1.88 (.21)	5.72	.000
First Fixation Landing position (character)				
Single fixations	.79 (.11)	.61 (.09)	-7.43	.000
First of multi-fixation	.50 (.06)	.47 (.07)	-1.38	.172
Fixation probabilities (%)				
Skipped words	8 (3)	4 (3)	-5.30	.000
Single fixated words	50 (11)	38 (9)	-4.44	.000
Multiply fixated words	42 (14)	58 (11)	4.98	.000
Launch site (character)				
Single fixations	.61 (.14)	.60 (.12)	-.18	.854
First of multi-fixation	.89 (.17)	.70 (.14)	-4.77	.000
Incoming saccade amplitude (character)				
Single fixations	1.49 (.19)	1.28 (.16)	-4.89	.000
First of multi-fixation	1.37 (.19)	1.16 (.18)	-4.40	.000

Note. a=based on fixated words. Only fixations on 2-character words with launch

sites smaller than 2 characters were reported for launch site and incoming saccade amplitude.

Figure Captions

Figure 1. Three-way interaction between type of fixation (panels), groups (lines within panels) and word length. Control children exhibit a particularly strong effect of word length on first fixation landing position when they read the word with a single fixation duration. Errorbands show 95% confidence intervals.

Figure 2. The partial effects of fixation type on launch site (left panel) and incoming saccade amplitude (right panel) for 2-character words. Errorbands show 95% confidence intervals.

Figure 1.

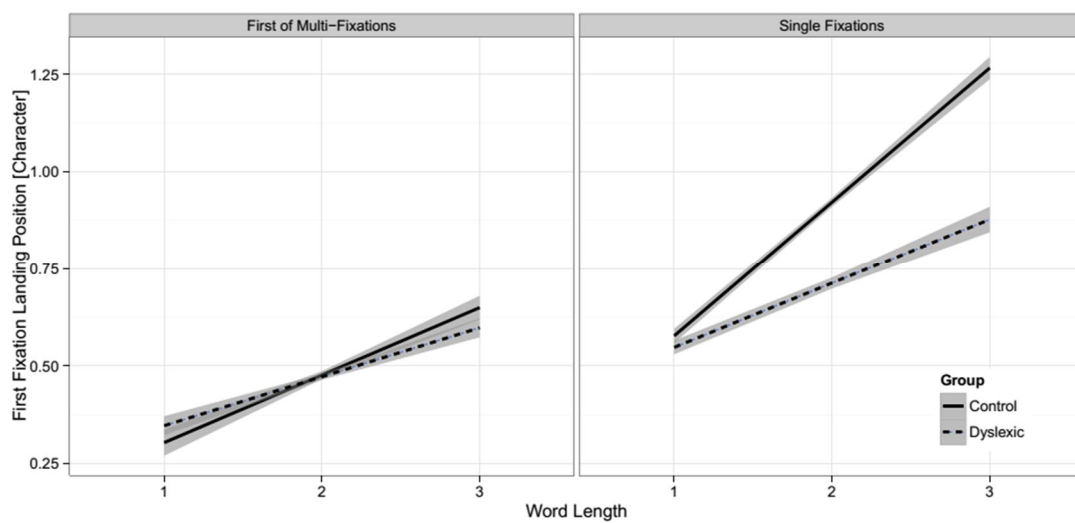


Figure 2.

