Word segmentation by alternating colors facilitates eye guidance in Chinese reading

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Abstract

During sentence reading, low spatial frequency information afforded by spaces between words is the primary factor for eye guidance in spaced writing systems, whereas saccade generation for unspaced writing systems is less clear and under debate. In the present study, we investigated whether word-boundary information, provided by alternating colors (consistent or inconsistent with word-boundary information) influences saccade-target selection in Chinese. In Experiment 1, as compared to a baseline (i.e., uniform color) condition, word segmentation with alternating color shifted fixation location towards the center of words. In contrast, incorrect word segmentation shifted fixation location towards the beginning of words. In Experiment 2, we used a gaze-contingent paradigm to restrict the color manipulation only to the upcoming parafoveal words and replicated the results, including fixation location effects, as observed in Experiment 1. These results indicate that Chinese readers are capable of making use of parafoveal word-boundary knowledge for saccade generation, even if such information is unfamiliar to them. The present study provides novel support for the hypothesis that word segmentation is involved in the decision about where to fixate next during Chinese reading.

Keywords Chinese · Word segmentation · Fixation location · Parafoveal · Color

Eye movement in reading involves dynamic decisions about where to fixate next, as reflected by fixation locations. For spaced alphabetic scripts, word center, which can be calculated on the basis of low spatial frequency information afforded by word spacing, is thought to serve as the intended fixation location. Because of random oculomotor error and systematic saccadic range effect (McConkie, Kerr, Reddix, & Zola, 1988; but see Nuthmann, Vitu, Engbert, & Kliegl, 2016, for a lack of evidence for a saccadic range effect) or an error occurring at the perceptual level (Engbert & Krügel, 2010), first-fixation locations (FLs) form a Gaussian distribution peaking close to

word centers, known as the preferred viewing location (PVL; Rayner, 1979). Arguably, lexical processing is optimal when fixating word center (O'Regan, Lévy-Schoen, Pynte, & Brugaillere, 1984). In contrast, in an unspaced logographic writing system, Chinese words are not segmented by explicit markers like word spacing (except for punctuations). Because of the lack of word spacing, whether or not word-boundary information is involved for saccade-generation during the reading of Chinese sentences is under debate (see Yan & Kliegl, 2016, for a recent review). In the present study, as a theoretical contribution to the debate about saccade targeting during sentence reading, we introduce a salient visual cue of word boundary by using alternating colors and report its facilitation to eye guidance in Chinese reading.

Most studies on eye guidance in reading have investigated spaced Indo-European languages. The commonly accepted rule of word-based saccade-target selection has been implemented as one of the core principles in current computational models of eye-movement control in reading, such as E-Z Reader (Reichle, Pollatsek, Fischer, & Rayner, 1998) and SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005). Apparently, word-based saccade-target selection requires clear knowledge about the beginning and end of the target word, which is normally afforded by word spacing. When

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word-boundary knowledge becomes unclear, for instance when spaces are removed from English texts, the FL distribution no longer follows a Gaussian shape, but decreases sharply and linearly from the beginning to the end of a word (Rayner, Fischer, & Pollatsek, 1998; Rayner & Pollatsek, 1996).

The word spacing in alphabetic scripts is a relatively late invention, introduced only around the 8th century and spread to the European continent in the late 10th century (Manguel, 1996; Saenger, 1997). Nowadays, there are still many scripts written naturally, without word spacing, such as Chinese, Japanese, Thai, etc. Because of the lack of explicit word boundary, a saccade-target selection mechanism in these writing systems is less clear. For example, in Chinese, the classical experiments reported by McConkie and colleagues (Tsai & McConkie, 2003; Yang & McConkie, 1999) showed flat FL distributions, and they argued that saccade target selection could either be character based or random: Readers simply deploy saccades of fixed amplitude with some random oculomotor error. However, their key finding has been challenged by some recent investigations (e.g., Yan, Kliegl, Richter, Nuthmann, & Shu, 2010).

Given that the effective field of vision, namely, the perceptual span (McConkie & Rayner, 1975), covers rightwards three or four characters from the current fixation in Chinese (Inhoff & Liu, 1998; Yan, Zhou, Shu, & Kliegl, 2015), which translates to more than two words in most cases, it is possible for skilled Chinese readers to obtain adequate information for parafoveal word segmentation. Yan et al. (2010) proposed a flexible eye guidance model in Chinese sentence reading: If readers fail to acquire enough knowledge about the boundary of the upcoming word during previous fixations, the first character of the upcoming word is chosen as the saccade target, leading to fixation location shifting towards word beginning. Alternatively, if parafoveal word boundary is obtained, readers make saccades aiming at the center of the upcoming word, leading to FL shifting away from word beginning. As a support to the flexible eye guidance model, Yan and Kliegl (2016) recently tested the reading of sentences with structurally ambiguous Chinese character strings (an analogous example in English: CarPrice vs. CarpRice) and found that ambiguous strings in the parafovea produced longer saccades and more rightward fixations for close launch sites than unambiguous ones did, and the reverse result was obtained for far launch sites. These results demonstrate that saccade generation in Chinese can be influenced by parafoveal word-boundary information.

An alternative account has been proposed, suggesting saccade-generation independent of word-boundary knowledge about parafoveal words. For instance, Li, Liu and Rayner (2011) argued that a fixed-length saccade model can generate the same shape of the PVL curve in Chinese. However computation simulation reported by Yan et al. (2010, Fig. 8) clearly showed that a fixed-length saccade model failed to replicate several eye-movement patterns in

Chinese, such as skipping and single fixation probabilities. As a revision of their original proposal, for example, Wei, Li and Pollatsek (2013) showed that properties of the currently fixated word can influence the amplitude of the outgoing saccade and proposed a so-called processing-based strategy for saccade selection in Chinese (see also Luo, Yan, & Zhou 2013 for an earlier demonstration of such an effect). However, the results can also be explained within the framework of the flexible eye guidance model proposed by Yan et al. (2010): Obviously, higher local processing load leads to a smaller perceptual span and thus reduces the possibility in successful word segmentation. In this case, word beginning is more likely chosen as the fixation location, leading to shorter saccade. To summarize, the critical difference between the two models is whether or not parafoveal processing of word segmentation contributes to saccade generation.

In the present study, we further explore if Chinese readers are able to make use of other types of information to achieve word segmentation for saccade target selection, such as information they are unfamiliar with. One common practice to understand the importance of explicit word boundary in general is to introduce artificial word spacing to unspaced writing systems (e.g., Hsu & Huang, 2000a, 2000b; Kohsom & Gobet, 1997; Liu, Yeh, Wang, & Chang, 1974; Perea & Acha, 2009). Only a few studies tested the effect of the insertion of word spacing on eye guidance. For instance, Reilly, Radach, Corbic, and Luksaneeyanawin (2005) reported that Thai readers' PVL for both unspaced and spaced text peaked near word center. Their findings were replicated by Winskel, Radach, and Luksaneeyanawin (2009), who showed that spaces between words facilitated word recognition but did not affect eye guidance or lexical segmentation among Thai–English bilinguals. Word-spacing effect on eye guidance in Japanese reading has been tested by Sainio, Hyönä, Bingushi, and Bertram (2007). It is reported that the insertion of word spacing facilitated both word identification and eye guidance only for the reading of pure syllabic kana characters, but not for the script containing ideographic kanji characters. It is argued that spacing information in mixed text provides redundant information because kanji characters, which are visually salient, already served as a visual cue for saccades (Sainio et al., 2007; see also Kajii, Nazir, & Osaka, 2001). In Chinese, Zang, Liang, Bai, Yan, and Liversedge (2013) reported that inserting word spacing produced shorter fixation duration, lower refixation probabilities, and further landing position for both children and adults, suggesting that word spacing facilitated not only word identification but also eye guidance.

Inserting word spacing into unspaced texts introduces changes in the reading situation that may limit the generalizability to normal unspaced reading. First, introducing spaces interferes with the well-established behavior of the readers of unspaced scripts over years (Kohsom & Gobet, 1997). Second, artificial word spacing pushes the upcoming words

into a more eccentric position and thus reduces parafoveal processing efficiency (Perea, Tejero, & Winsky, 2015). Third, introducing spaces increases launch site (i.e., the difference between the last fixation location and the beginning of the currently fixated word), which is a major determinant of fixation location within words (e.g., Engbert & Krügel, 2010; McConkie et al., 1988; Nuthmann, Engbert, & Kliegl, 2005). Finally, when comparing words with legal and illegal spacing, within-word spaces in the latter case apparently make words physically longer.

There is an alternative facilitation of word segmentation without introducing spaces: Bai, Yan, Liversedge, Zang, and Rayner (2008) used a background highlighting manipulation. Although, in principle, the variability in luminance may also have an effect on eye guidance which does not present in normal reading, this manipulation preserves the spatial layout of the text. We considered Perea et al.'s (2015) color-demarking method and other research using this technique reviewed in the next section as an even less intrusive option to facilitate word segmentation, and used a similar technique in Experiment 1 to test the effect of explicit word-boundary information on Chinese reading and saccade-target selection. In Experiment 2, we will use this technique in combination with a gaze-contingent moving-window paradigm to examine benefits and costs of word-boundary information presented in parafoveal vision, proving a further test for the theoretical debate on Chinese saccade selection.

Experiment 1

In this experiment, Chinese participants read sentences with words presented in alternating colors to make word boundaries explicit. The method of alternating colors has been used for other purposes during sentence processing. For instance, Inhoff, Seymour, and Radach (2012) used different colors for dialogues of female and male characters. Analyses of oculomotor activity demonstrated shorter viewing durations in congruent than in incongruent or no-color control conditions during dialogue reading. Häikiö, Hyönä and Bertram (2015) investigated whether alternating colors of syllables would facilitate word recognition during reading and found that it indeed elicited shorter reading times than did hyphenation. Reingold, Sheridan, Meadmore, Drieghe, and Liversedge (2016) showed different patterns between the processing of target words and critical distractors, which were presented in different colors.

The most relevant study for our experiment was reported by Perea et al. (2015). They examined whether colors could effectively segment words during reading in unspaced Spanish. In the unspaced alternating color condition, there was only a small, but significant reading cost relative to the spaced sentences, and performance was better when compared

to an unspaced one-color condition in a number of eye-movement measures. Thus, the lack of word spacing in Spanish could be compensated with alternating word colors to some degree for saccades target selection, but there still was some disruption due to unspaced layout. Of course, this effect may be due to the default spaced layout of Spanish. Given the default unspaced layout of Chinese, we expected (a) benefits for alternating word colors as well as (b) costs for alternating colors violated word boundaries, relative to normal uniform unspaced sentences.

Method

Participants

Thirty-six undergraduate students from Beijing Normal University were recruited to participate in the eye-tracking experiment. All were native speakers of Chinese and had normal or corrected-to-normal vision. None of them had been diagnosed of any color vision deficiency. All experimental procedures were reviewed and approved by the Ethics Committee of the State Key Lab of Cognitive Neuroscience and Learning, Beijing Normal University. Participants gave their written informed consent prior to the experiment, which conformed to the tenets of the Declaration of Helsinki.

Materials and design

Beijing Sentence Corpus (BSC) comprising 150 sentences (Yan et al., 2010) was employed as the material. The reading material was selected and edited to avoid word-boundary ambiguity. The sentences were 15 to 25 characters ($M = 21.0$, $SD = 2.5$) or seven to 15 words ($M = 11.2$, $SD = 1.6$) in length and comprised 1,686 tokens of 936 words (types). Being representative for Chinese language, most word types in the BSC were two characters in length.

As the experimental manipulation, we presented the sentences in three different conditions, as illustrated in Fig. 1. In the control condition the sentences were presented in the *uniform* colors. In the *word segment* condition, the alternating colors were consistent with the word boundaries. In the *nonword segment* condition, we assigned alternating colors on groups of characters that formed a nonword. For each sentence in each condition, we created two different versions that began with either a red or green color; therefore, there were equal numbers of characters and words in each color overall. There is no significant difference in number of segmentations between the word condition and nonword condition ($t = 1.142$, $p = .254$). The conditions were presented in blocks, and the order of the conditions was counterbalanced over subjects.

Uniform color condition

近来动物园首次对孔雀成功进行了人工繁殖。

Word segmentation condition

近来动物园首次对孔雀成功进行了人工繁殖。

Non-word segmentation condition

近来动物园首次对孔雀成功进行了人工繁殖。

Fig. 1 An illustration of experimental stimuli in different conditions in Experiment 1. The sentence is translated as: “*The zoo recently successfully conducted artificial propagation to peacocks for the first time.*” (Color figure online)

Apparatus

Readers’ eye movements were recorded by an EyeLink CL desktop system at a rate of 1000 Hz. Each sentence was presented on a vertical position one-third from the top of a 21-inch DELL P1130 CRT monitor (resolution, 1024×768 pixels; frame rate, 120 Hz). The distance between the monitor and subjects’ eyes was 60 cm. Each character occupied a 32×32 -pixel grid with one character equal to approximately 1.2 degrees of visual angle. All recordings and calibrations were done monocularly based on the right eye, and viewing was binocular.

Procedure

Participants were instructed to read the sentences silently for comprehension, then fixate on 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. Before the experiment, participants completed the calibration with a 9-point grid. After validation of calibration accuracy and prior to the presentation of each sentence, a fixation point appeared on the left side of the monitor for a drift check. On failure in detecting participants’ eyes around the initial fixation point, an extra calibration was performed. Fixation on the fixation point initiated presentation of the next sentence with its first character occupying the position of the fixation point. Thirty-eight sentences were followed by an easy yes–no question, which the participants answered with two different joystick buttons. Participants correctly answered 95% of all questions ($SD = 4\%$).

Data analysis

We adapted the algorithm for saccade detection (Engbert & Kliegl, 2003) to determine fixations in Chinese reading. For eye-movement measure analyses, sentences containing blinks, extremely low numbers of effectively fixated words

(i.e., less than three), coughs, or body movements during data collection were deleted ($n = 448$, 8%). For the analyses of all eye-movement measures, observation filters at different levels were applied. The first and last words and the first and last fixated words in a trial (i.e., a total of 11,438 words) were removed. First-fixation durations (FFDs; the first fixation on a word, irrespective of the number of fixations) shorter than 60 ms or longer than 800 ms and gaze durations (GDs; the sum of fixations during the first pass reading of a word) longer than 1,000 ms were excluded from the analyses of FFD, FL, GD, refixation probability (RP; how likely a word is fixated on more than once during the first-pass reading). Taken together, we sustained 30,585 fixated words (i.e., 99% of all valid words). Because most of the fixated words ($n = 23835$, 78%) were two characters in length, we focused on these words for eye-movement measure analyses. Finally, we excluded observations with an extremely far launch site (i.e., more than four characters); because the average saccade amplitude is only 2.3 characters in Chinese (e.g., Inhoff & Liu, 1998; Yan et al., 2015), these observations were very rare ($n = 393$, 1.6%) and may reflect oculomotor or tracker errors. To sum up, eye-movement measure analyses were based on 23,442 data points fixated on two-character words.

Estimates are based on linear mixed models (LMMs) for fixation location and duration analyses and on generalized linear mixed model (GLMMs) for skipping and refixation rate analyses, with variance components estimated for subjects and for items (i.e., varying intercepts and slopes), using the lmer program of the lme4 package (Version 1.1-12; Bates, Maechler, Bolker, & Walker, 2016) in the R environment for statistical computing and graphics (Version 3.3.0; R Core Team, 2016). Inferential statistics were based on a treatment contrast with the *uniform* color condition as a reference for the other two conditions. The main factors to determine eye-movement parameters are word length, word frequency, and launch site (i.e., the distance between the location of the last fixation and the beginning of the currently fixated word; McConkie et al., 1988). Therefore, in the following LMMs for FL, RP, FFD and GD, we included log-transformed word frequency (Cai & Brysbaert, 2010) and launch site as covariates (both were centered on their grand means). In LMMs, estimates 1.96 times larger than their standard errors are interpreted as significant at the 5% level, this is because given the number of subjects and the large number of observations for each subject, the t statistic in LMMs (i.e., M/SE) effectively corresponds to the z statistic. In addition, we report the 95% highest posterior density interval (computed using the profile function in the lme4 package) for each fixed effect in the LMM for FL. Log-transformed dependent variables of fixation durations are used in the models (Kliegl, Masson, & Richter, 2010).

Results

Global analyses

Subjects read sentences numerically fastest in the word segment condition at a rate of 369 cpm (characters per minute), which is not statistically different from the reading speed in the uniform color condition (364 cpm). The reading speed was slower in the nonword segment (338 cpm) than in the uniform color condition ($b = -0.079$, $SE = 0.024$, $t = -3.22$). On average, subjects skipped 29% of words. Skipping probability was lower in the nonword segment (27%) than in the uniform color condition (30%; $b = -0.162$, $SE = 0.027$, $z = -6.08$, $p < .001$). The difference between the word segment (30%) and uniform color conditions was not significant ($b = -0.011$, $SE = 0.026$, $z = -0.41$, $p = .684$). Effects of experimental manipulation on eye-movement measures are shown in Table 1 and Fig. 2.

Fixation location

FLs relative to word beginning (operationally defined as the distance between first-fixation location and word beginning in pixel divided by character length in pixel) shifted further away from word beginning with increasing word frequency ($b = 0.021$, $SE = 0.008$, $t = 2.57$) and with decreasing launch site ($b = -0.403$, $SE = 0.006$, $t = -62.52$). The most critical findings revealed in the analysis are partial effects of the experimental manipulation (i.e., based on LMM estimates after statistical control of other variables in the model and also the removal of subject- and sentence-related varying intercepts). FLs were closer to the word center in the word segment condition than in the uniform color condition ($b = 0.031$, $SE = 0.013$, $t = 2.42$), and FLs were closer to the word beginning in the nonword segment condition than in the uniform color condition ($b = -0.039$, $SE = 0.014$, $t = -2.73$).

Refixation probability

Using the same predictors as the LMM for FL (except that random slopes had to be dropped for successful model convergence), we found that as compared to the uniform color condition, readers were less likely to refixate on a word in the

word segment condition ($b = -0.128$, $SE = 0.052$, $z = -2.46$, $p = .014$), and they were more likely to do so in the nonword segment condition ($b = 0.325$, $SE = 0.049$, $z = 6.60$, $p < .001$). In addition, we also found that refixation probability decreased with increasing word frequency ($b = -0.223$, $SE = 0.047$, $z = -4.79$, $p < .001$) and with decreasing launch site ($b = 0.504$, $SE = 0.045$, $z = 11.28$, $p < .001$). Finally, there was also evidence that the difference between the word segment and uniform color conditions depends on launch site ($b = 0.135$, $SE = 0.060$, $z = 2.25$, $p = .024$).

Fixation duration

Fixation durations increased with increasing launch site (FFD: $b = 0.009$, $SE = 0.004$, $t = 2.14$; GD: $b = 0.044$, $SE = 0.005$, $t = 8.21$) and with decreasing word frequency (FFD: $b = -0.032$, $SE = 0.005$, $t = -7.0$; GD: $b = -0.049$, $SE = 0.006$, $t = -8.07$). As compared to the uniform color condition, readers have longer fixations in the nonword segment condition (FFD: $b = 0.027$, $SE = 0.010$, $t = 2.74$; GD: $b = 0.051$, $SE = 0.014$, $t = 3.61$). The experimental manipulation significantly interacted with launch site: As shown in Fig. 3, the difference in GD between the nonword segment and uniform color conditions was larger with far launch site ($b = 0.020$, $SE = 0.008$, $t = 2.54$); GD in the word segment condition was shorter than in the uniform color condition when launch site was close ($b = 0.017$, $SE = 0.008$, $t = 2.23$).

Discussion

In Experiment 1, we tested the effect of word boundary, as afforded by alternating colors, on eye-movement control in Chinese sentence reading. We hypothesized that as compared to the insertion of word spacing, alternating colors can serve as a more natural and effective cue to provide word boundary information because parafoveal words retain their eccentricities. Other methods, such as adding frames around word units (Chen & Tsai, 2016) or luminance contrasts (Bai et al., 2008), were also proposed to solve the eccentricity problem; in contrast, alternating colors apparently keep reading more natural. The results of Experiment 1 are overall very clear-cut:

Table 1 Eye movement measures in Experiment 1

Condition	RS	FFD	FL	GD	RP	SP
Uniform	364 (13)	268 (5)	.96 (.04)	302 (8)	12.7 (2.4)	30.1 (1.7)
Word	369 (13)	269 (6)	.99 (.04)	299 (9)	11.5 (2.4)	29.8 (1.7)
Nonword	338 (12)	275 (5)	.92 (.04)	319 (10)	16.1 (2.4)	26.9 (1.7)

Note. Means (and standard errors, in parentheses) of reading speed (RS) in characters per minute, first-fixation location (FL) in characters, first-fixation duration (FFD) in ms, gaze duration (GD) in ms, refixation probability (RP) in percentages, and skipping probability (SP) in percentages for the experimental conditions. Values are LMM partial effects

Fig. 2 Parameter estimates and 95% highest posterior density intervals (HPDIs) for square root of variance components (standard deviations) and fixed effects produced by the LMM for fixation location, gaze

duration and refixation rate in Experiment 1. Symbol sizes are in proportion to the precision of the estimates. The plot is based on the forest function of the metafor package in R (Viechtbauer, 2010)

Across different eye-movement measures, there is cost associated with incorrectly marked word boundaries and

benefit associated with correct ones. As compared to some previous studies that manipulated word spacing

Fig. 3 LMM partial effects of interactions between experimental effects and launch site in gaze duration in Experiment 1. Plots were generated with the remef package (Version 0.6.10; Hohenstein & Kliegl, 2015) and the ggplot2 package (Version 2.1.0; Wickham, 2009)

and reported limited benefit under restricted circumstances (e.g., Liu et al., 1974; Hsu & Huang, 2000a, 2000b), we offer a better understanding of the role that the word boundary plays for Chinese reading in Experiment 1 while retaining the natural unspaced spatial layout.

The central topic of the present study is whether Chinese readers are able to make use of the artificially introduced word-boundary information to facilitate eye guidance. As compared to the baseline, Chinese readers shifted FLs more rightward when color and word boundary were consistent and shifted more leftward when they were not. These results indicate that word boundary is indeed involved in eye guidance. These results are in agreement with the flexible saccade model proposed by Yan et al. (2010), indicating that fixation locations, refixations, and gaze durations in Chinese are associated with word-segmentation facilitation and word-segmentation difficulty. The results also agree with a view proposed by Lin and Yeh (2015) that peripheral characters can be grouped into words and facilitate reading, by aggregating the texts into fewer meaningful units and thus reduce the number of fixations. What are the implications of these results for competing accounts of eye guidance during reading Chinese script?

Our results are difficult to reconcile with random saccade models, which assume that saccades are generated to be of constant amplitude, with a certain distribution of random errors (e.g., see Yan et al., 2010, for a computational simulation). In the processing-based saccade model, it is proposed that saccades are generated independently of words and word segment processing occurs in foveal, but not parafoveal vision. Thus, according to this account, word boundaries afforded by alternating colors facilitate only *foveal* lexical processing. By reducing local processing load, more attentional resource is allowed for parafoveal processing (Henderson & Ferreira, 1990; Yan, et al., 2015). In this case, the processing-based strategy could potentially explain the results of Experiment 1 that readers program longer saccades when foveal processing demands are low.

Therefore, one limitation of Experiment 1 is that, because word boundary is provided in both parafovea and fovea, results do not tease apart two types of saccade models in Chinese: the flexible model and the processing-based strategy. Although the flexible model includes a character-based saccade component when parafoveal segmentation of the upcoming word fails, the processing-based saccade model (as a type of purely character-based model) differs from it in that the latter denies any use of word boundary knowledge before a word is fixated. In Experiment 2 we eliminating foveal word-boundary information to provide an additional test of these two competing accounts.

Experiment 2

The main results of Experiment 1 showed benefit from correctly color-marked word boundary, as well as cost from incorrectly color-marked word boundary, suggesting that alternating colors can be used as an efficient method to improve eye movement control in Chinese reading. However, it leaves open the question whether the benefit with respect to eye guidance was due to foveal or parafoveal processing of the word-boundary information. We sought to shed light on the debate of saccade-target selection in Chinese in Experiment 2 by combining the experimental manipulation with a gaze-contingent moving-window paradigm (McConkie & Rayner, 1975). Experiment 2 differs from Experiment 1 in that the color manipulation is gaze contingent and starts only with the next upcoming word. As illustrated in Fig. 4, across all conditions, color marking of characters only starts from the first word beyond the currently fixated one, and thus the end of the current word is always clear to readers. The boundaries of the upcoming words are correctly marked only in the parafoveal word segment condition but not in the other two. This way, any difference in FL can only be attributed to parafoveal but not to foveal word-boundary processing. If parafoveal word-boundary information is not used for saccade generation in Chinese reading, introducing explicit word-boundary information by alternating colors should not facilitate eye-movement control. Alternatively, the flexible model predicts FL depending on the ease of parafoveal word segmentation. The explicit word-boundary information should lead to FLs closer to word center as well as less refixations in the parafoveal word segment condition when explicit word-boundary is provided.

Parafoveal uniform color condition

近来动物园首次对孔雀成功进行了人工繁殖。

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Parafoveal word segmentation condition

近来动物园首次对孔雀成功进行了人工繁殖。

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Parafoveal non-word segmentation condition

近来动物园首次对孔雀成功进行了人工繁殖

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Fig. 4 Experimental stimuli in different conditions in Experiment 2. Asterisks indicate reader's fixation locations. (Color figure online)

Method

Participants

An independent sample of 33 undergraduate students from Beijing Normal University participated in Experiment 2. All were native speakers of Chinese and had normal or corrected-to-normal vision. None of them had color vision deficiency.

Materials, apparatus, procedure, and data analysis

Materials, apparatus, and procedure were largely identical to those of Experiment 1, except that the materials were now submitted to a gaze-contingent manipulation as shown in Fig. 4.

Participants correctly answered 95% ($SD = 4.0\%$) of all questions. Participants' blink, cough, or body movement during reading or tracker error resulted in a removal of 202 (i.e., 4%) trials. Using the same fixation filters as Experiment 1, we sustained 20,440 fixated two-character words (i.e., 98% of all valid words) for the following analyses.

Results

Global analyses

Subjects read sentences numerically but not statistically faster in the word segment condition at a rate of 440 cpm than in the uniform color condition (427 cpm) and the nonword condition (429 cpm). The skipping probability was lower in the uniform color condition (34%) than in the word segment condition (35%; $b = 0.072$, $SE = 0.026$, $z = 2.77$, $p = .006$). The difference between nonword segment (34%) and uniform color conditions was not significant ($b = 0.005$, $SE = 0.026$, $z = 0.18$, $p = .861$). Effects of experimental manipulation on eye-movement measures are shown in Table 2 and Fig. 5.

Fixation location

FLs increased with word frequency ($b = 0.022$, $SE = 0.008$, $t = 2.70$) and decreased with launch site ($b = -0.408$, $SE = 0.007$, $t = -60.34$). Similar to the results in Experiment 1 and, as

shown in Fig. 5, FLs shifted further away from word beginning in the word segment condition than in the uniform color condition ($b = 0.046$, $SE = 0.017$, $t = 2.73$). The main effect of the contrast between the nonword segment condition and the uniform color condition was not significant ($b = 0.004$, $SE = 0.020$, $t = 0.21$).

In an additional analysis, we found a significant interaction between word-uniform contrast and trial counts ($b = 0.0006$, $SE = 0.0002$, $t = 2.68$), indicating that there was a reliable difference in FL between the word and the uniform conditions only for the second half of trials ($b = 0.066$, $SE = 0.014$, $t = 4.82$) but not for the first half ($b = 0.018$, $SE = 0.012$, $t = 1.42$), suggesting that there is some learning effect associated with the benefit in reading triggered by color-based cues.

Refixation probability

Using the same GLMM as in Experiment 1, we replicated the findings that as compared to the uniform color condition, readers were less likely to refixate a word in the word segment condition ($b = -0.252$, $SE = 0.068$, $z = -3.70$, $p < .001$) and they were more likely to refixate a word in the nonword segment condition ($b = 0.255$, $SE = 0.062$, $z = 4.10$, $p < .001$). In addition, we also found that refixation probability decreased with increasing word frequency ($b = -0.244$, $SE = 0.055$, $z = -4.46$, $p < .001$) and with decreasing launch site ($b = 0.554$, $SE = 0.055$, $z = 10.10$, $p < .001$).

Fixation duration

Fixation duration increased with increasing launch site (GD: $b = 0.039$, $SE = 0.005$, $t = 7.76$) and with decreasing word frequency (FFD: $b = -0.030$, $SE = 0.005$, $t = -6.17$; GD: $b = -0.043$, $SE = 0.006$, $t = -7.12$). There were also interactions between launch site and word frequency on fixation duration (FFD: $b = -0.009$, $SE = 0.004$, $t = -1.95$; GD: $b = -0.012$, $SE = 0.005$, $t = -2.22$). Simple effect tests showed that the increase in fixation duration with increasing launch site was stronger for low-frequency words (FFD: $b = 0.010$, $SE = 0.004$, $t = 2.76$ and GD: $b = 0.044$, $SE = 0.004$, $t = 10.11$) than for high-frequency words (FFD: $b = 0.005$, $SE = 0.003$, $t = 1.48$ and GD: $b = 0.027$, $SE = 0.004$, $t = 6.61$). None of main

Table 2 Eye movement measures in Experiment 2

Condition	RS	FFD	FL	GD	RP	SP
Uniform	427 (20)	263 (7)	.98 (.04)	283 (8)	7.3 (1.5)	33.8 (2.2)
Word	440 (22)	264 (7)	1.03 (.04)	281 (9)	5.9 (1.5)	35.3 (2.2)
Nonword	429 (24)	266 (7)	.99 (.05)	290 (9)	9.0 (1.5)	33.9 (2.2)

Note. Means (and standard errors, in parentheses) of reading speed (RS) in characters per minute, first-fixation location (FL) in characters, first-fixation duration (FFD) in ms, gaze duration (GD) in ms, refixation probability (RP) in percentages, and skipping probability (SP) in percentages for the experimental conditions. Values are LMM partial effects

Fig. 5 Parameter estimates and 95% HPDIs for square root of variance components (standard deviations) and fixed effects produced by the LMM for fixation location, gaze duration, and refixation rate in

Experiment 2, generated using the metafor package in R (Viechtbauer, 2010). Symbol sizes are in proportion to the precision of the estimates

effects and interactions relating to the experimental manipulation were significant for FFD and GD.

Discussion

As introduced earlier, there is a theoretical debate about what constitutes the basic unit for saccade generation in Chinese. The fundamental difference between competing accounts relates to the use of parafoveal word-boundary information during saccade generation. In Experiment 2, we provided novel positive evidence for the flexible eye-guidance model in Chinese (Yan et al., 2010).

The model proposed by Li et al. (2011; see Li, 2015, for a recent summary) derives from a traditional view of purely low-level eye guidance in alphabetic scripts. Previously, studies on alphabetic scripts have achieved a commonly accepted understanding that saccade-target selection is primarily based on word length and launch site (see Radach & Kennedy, 2013, for a review). The view that saccade generation is based only on purely low-level visual features is currently challenged by some new findings. In two experiments, respectively implementing corpus-analytic and experimental control approaches, Yan et al. (2014) reported consistent effects of morphological complexity on FL during the reading of Uighur script, an Arabic-derived agglutinative alphabetic language with rich suffixes. In a replication of their critical findings in Finnish, another morphologically rich language, Hyönä, Yan, and Vainio (2016) found that FL shifted closer to the word beginning for morphologically complex than for monomorphemic words. Lexical effects on fixation locations have also been reported for German (Hohenstein, Matuschek, & Kliegl, 2017). These findings are theoretically relevant and suggest that, depending on the language environment, high-level factors can be jointly utilized with low-level factors to influence

saccade generation during reading. In Chinese, word boundaries are not explicitly marked. Therefore, the word-boundary influence on Chinese saccade generation in Experiment 2 clearly goes beyond a visual level effect.

Among different types of unspaced scripts, Japanese may naturally contain the most useful information related to word boundary due to the contrast between kanji and kana characters (Sainio et al., 2007). Chinese is different from Japanese in that no visual cue from different character sets can hinder word boundary. Although Zang et al. (2013) reported that word spacing facilitated eye guidance, due to the lack of an illegal word spacing condition as a baseline control, whether their results were due to the introduction of word boundary or simply due to a visual-crowding effect (Stuart & Burian, 1962) remains unclear. Using strings of Chinese characters with word-boundary parsing ambiguity, Yan and Kliegl (2016) demonstrated that saccade generation is influenced by parafoveal word segmentation as a proof of principle; the generalizability to Chinese sentences with no word-boundary ambiguity remains to be established. Experiment 2 answers such a call: The observed differences in FL and refixation probability are consistent with the prediction from the flexible eye-guidance model. The lack of difference in duration measures among experimental conditions may suggest that fixation durations are less affected by parafoveal word boundary, indicating that the when and where decisions of oculomotor control (i.e., when to move the eyes and where to send them) are largely independent of one another (e.g., Brysbaert, Drieghe, & Vitu, 2005; Vainio, Hyönä, & Pajunen, 2009).

Finally, the results can be considered together with a mathematical model proposed by Krügel and Engbert (2014), who proposed that the sensory noise during the computation of the word center from word boundary can have an impact on the distribution of FL. It is reasonable to assume that the word-

boundary information is noisier in the parafoveal nonword segmentation condition than in the parafoveal uniform color condition, leading to a boarder distribution of averaged sensory estimation of the word center. In this case, saccades are more likely to land in a nonoptimal viewing location, leading to more refixations (Nuthmann et al., 2005).

General discussion

In the present study, we applied the alternating colors to Chinese sentences as a salient visual cue for word boundary. As pointed out by Perea et al. (2015), alternating colors facilitate the processing of word segmentation without compromising visual acuity. Their results revealed only a small cost during the reading of unspaced alternating-color Spanish sentences as compared to normal-spaced sentences, demonstrating that color is useful to segment words for the reading of spaced orthographies. We propose, in the present study, that alternating colors is of greater importance for scripts that are naturally written without spaces because the normal spatial layout is preserved, allowing readers to maintain the processing advantage of the upcoming words with high visual acuity. However, the use of alternating colors for word segmentation may still not be a completely natural manipulation.

In Experiment 1, we observed facilitations in a number of eye-movement measures due to correctly color-marked word-boundary and processing costs in the nonword segment condition. Our results differ from a classic view assuming little benefit from introducing explicit word-boundary information to normal Chinese sentences (Liu et al., 1974). Arguably the insertion of word spacing reduces parafoveal processing efficiency and interferes with normal reading behavior and thus may not provide a fair test for the use of word-boundary information. Our results, especially those in fixation durations, indicate that clear word boundary is critical for foveal lexical processing and thus in principle agree with the findings by Inhoff and Wu (2005), who showed longer viewing time when processing Chinese character strings with word-boundary ambiguity as compared to unambiguous ones (see also Yan & Kliegl, 2016). These studies provided important evidence showing that all characters within the perceptual span can form viable word units without directional constraint. Obviously, explicit word-boundary afforded by alternating colors can minimize the competition between several possible candidates and thus lead to facilitation in lexical processing.

With respect to a theoretical contribution to saccade generation in Chinese reading, Experiment 1 did not provide strong evidence for or against the flexible model or the purely character-based model, although it does show that saccades are not generated at random. Experiment 2 was designed to test whether parafoveal word-boundary information

influences saccade generation in sentence reading. Differences in FL imply that saccade generation can make use of information beyond the character level, and thus are in agreement with the flexible eye-guidance model (Pan, Yan, Laubrock, Shu, & Kliegl, 2014; Yan et al., 2010). As compared to Yan and Kliegl (2016), the present results are obtained from a larger set and a more representative sample of materials.

To conclude, the present study provides further insight into the theoretical debate of saccade-target selection in Chinese, as well as to that of high-level versus low-level guidance of eye movements. We used a manipulation of alternating colors to facilitate the process of word segmentation without compromising visual acuity and found that word-boundary information afforded by alternating colors facilitates lexical processing and saccade generation. It will be of great theoretical interests to generalize the effect of word boundary to readers with different reading abilities and to different unspaced writing systems.

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