Further Tests of a Dynamic-Adjustment Account of Saccade Targeting During the Reading of Chinese

Yanping Liu[1], Ren Huang[1], Ding-Guo Gao[1], & Erik D. Reichle[2]

1. *Department of Psychology, Sun Yat-sen University, China*

2. *School of Psychology, University of Southampton, U.K.*

Author Note

Correspondence regarding this article should be addressed to Yanping Liu, Department of Psychology, Sun Yat-sen University, Guangzhou 510275, China (e-mail: liuyp33@mail.sysu.edu.cn). This research was supported by the grants from the China Postdoctoral Science Foundation (2013M541073 & 2014T70132) awarded to the first author, the National Natural Science Foundation of China (31500890 & 31371028) awarded to the first and third author, and the U.S. National Institute of Health (RO1HD075800) awarded to the last author.

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Running head: Dynamic Saccade Targeting

There are two accounts of how readers of unspaced writing systems (e.g., Chinese) know where to move their eyes: (1) saccades are directed towards default targets (e.g., centers of words that have been segmented in the parafovea); or (2) saccade lengths are adjusted dynamically, as a function of ongoing parafoveal processing. This article reports an eye-movement experiment supporting the latter hypothesis by demonstrating that the slope of the relationship between the saccade launch site on word *N* and the subsequent fixation landing site on word *N* + 1 is greater than 1, suggesting that saccades are lengthened from launch sites that afford more parafoveal processing. This conclusion is then evaluated and confirmed via simulations using implementations of both hypotheses (Liu, Reichle, & Li, 2016), with a discussion of these results for our understanding of saccadic targeting during reading and existing models of eye-movement control.

In writing systems with clearly demarcated word boundaries such as English, the mechanisms for deciding where to move the eyes during reading appear to be fairly well understood: Most progressive saccades are directed near the centers of upcoming words using information from parafoveal vision to locate the blank spaces between words, presumably because such viewing locations afford efficient lexical processing (referred as *default-targeting account*; Rayner, 1979, 1998). However, in writing systems without clear word boundaries such as Chinese, saccade targeting is not well understood because individual words (which also vary in length) are not demarcated by blank spaces, making it unclear how readers know where to move their eyes to identify words most efficiently. The purpose of this paper is to test a prediction of and thereby further evaluate one hypothesis of how readers of Chinese select saccade targets—the *dynamic-adjustment account* (Liu et al., 2016; see also Bicknell, Higgins, Levy, & Rayner, 2013). According to this account, saccade lengths are adjusted continuously in a manner that directly reflects the amount of information available from the parafovea, so as to move the eyes to nonspecific locations that support maximal lexical processing.

In contrast to the more widely endorsed view that saccades are simply directed towards default targets using low-level perceptual cues, the dynamic-adjustment hypothesis posits that, during each 200-250 ms fixation during reading, the brain systems that are engaged during reading acquire information from the fixated (i.e., foveal) word for the purpose of lexical processing, as well as some amount of information from the next (i.e., parafoveal) word for the purpose of deciding how far to move the eyes. According this account, a fixated word that is easy to identify (e.g., because it occurs frequently in printed text; Rayner, 1998) also affords more time for parafoveal processing, thereby allowing the eyes to be moved further from the word during the next saccade. The dynamic-adjustment hypothesis is thus in harmony with evidence suggesting that the locations of impending fixations may be preceded by covert attention shifts (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Rafal, Calabresi, Brennan, & Sciolto, 1989; Rayner, McConkie, & Ehrlich, 1978; Remington, 1980; Shepherd, Findlay, & Hockey, 1986), as well as evidence low processing load in the fovea allows more extensive parafoveal preview (e.g., Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White, Rayner, & Liversedge, 2005). The debate about saccade targeting during reading thus touches upon broader theoretical issues related to the role of attention during saccade targeting, and the question of how attention, lexical processing, and eye movements are coordinated to supported skilled reading.

To appreciate why it has been difficult differentiating between these two accounts, it is necessary to provide some background about what is known about saccade targeting during reading. Eye-movement experiments involving the reading of alphabetic languages like English indicate that readers tend to fixate just to the left of the centers of words, on the *preferred viewing location* (*PVL*; Rayner, 1979). This finding has led to the assumption that readers attempt to move their eyes towards specific saccade targets (e.g., the centers of words) but that, for any number of reasons (e.g., a bias to move the eyes some preferred distance; McConkie, Kerr, Reddix, & Zola, 1988) the distribution of fixations tend to be centered on the PVL. Indeed, this is the dominant assumption of current models of eye-movement control in reading (e.g., *E-Z Reader*: Reichle, Pollatsek, Fisher, & Rayner, 1998; *Glenmore*: Reilly & Radach, 2006; *SWIFT*: Engbert, Nuthmann, Richter, & Kliegl, 2005). On the basis of parsimony, therefore, one might assume that similar principles determine where readers of Chinese move their eyes with the possible caveat that precise saccade targets are more difficult to identify because of the absence of obvious word boundaries. This line of reasoning is tenable and the eye-movement data collected from eye-movement experiments involving the reading of Chinese has been interpreted in this way.

For example, a seminal study by Yan, Kliegl, Richter, Nuthmann, and Shu (2010) examined the PVL curves of Chinese readers and found something interesting: Although words that were the recipients of a single fixation tended to be fixated near their centers, words that were the recipients of two or more fixations tended to be initially fixated near their beginnings. This pattern was interpreted as follows: Words that were fixated once were more likely to have been segmented from the parafovea (i.e., during the previous fixation), allowing the eyes to be directed towards the PVL and thus making the word more likely to be identified during a single fixation; however, words that were fixated two or more times were unlikely to have been segmented from the parafovea, causing the eyes to be directed towards the word's beginning and thus increasing the necessity of a second fixation. The line of reasoning thus resulted in the following variant of the basic default-targeting hypothesis: Saccades are directed towards one default target (the PVL) of words that have been parafoveally segmented but directed towards a different default target (a word's beginning) for words that have not been segmented. This hypothesis is consistent with Yan et al.'s findings and is consistent with findings that the PVL moves towards the beginning of words when the spaces between words are removed (e.g., Kajii, Nazir & Osaka, 2001; Rayner, Fischer, & Pollatsek, 1998). But there are also at least a few results that appear problematic for this hypothesis.

For example, other eye-movement studies have shown that PVL curves during Chinese reading are very uniform (e.g., see Figure 8.1 in Tsai & McConkie, 2003; and Table 10.4 in Yang & McConkie, 1999), suggesting that readers of Chinese have no preferred saccade targets (because otherwise the PVL curves would appear bimodal, with peaks corresponding to the beginnings and centers of words). Consistent with this interpretation, there is also evidence that readers of Chinese are just as apt to fixate the blank spaces between characters as the characters themselves, also suggesting the lack of preferred saccade targets (e.g., see also Table 10.4 in Yang & McConkie, 1999). And similarly, the pattern reported by Yan et al. (2010) has been observed even under conditions in which parafoveal segmentation is not even necessary, such as when reading Chinese text in which the words boundaries have been made clear with inserted spaces (Zang, Liang, Bai, Yan, & Liversedge, 2013), or reading "shuffled" Chinese characters (Ma, Li, & Pollatsek, 2015), or even searching through character-like Landolt-*C* stimuli to detect targets (Liu, Reichle, & Huang, 2016).

And potentially more problematic is the fact that the relationship between the number of fixations on a word and the location of the initial fixation that is central to Yan et al.'s (2010) hypothesis may be an artifact of their statistical analysis. The crux of this potential problem is related to the question of causality. That is, does successful parafoveal segmentation of a word make it more likely that that word will be fixated only once, near its center, as Yan et al. proposed? Or alternatively, is a word that happens to be fixated once, near its center, less likely to be fixated twice? This second account was explicitly tested by Li, Liu, and Rayner (2011) using a Monte Carlo procedure to simulate saccade targeting during the reading of Chinese; the assumption of a constant saccade length (with some random variability) was sufficient to reproduce the pattern of eye movements observed by Yan et al., thus lending support to the interpretation that words that happen to be initially fixated near their center are simply less likely to be refixated.

The aforementioned studies provide evidence against a strong version of the default-targeting hypothesis—at least during the reading of Chinese. There is also evidence consistent with the dynamic-adjustment hypothesis during the reading of Chinese, but also during the reading of alphabetic languages like English. For example, Rayner, Ashby, Pollatsek, and Reichle (2004; see also White & Liversedge, 2006) showed that the length of saccade exiting a word is modulated by the word's frequency, with saccades being longer from high- than low-frequency words. Similar results have been reported with Chinese (e.g., Li, Bicknell, Liu, Wei, & Rayner, 2014; Wei, Li, & Pollatsek, 2013). Wei et al. proposed a "processing-based strategy" to account for these findings—one in which readers of Chinese use local processing difficulty to gauge how far to move their eyes so that saccades will move the eyes just to the right of characters being identified from each fixation[1]. Extending this work, Liu, Reichle, and Li (2015) further found that the lengths of saccades exiting target words were modulated by their frequency, but only when a preview of upcoming words was available, suggesting readers of Chinese may program or modulate saccade length based on the amount of parafoveal processing completed.

Unfortunately, the debate about how readers know where to move their eyes has not been resolved because both the default-targeting and dynamic-adjustment hypotheses explain findings like the ones described in the previous paragraph. For example, the default-targeting hypothesis can explain the finding that saccade length varies as a function of the frequency of the launch-site word by recourse to the well-established finding that foveal processing difficulty modulates parafoveal preview (Henderson & Ferriera, 1990; Kennison & Clifton, 1995; White et al., 2005). By this account, a fixation on a high-frequency word N affords more preview of word $N + 1$, making it more likely that word $N + 1$ will be processed to the degree required for it to be skipped, thus (on average) increasing the length of the saccade leaving word N.

To address this debate, Liu et al. (2016) used computer simulations to evaluate how well formally implemented variants of the default-targeting and dynamic-adjustment hypotheses account for the results of an eye-movement experiment that was specifically designed to examine the roles of lexical-processing difficulty and preview availability of saccadic targeting. This analysis showed that saccade lengths entering and exiting target words were modulated by their frequency and preview availability, with longer saccades when the words were high frequency and previewed normally (see also Yan & Kliegl, 2016). Importantly, the results of simulations using default-targeting and dynamic-adjustment model indicated that the latter provided a better account of the observed data than the former, using fewer parameters to do so.

However, one limitation of the aforementioned simulations is that they did not examine one variable that provides important clues about saccade targeting during reading—the relationship between the pre-target word saccade launch site and the subsequent target-word fixation. For example, McConkie et al. (1988, Figure 3) first showed that this relationship is linear and has a moderate slope (= 0.49), suggesting that saccades launched from near the beginning/end of the pre-target word are lengthened/shortened so as to direct the eyes towards the centers of the target words. This interpretation, which is consistent with the default-targeting hypothesis, may not be warranted, however, because McConkie et al.'s analyses included only those fixations that actually landed on the target words, under the assumption that other saccades (resulting in either refixations on the pre-target words or fixations on the post-target words) had missed their intended targets. This assumption is questionable because it is logically impossible to know the intended target of any given saccade. The exclusion of non-target fixations may therefore have obscured the true relationship between the launch- and landing-site locations. Indeed, the work reported by Tsai and McConkie (2003) supports this conjecture: A direct comparison of the fixation landing-site distributions observed during the reading of English versus Chinese showed that, relative to English, the distributions in Chinese are much broader (see Figure 8.2). This suggests that, during the reading of Chinese, the eyes are not being directed towards specific characters or words, thereby making questionable the exclusion of "mislocated" fixations for the purpose of specifying the relationship between the launch- and landing-site locations.

The present article attempts to redress this limitation by first quantifying the observed slope of the launch-site/landing-site relationship during the reading of Chinese, and by then comparing how well the default-targeting and dynamic-adjustment models (Liu et al., 2016) account for both this relationship and other observed eye-movement behaviors. Both models predict that launch sites closer to the end of a pre-target word afford better preview of the target. However, the default-targeting model predicts that better preview will increase the likelihood of the target being segmented, thereby increasing the probability of the saccade being directed towards its center and causing the launch-site/landing-site relationship to have a slope less than 1. In contrast, the dynamic-adjustment model predicts that enhanced preview will cause the eyes to be moved further into the target, causing the launch-site/landing-site relationship to have a slope greater than 1. To test these predictions, the experiment reported below controls the length and frequency of the pre-target words to allow accurate estimates of the launch-site/landing-site relationship.

Empirical Method

Participants. Forty native Chinese speaking students (19 males) from universities in Beijing were paid 30 yuan (approximately $5) to participate. All participants had normal or corrected-to-normal vision and were naive about the purpose of the experiment.

Apparatus. Eye movements were recorded by an SR EyeLink 1000 plus eye tracker (Kanata, ON, Canada) sampling at a rate of 1,000 Hz. The participants' heads were stabilized using a chin/forehead-rest. Sentences were displayed on a 21-inch CRT monitor using 20-point white Song font characters on a black background. Viewing was binocular, but only the movements of the right eye were recorded.

Materials and Experimental Design. Pre-target words (i.e., word *N*) consisted of 160 pairs of high-frequency (*M* = 121.5 per million; *SD* = 98.5; *min.* = 24.26; *max.* = 642.16) and low-frequency (*M* = 2.17 per million; *SD* = 1.53; *min.* = 0.02; *max.* = 5.51) 2-character words with similar meanings selected from the Modern Chinese Frequency Dictionary (1986). Word pairs were embedded near the center of the 160 sentence frames (see Figure 1) that ranged from 16 to 33 characters in length and that were obtained from an online corpus (Center for Chinese Linguistics, PKU: http://ccl.pku.edu.cn:8080/ccl_corpus/index.jsp?dir=xiandai). Prior to running the experiment, there was another sample in which 20 native Chinese speakers were asked to evaluate the naturalness of the sentences; all raters agreed that the sentences were natural (i.e., using a 5-point scale, *M* = 4 and *min*. = 3). There was another sample in which ten native Chinese speakers were asked to predict the identities of word *N* using their preceding sentence contexts; the words were not predictable (i.e., no word was predicted more than once). Finally, during the experiment, each participant read each sentence frame only once and read equal numbers of sentences in each condition in a counterbalanced design.

Insert Figure 1

Procedure. Participants were given instructions and provided informed consent upon their arrival. Participants then seated 58 cm away from the monitor so that one character subtended approximately 1° of visual angle. The eye tracker was calibrated and validated at the beginning of the experiment and as necessary by having participants look at a dot that was displayed in three random locations along a monitor-centered horizontal line. The maximal allowable eye tracker error was 0.4° of visual angle. Each trial began with a drift-check in the middle of the screen followed by a fixation box (1° × 1°, the size of a single character) being displayed at the location of the first character of the sentence (to check calibration), with a sentence appearing after the fixation box was successfully fixated. If the fixation box was not displayed or the drift check indicated more than a 0.4° error, then the participant was recalibrated. The eye tracker was also recalibrated at regular intervals. Each participant first read 15 practice sentences (which are not included in our analysis) and then read the 160 experimental sentences in random order. Participants were instructed to read silently with comprehension and to press a response button (Microsoft SideWinder Game Pad) to answer comprehension questions after one-third of the sentences. Participants also used the button box to start the next trial.

Empirical Results

Data Preparation. Trials containing an eye blink during a fixation on or immediately preceding or following word *N*, and trials containing three or more blinks, were excluded from analyses, resulting in 5.2% of the total trials being removed. Any fixation less than 80 ms in duration and within one character space of another fixation was combined with that fixation (1.14% of total fixations).

Comprehension Accuracy. Participants accurately answered 98% of the comprehension questions, indicating that they understood the sentences. The frequency of word *N* did not affect sentence comprehension ($p = 0.798$).

Eye-Movement Measures. To facilitate comparison of our results with those reported in the literature we first examined how the frequency of word *N* affected the following six first-pass measures: (1) *incoming-saccade length*, or the length of any saccade landing on word *N* from a prior word; (2) the probability of skipping word *N*; (3) the probability of making a single fixation on word *N*; (4) the probability of making multiple fixations on word *N*; (5) *first-fixation duration*, or the duration of the initial fixation on word *N*; and (6) *gaze duration*, or the sum of the first-pass fixations on word *N*.

For each of the above measures, linear mixed-effect models (or generalized linear mixed models for the probability measures; Jaeger, 2008) were fitted using the given measure as the dependent variable and the frequency of word *N* as the design factor (coded as sum contrasts; i.e., – 0.5 vs. 0.5 for low and high frequency). Therefore, each intercept estimates the grand mean of a given dependent variable, while the regression coefficient estimates the difference between factor levels. To maximize the generalizability of our analyses, the models used the maximal random-effects structure (Barr, Levy, Scheepers, & Tily, 2013). The significance values thus reflect the variance due to participants, items, and the slope of fixed effects for participants and items. The models were fitted using the lme4 package (ver. 1.1-11; Bates, Maechler, Bolker, & Walker, 2014; Pinheiro & Bates, 2000) and *p*-values were estimated by using the lmerTest package (ver. 2.0-30; Kuznetsova, Brockhoff, & Christensen, 2013) in R (ver. 3.2.3; R Development Core Team, 2016).

Table 1 shows that incoming saccades were longer when word *N* was high frequency ($b = 0.10$, $SE = 0.02$, $t = 4.25$, $p < 0.001$), and that these words were also skipped more often ($b = 0.16$, $SE = 0.07$, $z = 2.44$, $p = 0.015$), were the recipients of fewer multiple fixations ($b = -0.64$, $SE = 0.12$, $z = -5.44$, $p < 0.001$), elicited briefer first fixations ($b = -19.49$, $SE = 4.13$, $t = -4.72$, $p < 0.001$), and briefer gaze durations ($b = -40.68$, $SE = 6.64$; $t = -6.12$, $p < 0.001$). These results are consistent with previous findings that parafoveal-processing difficulty can modulate saccade length during the reading of Chinese (Liu, Reichle, & Li, 2015; Liu et al., 2016), and that high-frequency words are skipped more and the recipients of fewer, shorter fixations (e.g., Yan, Tian, Bai, & Rayner, 2006).

Insert Table 1

The remainder of our analyses examined how the frequency of word *N* and the launch-site location on that word affected the subsequent fixation landing site on and to the right of word *N* + 1. To do this in an unbiased manner, our analyses focus on all initial progressive saccades launched from word *N*, irrespective of whether they actually resulted in a fixation on word *N* + 1 (i.e., *progressive saccades*). However, to facilitate the comparison of our results with the literature, we also examined only those initial progressive saccades launched from word *N* that resulted in a fixation on word *N* + 1 (i.e., *incoming saccades*). Our linear mixed-effect models were thus completed using landing site as the dependent variable and launch site as the predictor variable, both aligned to the left-most boundary of word *N* + 1. These models also included the frequency of word *N* as a design factor, launch-site fixation duration as a covariate, and the interaction between word *N* frequency and launch site as a predictor. (Appendix A reports supplemental analyses that rule out possible non-linear effects.) Finally, for progressive saccades, the length of word *N* + 1 was included as a covariate because it might mediate the launch-site/landing-site relationship, whereas the more restrictive analyses of incoming saccades only included those sentences (50% of total) in which word *N* + 1 was two characters in length (with 37% of progressive saccades being excluded as over- or under-shot saccades).

The results of our analyses are presented in Figure 2. The slope between the saccade launch site and the subsequent fixation landing site for progressive saccades was significant ($b = 1.17$, $SE = 0.02$, $t = 47.45$, $p < 0.001$) and—as predicted by the dynamic-adjustment model—was greater than 1 ($t = 6.99$, $p < 0.001$). Although there was no significant main effect of the frequency of word *N* on the subsequent landing site ($p = 0.195$), there was a significant interaction between this variable and the saccade launch site: Saccade were longer from high-frequency launch sites, but only when launched from sites far from word *N* + 1 ($b = -0.13$, $SE = 0.05$, $t = -2.57$, $p = 0.010$). The launch-site fixation duration also influenced the subsequent landing site, with longer fixation durations resulting in fixations closer to the beginning of word *N* + 1 ($b = -0.001$, $SE = 0.0001$, $t = -4.81$, $p < 0.001$). Finally, the length of word *N* + 1 influenced the subsequent landing site of progressive saccades, with longer words resulting in fixations closer to the beginning of word *N* + 1 ($b = -0.16$, $SE = 0.04$, $t = -4.29$, $p < 0.001$).

In contrast to what was observed for progressive saccades, the arbitrary exclusion of fixations that under- or overshot word *N* + 1 in the more restrictive analysis of incoming saccades attenuated the slope of the launch-site/landing-site relationship ($b = 0.54$, $SE = 0.03$, $t = 20.73$, $p < 0.001$). Although there was no interaction between saccade launch site and the frequency of word *N* ($p = 0.665$), the effect of word frequency itself was marginally significant, with fixations on word *N* + 1 being further to the right when launched from high- than low-frequency words ($b =$

0.11, $SE = 0.06$, $t = 1.77$, $p = 0.077$; this main effect was significant after removing the insignificant interaction term, i.e., $p < 0.001$). Finally, as was observed with progressive saccades, the launch-site fixation duration also influenced the subsequent landing site, with longer fixation durations resulting in fixations closer to the beginning of word $N + 1$ ($b = -0.001$, $SE = 0.0001$, $t = -3.93$, $p < 0.001$).

The key finding that the slope of the launch-site/landing-site relationship is greater than 1 with progressive saccades is consistent with the core assumption of the dynamic-adjustment model—that launch sites located near the end of word *N* afford better preview of word *N* + 1, allowing the eyes to be moved further from word *N*. However, the more restrictive analysis of incoming saccades also suggests why previous analyses of the launch-site/landing-site relationship (e.g., McConkie et al., 1988) may have been interpreted as evidence for default saccade targeting: With the exclusion of saccades that result in either refixations on word *N* or the skipping of word *N* + 1, the slope of the launch-site/landing-site relationships is much attenuated, making it appear as if saccades made from the beginning/end of word *N* are lengthened/reduced to move the eyes closer to the center of word *N* + 1. A more precise demonstration of how this actually happens will be presented next.

Insert Figure 2

Simulation Method

To better understand our empirical results, we examined the launch-site/landing-site relationship using the default-targeting and dynamic-adjustment models described by Liu et al. (2016). Our main goal for doing this was not to develop a complete model of eye-movement control during the reading of Chinese, but to instead compare the patterns of eye-movement behaviors (the launch-site/landing-site relationship, the fixation probabilities, etc.) in a quantitative manner using the two models, as follows. First, during each Monte-Carlo simulation using one of the models, a launch-site was sampled from a uniform distribution covering word *N* (because the empirical distribution of progressive fixation positions on words is approximately uniform; e.g., Li et al., 2011). Next, a saccade target (Simulation 1, using the default-targeting model) or the saccade length (Simulation 2, using the dynamic-adjustment model) was specified and some amount of saccadic error introduced using the equations described below. This process was then repeated 10,000 times for each model. We now elaborate the specific assumptions that were used to instantiate the two models, and then conclude with the comparison of the simulation results.

Simulation 1: default-targeting model. The core assumption of this model is that Chinese readers select saccade targets that are contingent upon the successful completion of parafoveal word segmentation (e.g., Yan et al., 2010): If word $N + 1$ is segmented, then the eyes are directed towards its center; otherwise, the eyes are directed towards its beginning, often causing the word to be refixated. Although the default-targeting model does not specify what happens if word $N + 1$ is skipped, it is consistent with its "spirit" to assume that the eyes are directed towards the beginning of word $N + 2$ because it is unlikely to have been segmented from word N (because of limited visual acuity and the fact that the perceptual span only extends 2-3 characters to the right of fixation; Chen & Tang, 1998; Inhoff & Liu, 1998; Tang, Au Yeung, & Chen, 1997).

As indicated, this model does not specify how words are segmented and identified but instead extends Yan et al.'s (2010) assumptions about the relationship between parafoveal word segmentation and saccade targeting to estimate the probability of word $N + 1$ having been segmented from how often it was fixated. By this logic, because single fixations tend to be located near the centers of words whereas the first-of-multiple fixations tend to be located near the beginnings of words, these two types of fixations should provide observable "markers" of whether or not a word was likely to have been segmented from the parafovea. The probabilities of making single versus first-of-multiple fixations can therefore be used to estimate the probabilities of a word being segmented (causing the eyes to be directed towards a word's center) or not (causing the eyes to be directed towards a word's beginning). Finally, to minimize any detrimental effect that might result from using poor estimates, saccade-targeting behavior was evaluated using the full domain of possible estimates, ranging from one extreme (that word $N + 1$ is never segmented) to the other (that word $N + 1$ is always segmented). The simulation results are thus robust and do not depend on the precise values of our parameter estimates.

The core assumptions of the default-targeting model are implemented in the simplest manner possible, using second-order polynomial regression functions to estimate the probabilities of observing saccades of a particular length (targeting to one default position) from each saccade launch site within word *N*. (The *SERIF* model of eye-movement control in reading also uses ordinal and second-order polynomial regression functions to estimate the probabilities of various saccade targets; McDonald, Carpenter, & Shillcock, 2005; see also Reilly & O'Regan, 1998.) These estimated probabilities were derived from four mutually exclusive and exhaustive eye-movement behaviors: (1) refixating word *N*; (2) fixating word *N* + 1 and then moving the eyes from this word (presumably because it was segmented in the parafovea); (3) fixating word *N* + 1 and then refixating this word (presumably because it was not segmented in the parafovea); and (4) skipping word *N* + 1. The polynomial regression functions (see Equation 1) were fit to each possible saccade launch site, with the constraint that the probabilities of the four types of eye-movement behaviors from each saccade launch site summed to 1. In Equation 1, x represents the distance (in character spaces) between the saccade launch site on word *N* and the leftmost edge of word *N* + 1, and k_2, k_1, and k_0 respectively represent the coefficients of the 2°, 1°, and 0° polynomials.

(1) $p(x) = k_2 x^2 + k_1 x + k_0$

The estimated probabilities were then used to specify saccade targets, as follows: (1) a saccade to refixate word *N* resulted in the eyes being directed towards its center; (2) the successful segmentation of word *N* + 1 from the parafovea resulted in the eyes being directed towards its center; (c) a failure to segment word *N* + 1 resulted in the eyes being directed towards its beginning (i.e., the center of its first character); (d) a saccade to skip word *N* + 1 resulted in the eyes being directed toward the beginning of word *N* + 2 (i.e., the center of its first character). (As previously indicated, because of limited visual acuity and the perceptual span, rare instances in which the eyes might be moved past the beginning of word *N* + 2 were not simulated.) Finally, variance was added to the saccade target to simulate the effect of saccadic error. This saccadic error was sampled from a Gaussian distribution with $\mu = 0$, and the values of σ being selected to fit the empirical fixation-position distributions of incoming saccades on word *N* + 1. (The best fitting parameter values used to complete the simulation and the procedure used to find these values are described in Appendix B.) We will discuss the results of Simulation 1 below, in comparison to those of Simulation 2.

Simulation 2: dynamic-adjustment model. The core assumption of this model is that readers of Chinese do not move their eyes to default targets, but instead adjust their saccade lengths as a function of how much parafoveal processing has been completed. To implement this assumption, it was also necessary to use a simplifying assumption—that saccade length is a linear function of parafoveal word preview. To do this, the amount of word $N + 1$ preview completed from word N was sampled from a gamma distribution having a shape parameter, α, and a scale parameter, β, as described by Equation 2.

(2) $preview = gamma(\alpha, \beta)$

Using this equation, the amount of word $N + 1$ preview (as determined by the value of α) was modulated by both the frequency of word N and the launch site (i.e., to capture the effect of limited visual acuity), as specified by Equation 3. In this equation, η_0 is a constant representing the minimal value of α (i.e., some minimal amount of word $N + 1$ preview), η_1 is a parameter that modulates the influence of word N's frequency on α, η_2 is a parameter that modulates the influence of the launch site, x, on α, and η_3 is a parameter that modulates the influence of the interaction between word N's frequency and the launch site on α.

(3) $\alpha = \eta_0 + \eta_1 frequency + \eta_2 x + \eta_3 x \times frequency$

The final assumption is that saccade length (in character spaces) is linearly related to preview, as specified by Equation 4, where λ is a free parameter that scales this relationship. In contrast to Simulation 1, the saccadic error is intrinsic to Simulation 2, with variability in saccade length being determined by the parameter β.

(4) $$\begin{aligned} length &= \lambda\, preview \\ &= \lambda\, gamma(\alpha, \beta) \\ &= gamma(\eta_0 + \eta_1 frequency + \eta_2 x + \eta_3 x \times frequency, \lambda\beta) \end{aligned}$$

Simulation Results

The results of the both simulations and the empirical results are displayed in Figure 3 and 4, to facilitate comparison. Figure 3 shows how well the models fit the quantitative relationships observed between the saccade launch sites on high- and low-frequency word *N* and the subsequent fixation landing sites on word *N* + 1. A comparison of Simulations 1 and 2 indicates that the latter provides a better quantitative fit than the former for both progressive saccades (i.e., all saccades launched from word *N*, irrespective of whether they resulted in fixations on word *N* + 1; Simulation 1: *MSE* = 8.8×10^{-2}; Simulation 2: *MSE* = 2.8×10^{-3}) and incoming saccades (i.e., only those saccades launched from word *N* that resulted in fixations on word *N* + 1; Simulation 1: *MSE* = 3.5×10^{-2}; Simulation 2: *MSE* = 1.4×10^{-3}). Importantly, the slopes of launch-site/landing-site relationship predicted by Simulation 1 (i.e., the default-targeting model) were less than 1 for progressive saccades (HF = 0.77, LF = 0.84) and were further attenuated for incoming saccades (HF = 0.13, LF = 0.12). In contrast, the slopes of the launch-site/landing-site relationship predicted by the dynamic-adjustment model in Simulation 2 (i.e., the dynamic-adjustment model) were greater than 1 for progressive saccades (HF = 1.07, LF=1.23) but appropriately reduced for incoming saccades (HF = 0.45, LF = 0.40). It is important to note that the poor fit of Simulation 1 cannot be explained by suboptimal estimates of word-segmentation probabilities as evidenced by the shaded regions of Figure 3a (which show the model fits across the full domain of estimates).

Figure 4 shows the mean observed and simulated probabilities of refixating word *N*, and of fixating and skipping word *N* + 1. Between-simulation comparisons again indicate that Simulation 2 provided better quantitative fits of the data than Simulation 1: (1) refixating word *N* (Simulation 1: *MSE* = 4.5×10^{-3}; Simulation 2: *MSE* = 3.7×10^{-4}); (2) fixating word *N* + 1 (Simulation 1: *MSE* = 5.1×10^{-3}; Simulation 2: *MSE* = 1.6×10^{-3}); and (3) skipping word *N* + 1 (Simulation 1: *MSE* = 5.1×10^{-3}; Simulation 2: *MSE* = 4.8×10^{-4}).

Insert Figures 3 & 4

General Discussion

This article provided a novel test of the dynamic-adjustment hypothesis (Liu et al., 2016) by examining how the frequency of word *N* and both the location and duration of the launch-site fixation on that word influenced the subsequent location of the fixation landing site on word *N* + 1. Our results showed that the landing sites moved further to the right following launch-site fixations that afforded more parafoveal processing of word *N* + 1—from fixations on word *N* when it was high frequency and/or fixations close to word *N* + 1. And as predicted by the dynamic-adjustment hypothesis, the slope of the launch-site/landing-site relationship was greater than 1 for progressive saccades and was less than 1 for incoming saccades, in which "mislocated" fixations were excluded from analyses. And simulations using computational implementations of both the dynamic-adjustment and default-targeting hypotheses indicate that the former model accounts for the observed eye-movement behaviors better than the latter, providing additional support for the hypothesis that readers of Chinese adjust their saccade lengths in a manner that reflects ongoing parafoveal processing.

Of course, before one accepts this conclusion, one should consider the full range of possible slopes describing the launch-site/landing-site relationship and their implications for saccade targeting during reading. One possible critical value would be a slope of 0; such a relationship would imply that readers simply move their eyes to default positions (e.g., the center of words) and that launch-site locations have no influence on saccade targeting. A second critical value would be 1; such a relationship would imply that readers simply move their eyes (on average) some constant length. The fact that the launch-site/landing-site relationship has a slope of neither 0 nor 1 suggests that neither of the two simple saccade-targeting strategies is used by readers of spaced or unspaced writing systems. It is therefore necessary to examine the two remaining logical alternatives.

The first of these alternatives is a slope between 0 and 1, which would imply that readers attempt to move their eyes to specific targets (e.g., word centers), but that the eyes sometimes miss their intended targets. The second alternative is a slope greater than 1, which would imply that readers move their eyes distances that vary as a function of the amount of parafoveal processing that has been completed (which would be expected to increase as the distance between the launch site and parafoveal word decreases). As indicated previously, McConkie et al. (1988) estimated the strength of the launch-site/landing-site relationship to be 0.49, but the method used to derive this estimate may be fundamentally flawed in that it excluded "mislocated" fixations that either undershot or overshot their intended targets. In contrast, the method used in this article includes all first progressive saccades (i.e., all first forward saccades from word *N*, irrespective of whether or not the resulting fixation actually landed on word $N + 1$). The estimate derived from this unbiased method (slope = 1.17) is consistent with the core assumption of the dynamic-adjustment hypothesis—that readers of Chinese adjust their saccade lengths conditional upon how much parafoveal processing has been completed from each fixation location.

Given the growing body of evidence supporting the dynamic-adjustment hypothesis, one might ask: Why is such a strategy adaptive? The answer to this question may have to do with the fact that, during reading, the oculomotor system often begins programming a saccade before the fixated word has been fully identified. This is adaptive because it allows the reader to use the "dead time" required to program a saccade to continue processing the fixated word and—if time permits—to shift attention to and begin processing the next word (e.g., see Liu & Reichle, 2010; Liu, Reichle, & Gao, 2013; Reichle & Laurent, 2006). Because the boundaries of Chinese words are not clearly demarcated by low-level perceptual cues, there is no simple heuristic that the visual/cognitive system can use to direct the eyes towards the center of the next unidentified word in the limited time that is available to support skilled reading. For that reason, readers may instead use cues about the status of parafoveal processing to dynamically adjust the length of their saccades, with the goal of moving their eyes to locations that afford efficient extraction of new visual information and its coordination with ongoing lexical processing.

This inference about how parafoveal processing may modulate saccade length is also consistent with evidence suggesting that parafoveal processing is "deeper" in Chinese than in alphabetic languages like English. For example, there is evidence that morpho-semantic information is extracted from the parafovea in Chinese (e.g., Yan, Zhou, Shu, & Kliegl, 2012; Yang, Wang, Tong, & Rayner, 2012; Yen, Tsai, Tzeng, & Hung, 2008) and that lexical processing is less mediated by phonology but more reliant upon associations between orthography and meaning (Chen & Shu, 2001; Zhou & Marslen-Wilson, 2000). Enhanced parafoveal processing in the reading of Chinese may therefore require and allow more flexibility for saccade targeting than in languages like English.

Of course, given that word boundaries are clearly demarcated in spaced writing systems like English and German, the evidence and arguments supporting the dynamic-adjustment account of saccade targeting in Chinese may be limited to unspaced writing systems like Chinese and Thai. The default-targeting account may therefore provide an accurate description of how readers of languages like English and German move their eyes. However, there is some evidence suggesting that, even in these spaced languages, saccade lengths may be dynamically adjusted to some degree. For example, several experiments have shown that saccade lengths can be modulated by the orthographic familiarity or legality of the initial letters of a parafoveal word (e.g., Plummer & Rayner, 2012; Vonk, Radach, & van Rijn, 2000; White & Liversedge, 2006), and by the frequency of the initial morpheme in compound words (Hyönä & Pollatsek, 1998, 2000). These findings suggest that parafoveal processing also affects saccade targeting in a dynamic manner during the reading of spaced languages, but that these effects may be subtler, perhaps because the clear demarcation of word boundaries in spaced writing systems often allows saccade to be directed towards the center of next word by default. Thus, in the context of reading spaced languages like English and German, the default-targeting strategy may allow readers to accommodate the severe temporal constraints imposed by visual encoding, lexical processing, and saccade programming (e.g., for a review, see Reichle & Reingold, 2013), which might overshadow the subtler effects indicative of dynamic adjusting. But in the context of reading Chinese, the absence of clear word boundaries prevents default saccade targeting, making dynamic targeting the only option.

Finally, it is important to note that the results of our experiment are not easily explained by current models of eye-movement control in reading because they have largely incorporated the assumption that saccades are directed towards the centers of upcoming words by default (e.g., *E-Z Reader*; Reichle et al., 1998; Reichle, Pollatsek, & Rayner, 2012; *SWIFT*; Engbert et al., 2005). The challenge for future models, therefore, will be to explain both how Chinese readers move their eyes without the aid of the cues that afford default targeting (e.g., word boundaries), and how a balance between default targeting and dynamic adjustment is attained by readers of spaced languages. We believe that our experimental and simulation results indicate that such an account is still necessary and that future research on the reading of Chinese may reveal other important differences between spaced and unspaced writing systems that will change our understanding of eye-movement control in reading.

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Endnotes

1. A “processing-based account/strategy” was first mentioned by White and Liversedge (2006) and then adopted by Wei et al. (2013). Perhaps the main differences between this strategy and the dynamic-adjustment hypothesis is that the latter more clearly defines the role of parafoveal processing on saccade targeting, and has been formally implemented as a computer model.

Table 1. Incoming saccade length (in character spaces), and the probabilities of skipping, making a single fixation, and making multiple fixations on word *N*, and the first-fixation and gaze durations on word *N*, as a function of their frequencies.

Dependent Variable	Low-Frequency Word *N*		High-Frequency Word *N*		Inferential Statistics			
	M	*SE*	*M*	*SE*	*b*	*SE*	*t*- or *z*-value	*p*
Incoming-Saccade Length	2.60	0.10	2.70	0.10	0.10	0.02	4.25	< 0.001
Prob. Skipping	0.28	0.02	0.31	0.02	0.16	0.07	2.44	0.015
Prob. Single Fixation	0.63	0.01	0.64	0.02	0.03	0.07	0.45	0.650
Prob. Multiple Fixations	0.09	0.01	0.05	0.01	-0.64	0.12	-5.44	< 0.001
First-Fixation Duration	283	6	263	5	-19.49	4.13	-4.72	< 0.001
Gaze Duration	330	11	290	8	-40.68	6.64	-6.12	< 0.001

Note: Probability measures were fitted using generalized linear mixed models.

Figure Captions

Figure 1. Examples of the Chinese sentences used in the experiment and their English translations. (For illustrative purposes, words *N* and *N* + 1 are respectively indicated by solid and dashed lines, and the translations for word *N* are highlighted in gray.)

Figure 2. The observed relationship between the saccade launch site and the subsequent fixation landing site (in character spaces) using: (a) all sentences; and (b) only sentences in which word *N* + 1 was two characters in length. The symbols show the observed means averaged within each launch-distance bin. The black and gray lines represent progressive and incoming saccades, respectively, and both launch sites and landing sites are aligned to the beginning of word *N* + 1. The incoming saccades in panel (a) (i.e., all sentences) are extracted from saccades initiated from word *N* that are located anywhere within the subsequent two-character region. (*Note*: HF = high-frequency; LF = low-frequency.)

***Figure 3*.** The predicted relationship between the saccade launch site and the subsequent fixation landing site (in character spaces) generated by the: (a) default-targeting model (Simulation 1); and (b) dynamic-adjustment model (Simulation 2). The symbols show the observed means averaged within each launch-distance bin. The black and gray lines represent progressive and incoming saccades, respectively, and both launch sites and landing sites are aligned to the beginning of word *N* + 1. The shaded regions in panel (a) demarcates the Simulation 1's results for the two most extreme cases: word *N* + 1 is never vs. always segmented from the parafovea. (*Note*: HF = high-frequency; LF = low-frequency.)

***Figure 4*.** Mean observed and simulated probabilities of refixating word *N* (panels a-c), fixating word *N* + 1 (panels d-f) and skipping word *N* + 1 (panels g-i). (*Note*: HF = high-frequency; LF = low-frequency.)

Figure 1.

N $N+1$

High-Frequency:中国学生从英国老师那里学会了圣诞歌谣。

（The Chinese students have learned a Christmas song from the British teacher.）

Low-Frequency:中国学生从英国访客那里学会了圣诞歌谣。

（The Chinese students have learned a Christmas song from the British visitor.）

Figure 2.

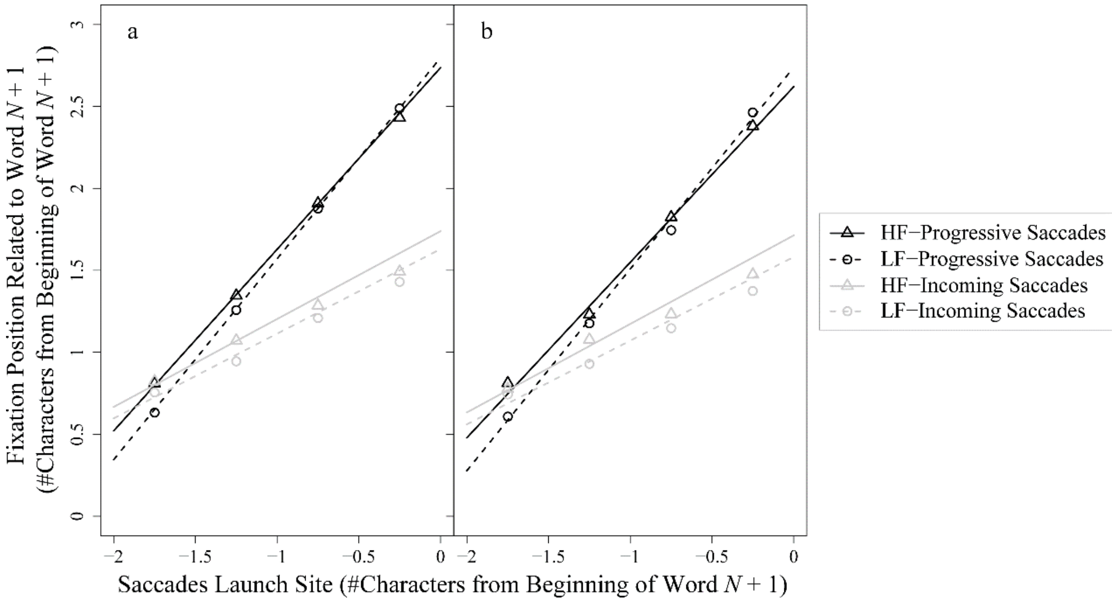

a
b
Fixation Position Related to Word N + 1
(#Characters from Beginning of Word N + 1)
Saccades Launch Site (#Characters from Beginning of Word N + 1)
HF−Progressive Saccades
LF−Progressive Saccades
HF−Incoming Saccades
LF−Incoming Saccades
0
0.5
1
1.5
2
2.5
3
−2
−1.5
−1
−0.5
0

Figure 3.

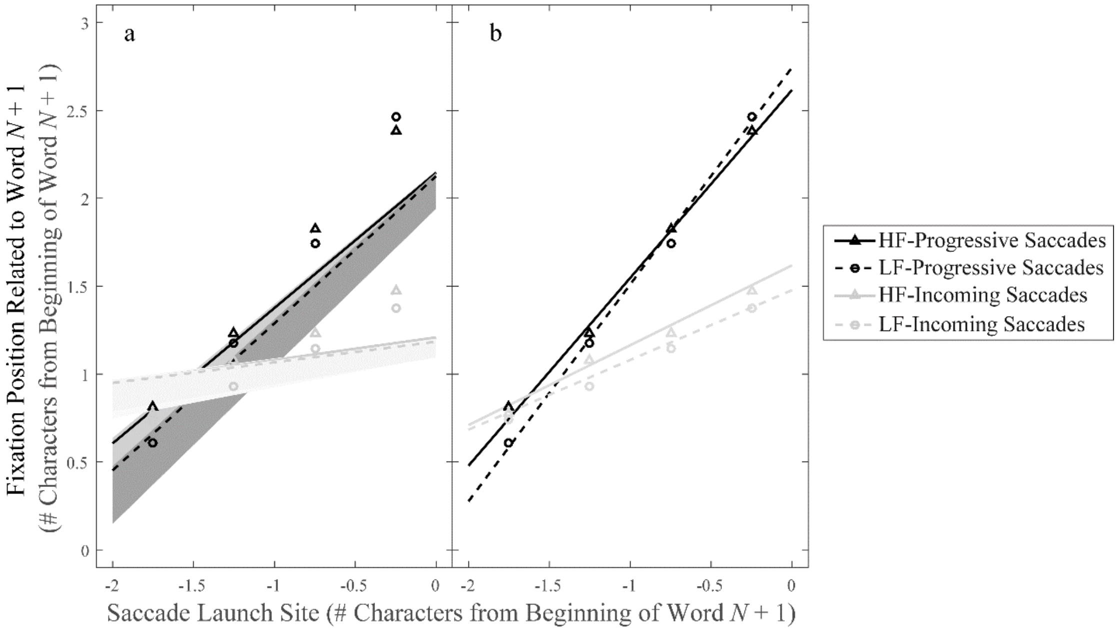
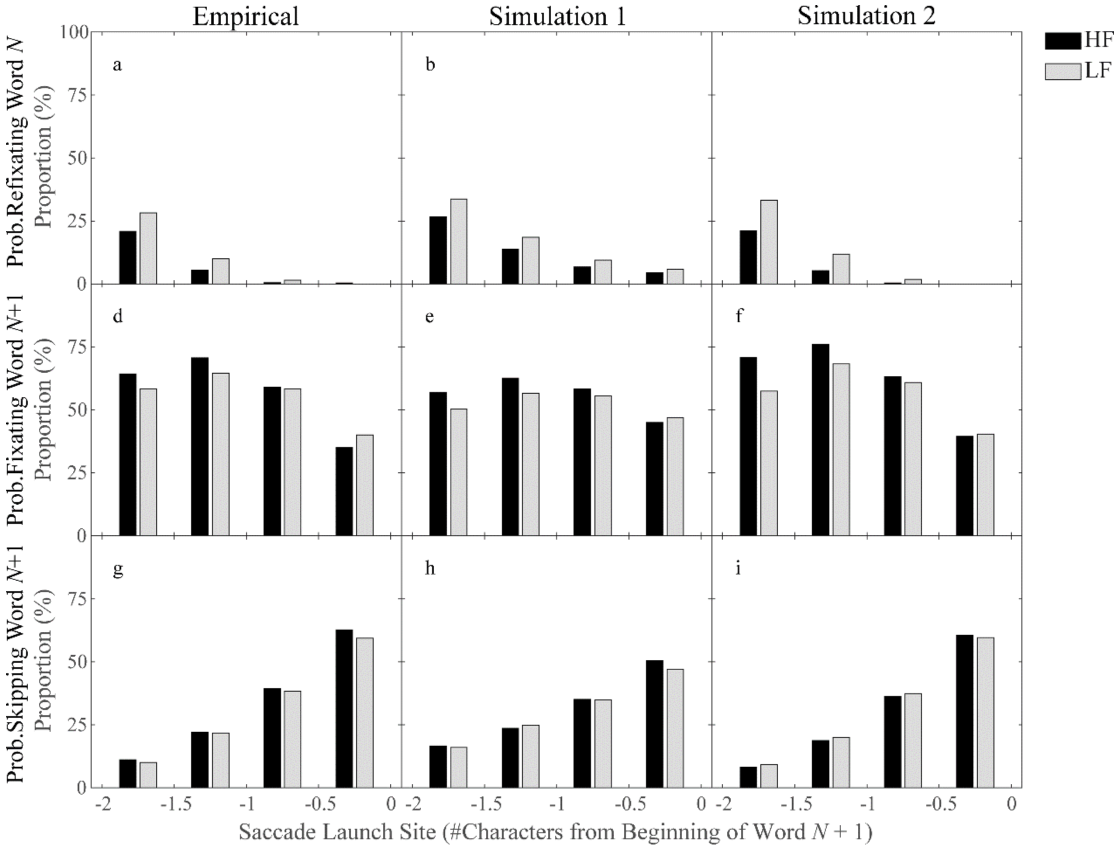

a
b
Fixation Position Related to Word N + 1
(# Characters from Beginning of Word N + 1)
Saccade Launch Site (# Characters from Beginning of Word N + 1)
HF-Progressive Saccades
LF-Progressive Saccades
HF-Incoming Saccades
LF-Incoming Saccades
0
0.5
1
1.5
2
2.5
3
-2
-1.5
-1
-0.5
0

Figure 4.


Empirical
Simulation 1
Simulation 2
HF
LF
Prob.Refixating Word *N*
Proportion (%)
Prob.Fixating Word *N*+1
Proportion (%)
Prob.Skipping Word *N*+1
Proportion (%)
a
b
c
d
e
f
g
h
i
100
75
50
25
0
-2
-1.5
-1
-0.5
0
Saccade Launch Site (#Characters from Beginning of Word *N* + 1)

Appendix A: Nonlinear Regression Analysis

This appendix reports analyses to determine if there is a nonlinear relationship between the saccade launch site and its subsequent landing site. Figure A1 shows all initial progressive saccades from word *N* in the scatter diagram (panel a) and their frequency distribution using launch-distance bins (panel b) when word *N* is high-frequency, and when word *N* is low frequency (panels c & d). The shaded regions identify those saccades that actually resulted in a fixation on word *N* + 1 (i.e., the incoming saccades). Consistent with Tsai and McConkie (2003), Figure A1 clearly shows that incoming saccades are an arbitrary subset of the saccades that are extracted from the continuous distribution of progressive saccades.

Nonlinear regression was used to explore whether or not there was nonlinear launch-site/landing-site relationship in progressive saccades. This was done by first building a reduced linear regression model for the progressive-saccade landing sites. This model only included the frequency of word *N*, the launch site on word *N*, and their interaction as predictors. To capture any potential non-linear relationship, second- and higher-order polynomials of launch site were iteratively introduced into the reduced model. The results of these attempts indicated that there were no reliable second- and higher-order polynomials in these more complex models ($p > 0.05$); the linear reduced model (i.e., the fitted lines in panel (a) and (c) of Figure A1) thus best represents the launch-site/landing-site relationship in the progressive saccades. The results are consistent with previous evidence that the relationship between launch-site and preview within an appropriate launch distance is approximately linear (e.g., see the right parts of the curves of Figure 2 in McDonald 2006; and Figures 3-5 in Kliegl, Hohenstein, Yan, & McDonald, 2013).

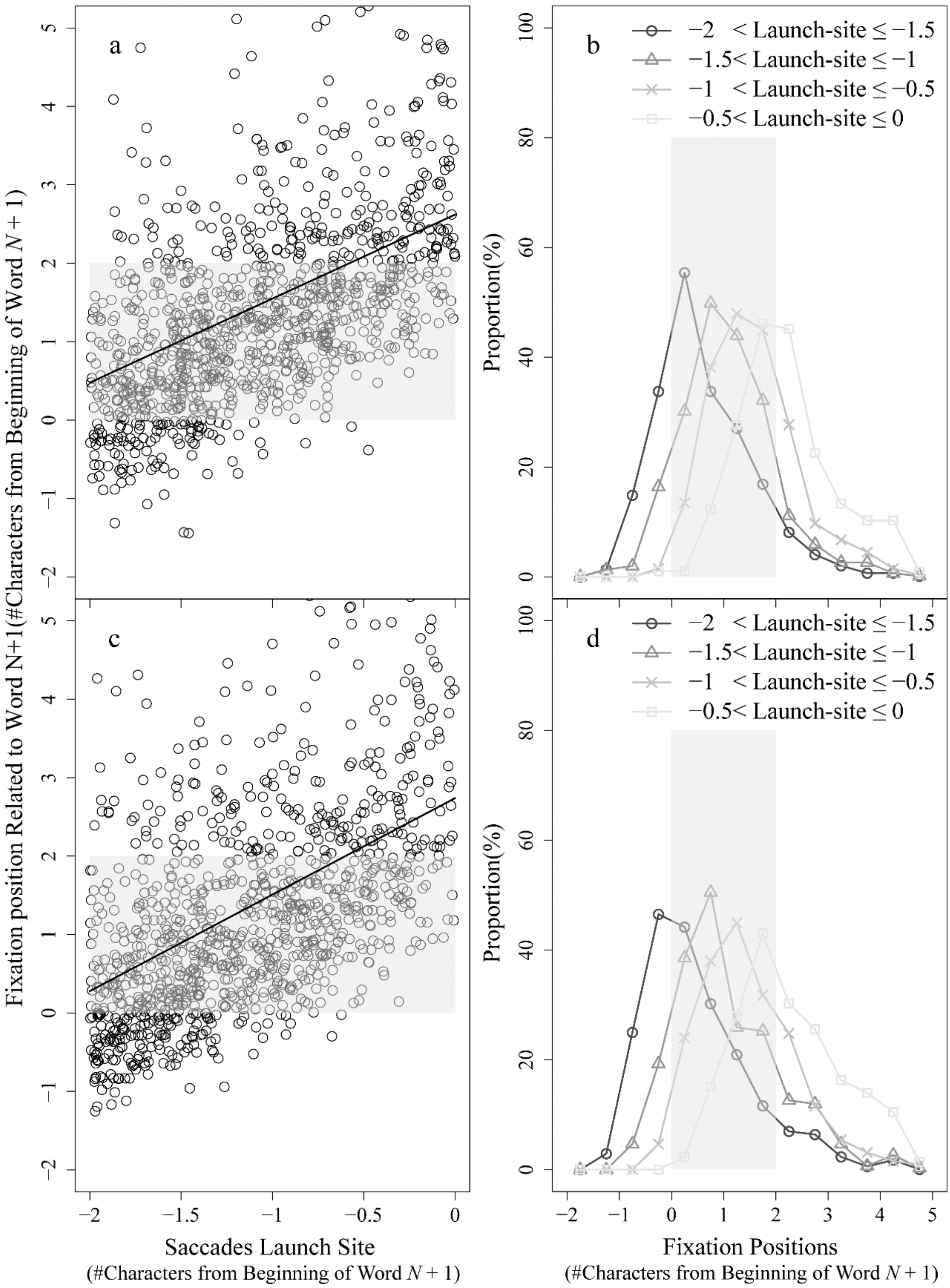


Figure A1. The relationship between the saccade launch site and the subsequent fixation landing site for progressive saccades from high- (a) and low-frequency (c) words, and their corresponding launch-distance/launch-site-contingent fixation landing-site distributions (b & d). The shaded regions indicate those progressive saccades that produce fixations on word $N + 1$ (i.e., incoming saccades). The best fitting lines in panels (a) and (c) show the linear launch-site/landing-site relationships.

Appendix B: Simulation Parameters

Simulation 1 parameters: As Equation 1 shows, polynomial regression functions were used to estimate the probabilities of observing the four different types of saccades with the method of least squares. Because these probabilities summed to 1 for each saccade launch site, only the probabilities associated with three saccades types were actually estimated (i.e., the probabilities of skipping word $N + 1$ could be calculated by subtracting the sum of the other three from 1). Finally, the values of σ, the parameter that controls the variability of saccadic error, were chosen to maximize the goodness-of-fit to the empirical fixation-position distributions of incoming saccades on the high- and low-frequency condition separately (HF: $MSE = 0.038$; LF: $MSE = 0.028$). Table B1 lists the best-fitting parameter values. Figure B1 shows that these parameters accurately describe the empirical data (i.e., the probability of refixating word N: $MSE = 2.24 \times 10^{-5}$; probability of fixating the center of word $N + 1$: $MSE = 3.88 \times 10^{-6}$; probability of fixating the beginning of word $N + 1$: $MSE = 2.12 \times 10^{-5}$). Simulation 1 thus required a total of 20 free parameters.

Simulation 2 parameters: The expected value of Equation 4 is $\lambda\beta(\eta_0 + \eta_1\, frequency + \eta_2 x + \eta_3 x \times frequency)$, or the predicted value using the mean first progressive saccade length from word N. Thus, four groups of parameters, $\lambda\beta\eta_3$, $\lambda\beta\eta_2$, $\lambda\beta\eta_1$, and $\lambda\beta\eta_0$, are coefficients for a regression equation for progressive saccade length using saccade launch site, x, on word N, the frequency of word N (i.e., low-frequency = -0.5, high-frequency = 0.5), and their interaction as three predictor variables. And because the variance associated with Equation 4 (i.e., the variance associated with saccadic error) is given by the quantity $\lambda^2\beta^2(\eta_3 x \times frequency + \eta_2 x + \eta_1 frequency + \eta_0)$, the parameter pair $\lambda\beta$ can also be estimated using the empirical distribution of fixations on word $N + 1$, doing so separately for the high- and low-frequency conditions. The final parameter values used to simulate the high-frequency condition were: $\eta_0 = 9.08$; $\eta_1 = -0.40$; $\eta_2 = 0.33$; $\eta_3 = 0.51$; and $\lambda\beta = -0.54$. The parameter values for the low-frequency condition were: $\eta_0 = 5.89$; $\eta_1 = -0.26$; $\eta_2 = 0.33$; $\eta_3 = 0.33$; and $\lambda\beta = -0.35$. Simulation 2 thus required a total of 12 free parameters.

Table B1. The best-fitting parameters for Simulation 1.

Frequency of Word *N*	Saccade Type	k_2	k_1	k_0	σ
High	Refixate Word *N*	0.153	0.173	0.040	0.76
	Fixate Center of Word *N*+1	-0.274	-0.728	0.168	
	Fixate Beginning of Word *N*+1	-0.029	-0.076	-0.002	
Low	Refixate Word *N*	0.168	0.149	0.028	0.85
	Fixate Center of Word *N*+1	-0.209	-0.523	0.255	
	Fixate Beginning of Word N+1	-0.036	-0.088	0.008	

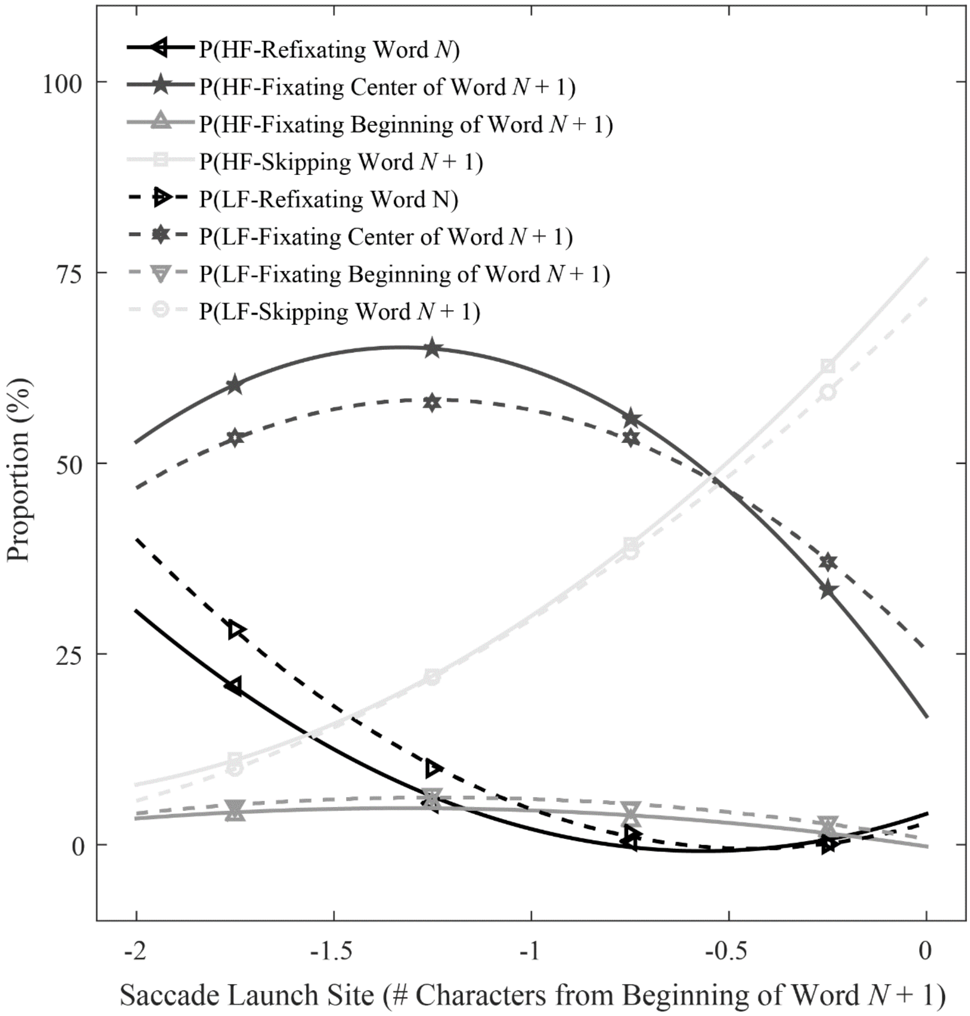


Figure B1. The observed (symbols) and estimated (lines) probabilities of refixating word *N*, fixating the center of word *N* + 1 (i.e., single fixation), fixating the beginning of word *N* + 1 (i.e., first-of-multiple fixations), and skipping word *N* + 1 as a function of the frequency of word *N*. (*Note*: HF = high-frequency; LF = low-frequency.)