Beyond the leftward limit of the perceptual span: Parafoveal processing to the left of fixation in Chinese reading

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Abstract

During reading, Chinese readers have been found to obtain useful visual information from one character to the left to three characters to the right of fixation. The perceptual span is asymmetrical and its leftward extent seems to be limited compared to the rightward extent. We conducted an experiment to investigate whether Chinese readers could process written information beyond the leftward extent of the perceptual span. We did this by using a variation of the gaze-contingent display change paradigm (Rayner, 1975) in order to manipulate the parafoveal "post-view" that was available to the left of where readers were fixating. Each sentence contained an invisible boundary. Once the readers' eyes crossed the boundary, all of the characters to the left of the boundary except for one, two, or three characters directly to the left of the boundary were replaced with visually similar characters. The change lasted for only one single fixation, resulting in four different "post-view" conditions including a control condition (n-1, n-2, n-3, control). The results showed that, compared with the control condition, there were more regressions to the display change area immediately after readers' eyes crossed the boundary in the n-1, n-2 and n-3 condition, demonstrating that readers can acquire information from the three characters to the left of fixation at least.

Key words: Chinese reading; leftward perceptual span; boundary paradigm

The amount of information that can be obtained in a single fixation during reading is limited. The *perceptual span* is usually defined as the spatial extent from which useful information is available during reading (Rayner, 1998; Rayner, 2009). The perceptual span is usually measured using the gaze-contingent moving window paradigm (McConkie & Rayner, 1975). In this paradigm, participants read sentences on a computer screen. On each trial, the sentence is masked except for a region around the current fixation (the *window*). The location of the window is updated every time as the reader's eyes move. The perceptual span is usually measured by manipulating the size of the window and comparing the reading performance in each window condition with the full-line condition (no window). The size of the perceptual span is the smallest window size in which reading performance resembles that during a no-mask control condition. According to the previous research, for skilled readers, the perceptual span measures four letters to the left of fixation to 14-15 letters to the right of fixation in an alphabetic language like English (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980). Rayner et al. (1980) found no difference in reading performance between a condition where the window extended four letters to the left of fixation and a condition where the window extended 20 letters to the left of fixation. They concluded that readers did not obtain useful information from farther than four letters to the left of fixation. As a consequence, the perceptual span seems to be asymmetrical, with the rightward perceptual span being much larger than the leftward span.

Concerning reading in Chinese, Inhoff and Liu (1998) found that readers could obtain information from one character to the left of fixation to three characters to the right. The extent of the perceptual span (measured by the number of characters or the degrees of visual angle) in Chinese reading is much smaller than that in English, which is likely related to the high information density in Chinese characters (Yan, Zhou, Shu, & Kliegl, 2015). Since Chinese characters are written unspaced, all characters are designed to fit into the same rectangular space, and many consist of multiple strokes leading to high visual complexity.

The rightward asymmetry of the perceptual span in both English and Chinese is likely that readers allocate more attention towards their reading direction (Pollatsek, Bolozky, Well, & Rayner, 1981). Although much research has been conducted to investigate parafoveal processing to the right of fixation, we know little about parafoveal processing to the left of fixation. Physiologically, there is no reason that the visual acuity on the left side of fixation is lower than that on the right. In principle, readers should be able to obtain the same amount of information from each side of the visual field.

Binder, Pollatsek and Rayner (1999) found that readers could obtain information from the word to the left of fixation using a variation of the gaze-contingent display change paradigm (Rayner, 1975). An invisible boundary was placed inside the sentence, when the readers' eyes crossed the boundary, the target word to the left of the boundary was replaced with a parafoveal "post-view" stimulus, which was either related or unrelated to the target word. In the control condition, the post-view target word did not change. The post-view stimulus remained on the screen until the subsequent saccade was made, and the display reverted to the actual target word. They found that, compared to a control condition without a visible display change, presentation of the post-view stimulus resulted in increased regressive fixation durations on the target-word region, demonstrating that some information about the word to the left of fixation was processed, even though it was located outside of the leftward perceptual span as previously reported in English reading.

Jordan, McGowan, Kurtev and Paterson (2016) conducted a study using a variation of the moving window paradigm to further explore the effect of the text to the left of fixation during reading. In the experiments, invisible boundaries were located at the leftmost edge of each word, and the post-view available to readers was manipulated such that all the letters beyond one, two, three or four words to the left of the boundary were replaced with visually similar or dissimilar letters after a reader's gaze crossed the boundary. This display change was reverted immediately on the next saccade. They found that English readers could acquire information from as far as two words to the left of fixation, which was much larger than the leftward extent of the perceptual span reported before. In Jordan et al.’s experiments, there was a boundary before each word in the sentence. While this approach maintains consistent viewing conditions across the sentence, it requires many display changes, making the manipulation quite salient.

In Chinese, a study conducted by Wang, Tsai, Inhoff, and Tzeng (2009) showed that readers could obtain phonological and semantic information to the left of the fixated character. Wang et al. placed an invisible boundary within a two-character target word that was embedded in a sentence. When a readers’ gaze crossed the boundary, the first character of the target word was replaced with a post-view character. They found more regressions and longer gaze durations on the target word when the replaced character could not constitute a word with the second character in the target word. The results fit in well with Inhoff and Liu’s (1998) estimate of the extent of the perceptual span in Chinese. However, as the information density of Chinese text is much higher than that of English, we hypothesize that Chinese readers might be able to obtain even more information to the left of fixation, beyond the one-character limit previously established (Inhoff & Liu, 1998). In the present study, we attempted to test this hypothesis and also aimed to establish the precise spatial limit of such processing. In our research, we decided to adopt the post-view boundary paradigm, as well, but we only used one boundary in the sentence and manipulated the distance of the post-view stimuli from the boundary in several conditions (n-1, n-2, n-3, control), the post-view stimuli were all visually similar characters of the original ones. We assume that if readers could process the changed information to the left of fixation, their reading behavior should be affected. The farthest distance of display change having an influence on the reading performance will be regarded as the area from which readers could obtain useful information from.

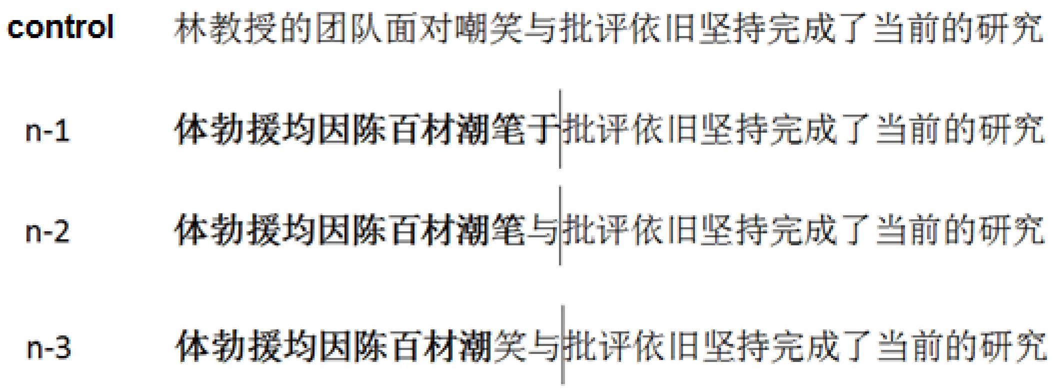
Method

Participants. Twenty-eight participants took part in this experiment, aging from 19 to 28 (mean age: 22.6). Participants were all native Chinese speakers, who had normal or corrected-to-normal vision.

Apparatus. The sentences were presented on a 21-in CRT monitor with a resolution of 1,024×768 pixels and a refresh rate of 150 Hz. The characters were shown in Song 24 font in black color on a white background. One character subtended one degree of visual angle. The readers' eye movements were monitored by an Eyelink 1000 eye-tracker with a sampling rate of 1,000 Hz.

Materials and Procedure. Ninety-six sentences were used in the experiment (see https://osf.io/e576q/ for the sentences). The sentences were 22 to 27 characters in length and each of them was presented in a single line. Each sentence contained an invisible boundary which was located randomly in the sentences and never appeared at the beginning or the end of the sentence. There were four display conditions in this experiment: three experimental conditions (n-1, n-2, n-3 conditions) and a control condition. In the n-1 condition, all characters from the beginning of the sentence to (and including) the first character to the left of the boundary were replaced with visually similar characters after the eyes crossed the boundary. In the n-2 condition, the characters from the start of the sentence to the second character to the left of the boundary (including the n-2 character itself) were replaced, and so forth. The post-view characters were all visually similar to the original characters and shared the same structure (almost all of them) and even one radical with the original character at the same position (approximately 79% characters in total). In the control condition, no change took place.

The change was displayed only for a single fixation after crossing the boundary and would revert immediately in the next saccade. The conditions were fully counterbalanced across sentences and participants. Examples of the displays in each condition are shown in Figure 1.



control 林教授的团队面对嘲笑与批评依旧坚持完成了当前的研究

n-1 **体勃援均因陈百材潮笔于**|批评依旧坚持完成了当前的研究

n-2 **体勃援均因陈百材潮笔**与|批评依旧坚持完成了当前的研究

n-3 **体勃援均因陈百材潮**笑与|批评依旧坚持完成了当前的研究

Figure 1. Examples of three display conditions to the left of boundary after the eyes crossing the boundary. The "|" indicates the invisible boundary location in the sentence. When the eyes crossed the boundary, the characters to the left of the boundary were replaced with the visually similar characters. The visually similar mask characters in the sentences were not in bold in the experiment. Example sentence translation: Professor Lin's team, facing ridicule and criticism, persisted in the present research and finally completed it.

At the beginning of the experiment, the eye tracker was calibrated in a three-point calibration procedure; this was repeated until validation error was less than 0.5° visual angle. Then, participants were instructed to read the sentences. Sixteen practice trials were presented before the experimental sentences. One third of the sentences were followed by a comprehension question. After the experiment, participants were asked whether they were aware of the display change in the sentences. Although some of them reported seeing a flash in a few trials, none of the participants were aware of the change.

Results

The mean accuracy of the comprehension questions was 95%, indicating that participants understood the sentences very well. In order to measure the effect of the display change, we recorded sentence reading time, average fixation duration, the number of forward saccades and regressions in the whole sentence, the probability of immediate regression after crossing the boundary and the total time in the pre-boundary area (a three-character region before the boundary).

Eye movement measurements were analyzed using a *linear mixed-effects model* (*lme4* package, Bates, Maechler, Bolker, Walker, 2015) in the *R* statistical software (R Core Team, 2017; see also Baayen, Davidson, & Bates, 2008). For the LMMs with the number of regressions as the dependent variable, we included random slopes for condition over items and random intercepts for both participants and items. A likelihood-ratio test showed that the model with random slopes over items was significantly better than a model with random intercepts only ($p = 0.03$). However, the more general model with random slopes over both subjects and items was not significantly better than the more restricted model with random slopes only for items ($p = 0.11$; this would be the maximal random effects structure; see Barr, Levy, Scheepers & Tily, 2013). Including non-significant random effects in a model can reduce its power and increase the probability of a Type II error, so we chose to use the more restricted model. Similarly, for the number of saccades, we included random slopes for condition over items and participants, but did not include correlations between random effects. For the probability of immediately making a regression after crossing the boundary, we only included random intercepts for participants and items, as none of the more general models converged if random slopes were included.[1] For reading time, average fixation duration in the whole sentence, and the total viewing time in the pre-boundary area, we used a model with random intercepts only, as the other models containing random slopes did not generate a better performance than the random-intercepts-only model. For the display conditions, we adopted treatment contrasts with the control condition as the baseline. For gLMMs, we obtained p-values based on asymptotic Wald tests (z-values). For LMMs, we report p-values from the Wald t-tests using the Satterthwaite approximation (Kuznetsova, Brockhoff & Christensen, 2017). The means and standard error of each measurement was calculated in each display condition and shown in Table 1.

Overall analysis

Compared with the control condition, there were more regressions in the whole sentences in the n-1 condition *(b=.35, SE=.18, t=2.00, p=.049)* and in the n-2 condition *(b=.56, SE=.19, t=2.87, p=.005)*. The difference between the n-3 condition and the control condition was marginally significant *(b=.31, SE=.17, t=1.83, p=.069)*. None of the differences were reliable for the number of forward saccades, average fixation

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[1] This included a model without any correlations of random effects and a model using sum contrasts instead of treatment contrasts for the condition variable. None of these models converged.

duration and sentence reading time on the level of the whole sentence. Since there was only a single display change in the experimental sentences in our study, the effect of the display change is unlikely to be reflected on the measurements in the whole sentence.

Regressions immediately after the display change

In addition to the global measures, we calculated the probability of making regressions back to the left of boundary immediately after crossing it for the first time. Compared with the control condition, the probability of regressions to the left of boundary was higher in the n-1 condition *(b=.43, SE=.17, t=2.59, p=.01),* the n-2 condition *(b=.44, SE=.17, t=2.66, p=.008)* and the n-3 condition *(b= .41, SE= .17, t = 2.46, p= .014)*, respectively. This shows that the masked text to the left of the boundary could be recognized during a single fixation after crossing the boundary and readers could recognize the changed characters up to three characters to the left of the boundary.

Additionally, we also found differences in the total time spent in the pre-boundary area. Compared to the control condition, the total time was longer in the n-1 condition *(b = 66.00, SE = 22.64, t = 2.91, p = .004)* and the n-2 condition *(b = 43.64, SE = 22.63, t = 1.93, p = .05)*. This effect did not reach significance in the n-3 condition (p > .05).

Table 1. The means and standard error (in parentheses) of eye measurements in each display condition.

	n-1	n-2	n-3	control
Number of regressions	5.09 (0.45)	5.30 (0.47)	5.03 (0.38)	4.72 (0.37)
Number of forward saccades	12.43 (0.85)	12.44 (0.89)	12.00 (0.71)	11.99 (0.81)
Average fixation duration (in ms)	230.49 (0.20)	231.28 (0.21)	230.80 (0.20)	232.75 (0.20)
Reading time (in ms)	4947.88 (376.48)	5023.19 (382.48)	4862.35 (311.24)	4765.69 (335.85)

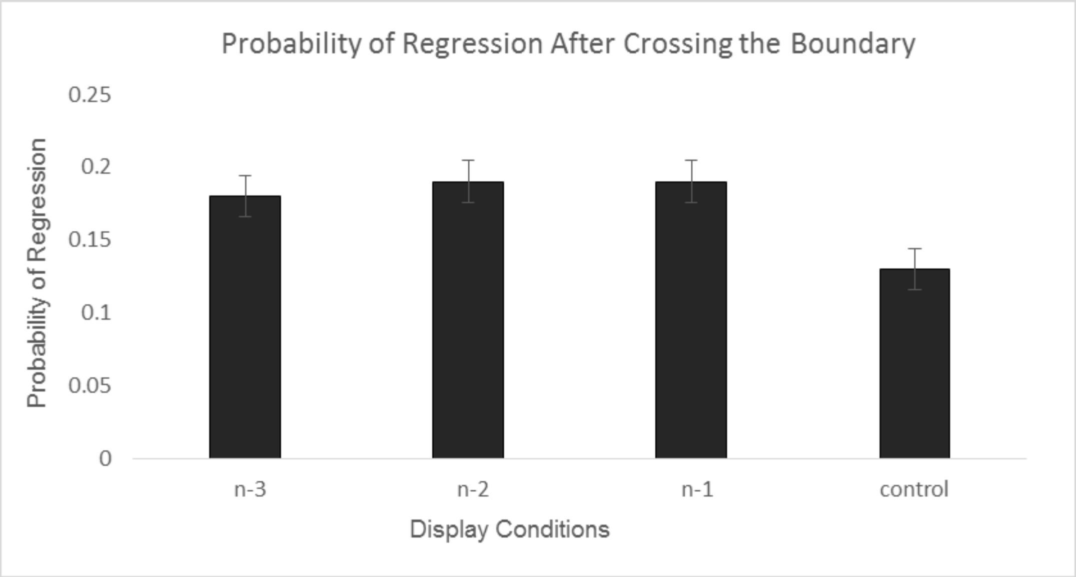

Figure 2. The barplot illustrates the probability of regression immediately after crossing the boundary in each display conditions, the error bars represent the standard errors.

Discussion

We performed an experiment manipulating the parafoveal information available to Chinese readers to the left of the current fixation position (i.e. parafoveal information about characters readers had either already fixated or skipped). We did this to test whether Chinese readers could recognize parafoveal information to the left of fixation outside the established extent of the perceptual span. The findings in our study clearly support this hypothesis: changing information to the left of fixation caused readers to make more regressions immediately after crossing the boundary, even when the change was as far away as three characters from the currently fixated character.

We cannot completely exclude the possibility that the regressions were triggered by readers noticing the display changes but we consider this unlikely to be the major cause of this effect for the following reasons: First, the display changes took place during a saccade, during which vision is suppressed (Matin, 1974). We observed the effect across all preview conditions, even in the n-3 condition, during which the change region was more than two character spaces away from the boundary, making it very unlikely for readers to perceive the change. Second, the masks consisted of valid Chinese characters selected to be visually similar to the actual characters in that position, often even sharing one or more radicals, and thus did not contain any unusual visual configurations or unfamiliar shapes. This means that readers could not detect changes based only on low-level visual information such as character shapes. The post-view effect we observed therefore has to be based either on the inter-character level (unusual character sequences) or in the interaction of the previously identified characters in memory with the new parafoveal input.

Taken together, the results suggest that Chinese readers can obtain information from at least three characters to the left of fixation, which are beyond the previous estimates for the leftward perceptual span in Chinese reading.

How can our results be reconciled with the previous results on the extent of the perceptual span? According to the logic of the measurement of the perceptual span using the gaze-contingent moving window paradigm, a perceptual span of one character to the left of fixation means that global measures of reading performance did not differ significantly between one- and two-character windows to the left of fixation. This indicates that, usually, having an extra parafoveal character available to the left does not improve reading efficiency and readers are perfectly capable of reading at an approximately normal speed without this extra information. However, readers do not need this extra information does not mean that they are incapable of perceiving it at all. The moving window paradigm tells us which parafoveal information is essential for efficient processing during reading. According to previous research in Chinese reading, only the information from the first character to the left of fixation is essential. This is likely because characters further to the left have already been processed by the time the eyes crossed the boundary. However, our experiment suggests that, while not essential, information from further to the left of fixation can be obtained and used in some circumstances. For example, this type of processing could act as an error correction mechanism in case the previous characters were misread.

In comparison to past research, in our research, we observed readers making more regressions back across the boundary immediately after they cross it for the first time in the n-1, n-2 and n-3 conditions, as well as more regressions across the sentence. However, we found no significance in other eye movement measurements. In contrast, Jordan et al. (2016) showed a large difference between the experimental conditions n-1, n-2 and the control condition in average fixation duration, reading time, forward and regressive saccade amplitudes and the number of forward saccades and regressions. This is likely due to the paradigm we used. In Jordan et al.’s research, the invisible boundaries were located between all words, and a display change took place every time the eyes crossed a boundary. The large number of display changes increased the participants’ awareness of the manipulation and was not similar to the natural reading. Consequently, all eye-movement measures in Jordan et al.’s study showed significant differences between the n-1 and the normal condition as well as between the n-2 and the normal condition, respectively. In our study, there was only a single invisible boundary located in the sentence. When there was a display change, the mask was displayed on the screen for only a single fixation. Our results showed a significantly higher probability of regression to the left of boundary in the experimental conditions compared with the control condition, suggesting a stronger influence of the text to the left of fixation on the reading performance. In our study, there was no display change in the control condition, and the change took place only on a single region in the experimental sentences. Thus, the display changes were very subtle and should not have been salient to readers. As a result, it would be unlikely for readers to develop an experimentally-induced bias toward the text to the left of fixation. Furthermore, Jordan's research showed that the finding that readers could recognize information beyond the left limit of the perceptual span was not affected by the inclusion of display changes to the right of fixation.

Can our results be explained by current models of eye movement control in reading? The two most widely cited models of eye movement control during reading (*E-Z Reader and SWIFT*) describe how visual processing and cognition interact with oculomotor control to affect eye movement measures during reading (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle et al., 2013; Engbert, Nuthmann, Richter, & Kliegl, 2005). According to the E-Z Reader model, attention is allocated strictly serially and only to one word at the same time (serial-attention shift). Saccadic programming and attention shifts do not occur concurrently. When the first stage of lexical processing completes, a saccadic program will be initiated to the next word. On the other hand, attention shifts to the next word are triggered at the end of the second stage of lexical processing (lexical completion). The results in our study were not strictly consistent with the assumptions of the E-Z Reader model, as readers should not need to acquire any parafoveal information from a word that they have already finished processing lexically.

Our results are not fully compatible with the SWIFT model, either. According to the SWIFT model, attention is allocated as a gradient and all the words in the perceptual span can be processed simultaneously. This means that readers might still be processing the words to the left of fixation if they have not finished processing before making a saccade away from them. However, the SWIFT model assumes that only foveal processing can affect the duration of the current fixation. Our study demonstrated that the post-view condition influenced processing during the current fixation, which is incompatible with this SWIFT assumption.

An alternative interpretation of our results uses the Rational Model of Eye Movement Control in reading by Bicknell and Levy (2010). In this Bayesian approach to reading, Bicknell and Levy assumed that readers maintain uncertainty about all the words in a sentence. If the perceptual input is not coherent with the reader’s lexical and grammatical knowledge about the rest of the sentence, their confidence about the content of the sentence will decrease and they will tend to compensate by making longer fixations and more regressions to the previous text they have read

(Levy, Bicknell, Slattery, & Rayner, 2010). In our experiment, when the boundary was crossed, characters to the left of the boundary were replaced with visually similar characters. The change only lasted for a single fixation, but may enable readers to integrate the new perceptual input with their previous representation of the sentence. Since the new input was incompatible with the previous information of the characters, readers' confidence of the identity of those characters decreased and they therefore made more regressions to the display change areas (Bicknell & Levy, 2011).

To summarize, we found that Chinese readers can perceive parafoveal information from at least three characters to the left of fixation, perhaps even further from that. We suggest that, unlike previously assumed, the perceptual span does not necessarily constitute an absolute limit beyond which no parafoveal information can be obtained, at least in Chinese reading.

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