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Parafoveal Load of Word N+1 Modulates Preprocessing Effectiveness of Word N+2 in Chinese Reading

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Preview benefits (PBs) from two words to the right of the fixated one (i.e., word N + 2) and associated parafoveal-on-foveal effects are critical for proposals of distributed lexical processing during reading. This experiment examined parafoveal processing during reading of Chinese sentences, using a boundary manipulation of N + 2-word preview with low- and high-frequency words N + 1. The main findings were (a) an identity PB for word N + 2 that was (b) primarily observed when word N + 1 was of high frequency (i.e., an interaction between frequency of word N + 1 and PB for word N + 2), and (c) a parafoveal-on-foveal frequency effect of word N + 1 for fixation durations on word N. We discuss implications for theories of serial attention shifts and parallel distributed processing of words during reading.

Keywords: eye movements, Chinese reading, preview benefit, parafoveal-on-foveal effects

The phenomenology of reading conveys the simultaneous visibility of the majority of words on a line of text. In contrast to this experience, the spatial extent of visual processing during a fixation is surprisingly narrow (Rayner & Bertera, 1979). Specifically, the area from which readers can obtain useful information, the perceptual span, extends 3–4 letters to the left and 14–15 letters to the right of fixation during reading of alphabetic languages (McConkie & Rayner, 1975); letter-specific influence, however, is restricted to 10–11 letters (McConkie & Rayner, 1975) or even only 7–8 letters (Rayner, Well, Pollatsek, & Bertera, 1982) to the right of fixation. During reading Chinese, the perceptual span extends 1 character to the left and 2–3 characters to the right of fixation during reading Chinese (Tsai & McConkie, 1995; Inhoff & Liu, 1998). In principle, with a sufficiently short word to the right of a fixated word N, chances are high that even the word beyond the next one (i.e., word N + 2) may fall into the perceptual span. Moreover, the size of the perceptual span may vary with the difficulty of foveal processing (Henderson & Ferreira, 1990). Here we test such a dynamical modulation of the perceptual span by the frequency of the *parafoveal* word N + 1 during reading Chinese.

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Research on N + 2 effects started with Rayner, Juhasz, and Brown (2007a) who proposed that with three words in the perceptual span we can derive contrasting predictions from serial lexical processing and parallel distributed processing models of eye-movement control in reading. Specifically, sequential attention shift (SAS) models like E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; see Engbert & Kliegl, 2001, for a different SAS variant, and Rayner, Li, & Pollatsek, 2007b, for an adaptation for reading Chinese) assume that lexical processing occurs only at the attended word and that attention shifts to the next word only after lexical access is completed. Thus, preprocessing of word N + 2 is generally not expected in serial lexical processing models except when word N + 1 is processed completely and attention shifts to word N + 2 while the eye still fixates on word N. In this case, the saccade program to word N + 1 is cancelled and re-programmed for word N + 2. On the other hand, guidance by attentional gradient (GAG) models such as SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005) or Glenmore (Reilly & Radach, 2006) assume distributed lexical processing in the perceptual span. As a consequence of this principle, GAG models generally allow parafoveal preprocessing to go beyond word N + 1 if the words fall into the perceptual span. From the outset, these model predictions were qualified: Not all evidence for N + 2 preview effects is incompatible with SAS models and not all evidence against N + 2 preview effects is incompatible with GAG models (e.g., Angele, Slattery, Yang, Kliegl, & Rayner, 2008; see also Discussion of present paper). Before these theoretical qualifications can be resolved we need to determine the conditions for obtaining statistically reliable N + 2 effects.

Experimental Evidence for and Against Processing of Word N + 2

Experimental evidence for parafoveal processing derives primarily from research with the boundary paradigm that manipulates the kind of information available in a parafoveal word N + 1 (or in the present case: N + 2) when the eye fixates on word N (Rayner, 1975). In the no-preview condition, the preview consists of a random letter string; in the identical preview condition, the target word is always visible. During the saccade from word N toward word N + 1 the preview in position N + 1 (or in the present case: N + 2) is replaced with the target word. Shorter fixations on the target word for identical than for random-letter preview are indicative of preview benefit (PB). PBs have been solidly established for word N + 1 for alphabetic scripts (see Rayner, 1998 for a review) and also for character-based scripts like Chinese (e.g., most recently by Yan, Richter, Shu, & Kliegl, 2009; Yang, Wang, Xu, & Rayner, 2009; Yen, Radach, Tzeng, Hung, & Tsai, 2009).

In contrast to pervasive PBs for word N + 1, experimental evidence is mixed for PBs relating to word N + 2. Rayner et al. (2007a) and Angele et al. (2008) found no evidence of PB for word N + 2, whereas Kliegl, Risse, and Laubrock (2007) demonstrated a PB for word N + 2 in the fixation on word N + 1. Yang et al. (2009) also reported a significant PB for word N + 2 in the first experiment, but it was not clear whether this effect arose due to character N + 2 being perceived as the second character of word N + 1 at least some of the time. In Experiment 2 which controlled for this ambiguity, the PB of word N + 2 was no longer significant for first-fixation durations (FFDs) and only marginally significant for gaze durations (GDs). Yang et al. suggested that the PB in Experiment 1 might have been due to highly frequent N + 1 words.

Dynamic Modulation of the Perceptual Span

Yang et al.'s (2009) conjecture holds much promise, because if their result can be established as statistically reliable in a controlled setting, it substantially extends the theoretical proposal that the size of the perceptual span is dynamically modulated not only by foveal (Henderson & Ferreira, 1990) but also by parafoveal load. In Henderson and Ferreira's two experiments, the PBs for target words were smaller when foveal processing was more difficult (i.e., less frequent words in Experiment 1 and words that lead to syntactic garden path effect in Experiment 2), suggesting that the attentional focus on the difficult foveal word narrowed the perceptual span, and as a consequence, less information was acquired parafoveally. Similar results were reported in later studies (Schroyens, Vitu, Brysbaert, & d'Ydevalle, 1999; White, Rayner, & Liversedge, 2005).

Yang et al.'s (2009) conjecture that PB of word N + 2 might depend on high-frequency words in position N + 1 has actually been tested for English and German, but was not supported by results. Kliegl et al. (2007) reported a spillover of N + 1 frequency on word N + 2, but did not find an interaction involving preview of word N + 2. Similarly, Angele et al. (2008) failed to demonstrate PB for word N + 2 being modulated by the parafoveal load of frequency of word N + 1, but their lack of significant effects relating to word N + 2, may have been a consequence of word N + 1 being generally too long. In summary, to our knowledge, although there is suggestive evidence from Yang et al.'s (2009) study of Chinese reading, the modulation of preprocessing of word N + 2 by *parafoveal load* of word N + 1 frequency has not been demonstrated in any language.

Relevant Aspects of Chinese Script

The Chinese script is particularly well suited for the demonstration of parafoveal processing. The majority of Chinese words are two characters long (Yu et al., 1985), varying from one to rarely longer than four characters. Each character takes up the same amount of horizontal extent in a passage of text, irrespective of the visual complexity of the character, which usually is indexed by number of strokes. The majority of modern Chinese characters are semantic-phonetic compounds. These characters are composed of a semantic unit indicative of its meaning, typically found on the left half, whereas the component on the right gives a hint to the pronunciation. A Chinese character typically occupies the space of three letters in alphabetic languages (i.e., Tsai & McConkie, 1995), but carries comparatively more information about the meaning of the word. Although the perceptual span in alphabetic and Chinese scripts differ in size, in principle two words can be identified on a single fixation in both scripts.

The boundary paradigm affords not only the measurement of identical PB, but one can also vary the orthographic, phonological, or semantic properties of word N + 1 (or N + 2) to determine what kinds of PB can be obtained. There is already uncontroversial evidence that readers of Chinese, like those of alphabetic languages, obtain various types of information from parafoveal word N + 1. For example, Liu, Inhoff, Ye, and Wu (2002) demonstrated PB effects from graphemically similar previews over dissimilar previews. Tsai, Lee, Tzeng, Hung, and Yen (2004) reported PB effects for both orthographically and phonologically similar previews.

A theoretically important difference between languages, however, relates to parafoveal semantic information. So far there is no reliable evidence for semantic PB in alphabetic languages (Rayner, White, Kambe, Miller, & Liversedge, 2003, for a review), but due to the characteristics of Chinese reviewed above, characters afford easier access to semantic features of words (Zhou & Marslen-Wilson, 1999, 2000). This makes it possible for Chinese readers to obtain not only parafoveal orthographic and phonological but also semantic features of word N + 1 (Yan et al., 2009). The present experiment tested not only the general PB from word N + 2, but also whether orthographic or semantic PB is available from this position.

The Present Experiment

The present experiment combined the design ideas reviewed above. In addition to different preview types at the word N + 2 position (i.e., identical, semantically related, orthographically related, and nonword), we also manipulated the parafoveal load with respect to the frequency of word N + 1. As a consequence of modulation of the perceptual span by parafoveal load, the preview benefit should be weaker or even disappear for a high processing load on word N + 1 (i.e., for a low-frequency parafoveal N + 1 words). The main questions of the present study are, (a) to what extent are readers able to obtain parafoveal information from word N + 2 in Chinese script under different preview conditions and (b) to what extent is parafoveal processing modulated by parafoveal load? Chinese script, "a writing system that is perhaps the most different from English" (Yang et al., 2009, p. 1193) with parafoveal lexical information densely packed in spatial proximity to the fixation location, may be more sensitive to parafoveal preprocessing than alphabetic script. Therefore, we expected readers of Chinese to reveal evidence for preprocessing word N + 2.

Method

Subjects

Seventy-four[1] students from the Beijing Normal University with normal or corrected to normal vision, who were native speakers of Chinese, participated in the eye-tracking experiment.

Material

Word N + 2. Forty-eight target characters were selected for the preview-type manipulation at word N + 2 position. For each target character, four types of preview characters served as identical, orthographically related, semantically related, and unrelated previews. All preview characters are simple and non-compound so as to avoid sublexical/radical activation during reading. There were no differences between the four preview types with respect to visual complexity [i.e., number of strokes; mean strokes: 5.0, 4.8, 5.5 and 4.9, for identical, orthographically related, semantically related, and unrelated characters, respectively; $F(3, 188) = 1.1$, $p > .1$] and frequency (Beijing Language Institute Publisher, 1986) [mean frequencies: 1150, 1154, 1164, and 1163, for identical, orthographically related, semantically related, and unrelated characters, respectively; $F(3, 188) < 1$]. Independent ratings of orthographic ($n = 18$ subjects) and semantic ($n = 16$) relatedness between the target and each type of the preview characters were collected. Each type of preview character related to targets only on the desired dimensions: semantic related previews were rated 4.1 out of a 5-point scale and orthographic related previews were rated 3.8 on the relevant dimensions, all ratings for the other conditions were smaller than 1.7.

Word N + 1. Ten high-frequency and 32 low-frequency single-character words were selected for the N + 1 frequency manipulation, some of them were used more than once across sentences so that each of the two frequency groups has 48 words. The two groups of words differed in frequency [mean frequencies: 38657 and 1451, for high and low frequency word N + 1, respectively; $F(1, 94) = 550.6$, $p < .001$] but not visual complexity [mean strokes: 7.5 and 7.1, for high and low frequency word N + 1, respectively; $F(1, 94) = 1.8$, $p > .1$].

Sentence frames. Two sentence frames were constructed out of each pair of N + 1 and N + 2 word combination. Sentences containing the target words were 20 to 29 characters in length ($M = 23.9$, $SD = 2.4$). The target characters were never among the first three and the last three words. The invisible boundary that triggered the display change was located just to the left of the space before word N + 1. Words before the boundary (word N) were always two-character words. Each sentence was only presented once to a subject with the eight conditions counterbalanced over subjects. An example of sentences is shown in Figure 1.

Apparatus

Eye movements were recorded with an EyeLink II system (500 Hz). Single sentences were presented on the vertical position one third of the way from the top of the screen of a 21-inch Dell Trinitron Monitor (1280 × 1024 resolution; frame rate 100 Hz). Therefore, it took at most 16 ms to complete the display change. This upper limit is much shorter than the mean

Low parafoveal load, identical preview
他建议当地政府应注意的户籍管理方面的问题已经得到解决。
*

Low parafoveal load, orthographically related preview
他建议当地政府应注意的广籍管理方面的问题已经得到解决。
*

Low parafoveal load, semantically related preview
他建议当地政府应注意的门籍管理方面的问题已经得到解决。
*

Low parafoveal load, unrelated preview
他建议当地政府应注意的丹籍管理方面的问题已经得到解决。
*

Low parafoveal load, target
他建议当地政府应注意的户籍管理方面的问题已经得到解决。
*
N N+1 N+2

High parafoveal load, identical preview
他建议当地政府应注意非户籍学生接受义务教育的权利。
*

High parafoveal load, orthographically related preview
他建议当地政府应注意非广籍学生接受义务教育的权利。
*

High parafoveal load, semantically related preview
他建议当地政府应注意非门籍学生接受义务教育的权利。
*

High parafoveal load, unrelated preview
他建议当地政府应注意非丹籍学生接受义务教育的权利。

High parafoveal load, target
他建议当地政府应注意非户籍学生接受义务教育的权利。
*
N N+1 N+2

Figure 1. A set of example Chinese sentences using the boundary paradigm. The low parafoveal load target sentence is translated as "the problems concerning the management of domicile that he suggested to the local government has been solved" and the high parafoveal load target sentence is translated as "he suggested that the local government should pay more attention to the compulsory education of non-residential students." The preview characters (广, 门 or 丹) that are initially displayed in the target location are replaced by the target character (户) as soon as the reader's eyes cross the invisible boundary located between word N (注意) and the either high-frequency word N + 1 (的) or low-frequency word N + 1 (非).

[1] Five subjects were excluded due to calibration failure and data of one because of low comprehension.

duration of the saccade (M = 25 ms; SD = 7 ms) that crossed the boundary.

The font Song 40 was used with one character equal to 0.9 degrees of visual angle. The experiment was controlled by a P4 computer, running at 2.8 GHz under the Windows XP environment. Subjects read with the head positioned on a chin rest 80 cm from the monitor. All recordings and calibrations were binocular.

Procedure

Subjects were calibrated with a nine-point grid for both eyes. They were instructed to read the sentences for comprehension, then fixate a dot in the lower right corner of the monitor, and finally press a button to signal completion of the trial. As shown in Figure 1, before readers' eyes cross the invisible boundary from word N to word N + 1, they get any one of the four previews at the position of word N + 2. During this critical saccade, the preview word is replaced by the target word. On 26 trials the sentence was followed by an easy yes–no question. Subjects correctly answered 91% of all questions (SD = 7%). Fixation on the fixation point initiated presentation of the next sentence or a drift correction. An extra calibration occurred if the tracker did not detect both eyes within a predefined window around the initial fixation point. All subjects read 131 sentences (i.e., 96 experimental sentences and 35 fillers). After the experiment, subjects were asked to report anything unusual during the sentence reading, some reported 'flashes' on the screen for only a few trials (M = 4, SD = 3), but they could not report what they saw.

Data Analysis

Data analysis was based on 74 subjects. Their data were reduced to a fixation format using an algorithm for the binocular detection of saccades (Engbert & Kliegl, 2003). Sentences containing a blink or loss of measurement were deleted (i.e., 5%). Analyses were based on right-eye fixations. First- and single-fixation durations as well as GDs with FFDs shorter than 60 ms or longer than 600 ms were excluded (2% of all fixations). First-fixation duration is the duration of the initial fixation on a word irrespective of number of fixations on the word; single-fixation duration is the duration of fixation on a word that is fixated exactly only once; and GD is the sum of all first-pass fixations on a word before making a saccade to another word.

Inferential statistics are based on *a priori* contrasts with random letter preview as reference for the two related and the identity previews. Estimates are from a linear mixed model (LMM) for durations and a generalized linear mixed model (GLMM) for skipping with crossed random effects for subjects and items using the *lmer* program of the *lme4* package (Bates, Maechler, & Dai, 2008) in the R environment for statistical computing and graphics (R-Core Development Team, 2008). We used log-transformed continuous frequency values as predictors in the models. Analyses for untransformed and log-transformed durations yielded the same pattern of significance; statistics are reported for log-transformed durations.

Results

Word N + 2 Region-Preview Benefits

Two main goals of the present study were to test (a) whether readers of Chinese are able to obtain useful information from parafoveal word N + 2 position and (b) whether parafoveal load dynamically modulates the perceptual span. A total of 5903 trials contributed to the following analyses. Relative to unrelated previews, there were significant preview benefits of 7 ms (b = .029, SE = .010, t = 2.9) for FFD and 12 ms (b = .040, SE = .013, t = 3.0) for GD on word N + 2. The skipping probability of word N + 2 under identical preview was also higher than unrelated previews (b = 0.22, SE = 0.11, z = 2.0, $p < .05$). We also tested what type of information is preprocessed at the word N + 2 position. However, neither durations nor skipping probabilities for the orthographically and semantically similar conditions were significantly different from unrelated controls (all t-values < 1).

Although the main effect of frequency was not significant (both t-values < 1.2), we did obtain an interaction between frequency of word N + 1 and the identity contrast for FFD analysis (b = .013, SE = .006, t = 2.3). Differences in parafoveal load of word N + 1 lead to different patterns of preprocessing of word N + 2 in agreement with dynamical modulation of the perceptual span (see Table 1a and Figure 2). Specifically, in a post-hoc analysis, the Identity contrast was significant only when N + 1 words were of high frequency (12 ms; b = .042, SE = .013, t = 3.2) but not when they were of low frequency (3 ms; b = .016, SE = .015, t = 1.1). The same numeric

Table 1
Means (Standard Deviations) of First-Fixation Duration (FFD), Gaze Duration (GD) and Skipping Probability (SP) for Word N + 2, Word N + 1, and Word N Broken Down by Preview Condition (Word N + 2) and Frequency of Word N + 1

	Type of Preview			
Frequency	Identity	Orthography	Semantics	Control
(a) Word N + 2				
FFD-HF	269 (49)	284 (51)	278 (45)	282 (43)
FFD-LF	280 (46)	285 (53)	288 (49)	283 (50)
GD-HF	306 (63)	329 (66)	321 (70)	326 (60)
GD-LF	328 (77)	335 (82)	333 (75)	337 (75)
S*p* -HF	.13 (.14)	.11 (.12)	.11 (.13)	.10 (.12)
S*p* -LF	.13 (.13)	.14 (.12)	.14 (.14)	.12 (.14)
(b) Word N + 1				
FFD-HF	246 (48)	261 (59)	252 (55)	260 (83)
FFD-LF	290 (62)	297 (61)	296 (66)	301 (63)
GD-HF	249 (53)	263 (60)	253 (55)	264 (86)
GD-LF	293 (63)	303 (62)	300 (66)	307 (63)
S*p* -HF	.58 (.18)	.63 (.17)	.61 (.17)	.60 (.16)
S*p* -LF	.50 (.18)	.50 (.17)	.43 (.18)	.46 (.19)
(c) Word N				
FFD-HF	263 (46)	257 (42)	258 (39)	261 (46)
FFD-LF	264 (45)	261 (42)	263 (43)	268 (44)
GD-HF	289 (71)	287 (60)	291 (58)	288 (60)
GD-LF	303 (71)	295 (64)	305 (69)	306 (75)
S*p* -HF	.18 (.18)	.14 (.14)	.15 (.14)	.14 (.14)
S*p* -LF	.14 (.13)	.13 (.13)	.15 (.15)	.13 (.12)

Note. HF = high-frequency word; LH = low-frequency word. Means and standard deviations are computed across subject means.

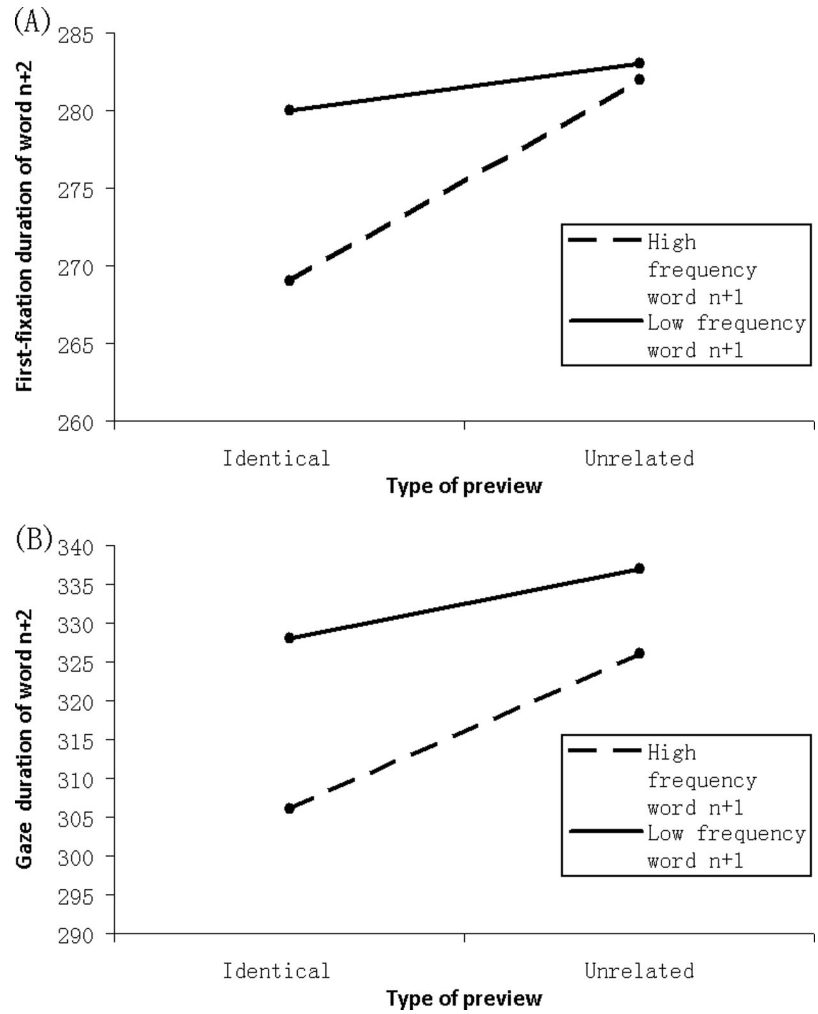

Figure 2. Differences in parafoveal load of word N + 1 lead to different patterns of preprocessing of word N + 2 in first-fixation duration (A) and gaze duration (B).

pattern is observed for GDs for PB under high-frequency (18 ms; *b* = .059, *SE* = .019, t = 3.2) and low-frequency (6 ms; *b* = .024, *SE* = .020, t = 1.2) conditions for word N + 1, but the interaction was not significant (t = 1.7).

Three extra analyses were conducted in order to rule out confounds regarding the display change issue. Table 2 summarizes the means (standard deviations) for FFDs and GDs obtained in these analyses, broken down by type of preview character and frequency of word N + 1.

First, most subjects (89%) detected 'flashes' in less than five trials, but only 22 subjects reported absolutely no changes on the screen. Dropping subjects with any flash detection greatly reduces statistical power, but these 22 subjects still yielded a similar pattern of means. For example, there was a significant PB for word N + 2 (*b* = .037, *SE* = .019, t = 2.0 and *b* = .065, *SE* = .026, t = 2.5, for FFD and GD analyses, respectively), and the PB was stronger when words N + 1 were highly frequent (*b* = .045, *SE* = .024, t = 1.9 and *b* = .066, *SE* = .034, t = 2.0, for FFD and GD analyses, respectively) compared to when they were low frequent (*b* = .033, *SE* = .029, t = 1.2 and *b* = .066, *SE* = .039, t = 1.7, for FFD and GD analyses, respectively).

Second, we excluded the trials in which the saccade crossed the boundary near the end of the saccade (i.e., during the final 20% of the saccade duration), because readers should be more likely to perceive a display change or a flash at this time. Again, although suffering reduced statistical power by dropping such trials, we replicated the same pattern as reported above based on 4700 trials. There was a significant main effect of PB for word N + 2 (*b* = .029, *SE* = .011, t = 2.5 and *b* = .049, *SE* = .015, t = 3.2, for FFD and GD analyses, respectively), and the PB was significant only when words N + 1 were of high frequency (*b* = .041, *SE* = .015, *t* = 2.7 and b = .072, *SE* = .020, t = 3.6, for FFD and GD analyses, respectively), but not when they were of low frequency (*b* = .018, *SE* = .017, t = 1.1 and *b* = .030, *SE* = .023, t = 1.3, for FFD and GD analyses, respectively).

Finally, given that only the first character of the target word was varied as part of the preview, it is reasonable to test whether the

Table 2
Means (Standard Deviations) of First-Fixation Duration (FFD), Gaze Duration (GD) for Three Extra Analyses on Word N + 2 Based on (A) 22 Subjects Who Reported Absolutely No Changes on the screen, (B) Trials in Which the Saccade Crossed the Boundary Far From the End of the Saccade (The First 80% of the Saccade Duration), and (C) Trials in Which Fixations Landed on the First Character of the Target Word

	Type of Preview			
Frequency	Identity	Orthography	Semantics	Control
(A)				
FFD-HF	276 (39)	302 (43)	289 (30)	287 (29)
FFD-LF	284 (33)	296 (43)	307 (54)	289 (33)
GD-HF	326 (61)	347 (68)	353 (85)	342 (57)
GD-LF	332 (69)	363 (62)	365 (81)	353 (66)
(B)				
FFD-HF	264 (41)	276 (46)	274 (42)	276 (40)
FFD-LF	270 (38)	279 (42)	281 (47)	272 (42)
GD-HF	301 (59)	325 (69)	322 (75)	323 (59)
GD-LF	320 (72)	334 (76)	332 (75)	328 (75)
(C)				
FFD-HF	265 (41)	278 (45)	274 (41)	277 (39)
FFD-LF	273 (40)	278 (43)	281 (46)	276 (42)
GD-HF	302 (57)	323 (63)	316 (68)	320 (57)
GD-LF	321 (69)	328 (73)	325 (71)	329 (71)

Note. HF = high-frequency word; LH = low-frequency word. Means and standard deviations are computed across subject means.

results hold if we examine only fixations on the character that was changed. Despite the reduced number of observations (3461 of 5903 trials), exactly the same results were obtained, including PB effects for word N + 2 (b = .035, SE = .013, t = 2.7 and b = .046, SE = .019, t = 2.4, for FFDs and GDs, respectively) and the interaction of PB and word N + 1 frequency (b = .019, SE = .008, t = 2.5 and b = .019, SE = .011, t = 1.8, for FFDs and GDs, respectively).

Word N + 1 Region

Frequency effect. The mean profile of FFD, GD, and skipping probability of word N + 1 is shown in Table 1b. Due to the high skipping rate (54%) the duration analyses are based on only 3105 observations. The main effect of frequency reached significance for effects on FFD (39 ms; b = .037, SE = .007, t = 5.3), GD (41 ms; b = .037, SE = .008, t = 4.5), and skipping probability (b = 0.17, SE = 0.04, z = 4.2, $p < .01$). The effect is the ordinary immediate frequency effect.

Relatedness effect. We also observed a significant skipping rate difference between the orthographically similar condition and the unrelated condition (b = 0.15, SE = 0.07, z = 2.1, $p < .05$), but do not know how to explain this effect, given that none of the other preview type contrasts nor any of the interactions were significant (all t-values < 2).

Preview benefit. On word N + 1, the FFD is numerically (13 ms; b = .024, SE = .014, t = 1.8) and GD is significantly (14 ms; b = .029, SE = .014, t = 2.1), shorter for identical than for unrelated word N + 2 previews. The direction of these effects agrees with those reported as significant in Kliegl et al. (2007).

Word N Region-Parafoveal-on-Foveal Effects

An alternative measure of preprocessing is to assess the impact of parafoveal information of words N + 2 directly during fixations on word N.

Fixation durations. Word N was identical in all eight conditions. The means (standard errors) of FFD and GD (based on 5752 observations) on the pre-boundary word N are shown in Table 1c. There was a significant word N + 1-frequency effect on FFDs (5 ms; b = .006, SE = .002, t = 2.9) and GDs (14 ms; b = .011, SE = .004, t = 2.6) on word N. However, none of the preview type contrasts nor their interactions with parafoveal load were significant (all t-values < 1.7).

First-fixation landing position. Parafoveal-on-foveal effects could be a consequence of mislocated fixations that were intended for word N + 1 (e.g., Drieghe, Rayner, & Pollatsek, 2008, but see Wang, Inhoff, & Radach, 2009). In this case, fixations leading to POF effects should be close to the word boundary between word N and word N + 1. Using again the same set of contrasts, the mean first-fixation landing position was 0.9 characters to the right of word beginning (i.e., slightly to the left of word center, since word N is always a two-character word), and the analysis of these fixation locations did not yield significant condition-specific differences (all t-values < 1.3).

Discussion

This experiment examined parafoveal processing of the word that is two words away from fixation (word N + 2) during reading of Chinese sentences. The main findings were (a) an identity PB for word N + 2 that was (b) primarily observed when word N + 1 was of high frequency (i.e., an interaction between frequency of word N + 1 and PB for word N + 2), and (c) a parafoveal-on-foveal frequency effect of word N + 1 for fixation durations on word N. These results establish as statistically significant a previous report with a marginally significant trend in this direction (Yang et al., 2009). Moreover, our results provide critical support for theoretical proposals about dynamical modulation of the size of the perceptual span by local processing difficulty. We expect that future processing gradient models of eye-movement control in reading are likely to include this property.

Preview Benefit for Word N + 2

The PB for word N + 2 had not been significant in four earlier experiments with alphabetic scripts (Angele et al., 2008; Kliegl et al., 2007; McDonald, 2006; Rayner et al., 2007a). We were able to detect the PB for word N + 2 because, on average, more information falls into the perceptual span of Chinese readers. Presumably it also helped that we used simple, non-compound characters in the N + 2-preview position. Previous Chinese reading studies demonstrated PBs on word N + 1 (Liu et al., 2002; Tsai et al., 2004; Yan et al., 2009; Yang et al., 2009). Yang et al. (2009) also tested preprocessing of word N + 2 and reported a weak (i.e., not significant for FFD analysis and marginally significant for GD analysis) PB for word N + 2. The present study is the first to report unqualified significant evidence that Chinese readers preprocess parafoveal characters/words N + 2 before they fixate them.

We also tested which information is obtained from word N + 2. Previous studies with Chinese demonstrated extraction of orthographical, phonological, and even semantic information from word N + 1. Since pure phonological preprocessing in Chinese reading is relatively weak and its effect is observed mainly in GDs (Liu et al., 2002; Tsai et al., 2004; Yan et al., 2009), we tested PB only for orthographically and semantically related conditions. However, neither semantic nor orthographic previews facilitated subsequent processing of word N + 2. Although readers of Chinese are able to obtain information from two words away, semantic and orthographic features by themselves were not strong enough to trigger reliable evidence for parafoveal processing in this study.

The research on PBs of word N + 2 was initiated because they are considered litmus tests of current computational models of eye-movement control (Rayner et al., 2007a). SAS models like E-Z Reader generally do not predict PB for word N + 2 due to the serial lexical processing assumption (Rayner et al., 2007b; Reichle et al., 1998). However, if lexical access is fast (i.e., if a word is of high frequency or can be predicted well from the prior sentence context), attention may shift from a fixated word N to word N + 1 and, again, from there to word N + 2 while the eyes are still at word N. It remains to be seen and demonstrated via simulation that PBs on word N + 2 after high-frequency words N + 1 are within this explanatory scope of the SAS perspective. On the other hand, while N + 2 PBs are in the spirit of GAG models, simulating them in a computational model like SWIFT remains a formidable challenge (Risse, Engbert, & Kliegl, 2008). Indeed, their simulation may require the implementation of a dynamical modulation of the perceptual span by local processing difficulty, as suggested previously, for example, by Inhoff and Rayner (1986; also Rayner, 1986).

Dynamic Modulation of the Perceptual Span

The most important contribution of the present experiment is its support of dynamical modulation of the perceptual or attentional span by parafoveal load (i.e., the frequency of word N + 1). It has been previously shown that the perceptual span is modulated by the foveal load, but modulations by parafoveal load have been elusive in alphabetic reading where PB effects on word N + 2 depend not only on the frequency of word N + 1 but also on its length (see Juhasz, White, Liversedge, & Rayner, 2008, for a review). In other words, length and frequency of word N + 1 jointly determine the rate of preprocessing of word N + 1. Due to a strong correlation of around −0.70 between word length and frequency in alphabetic languages, it is difficult to orthogonally manipulate these two factors without costs of generalizability.

In contrast, the narrow distribution of word length in modern Chinese (Yu et al., 1985) allows us to avoid this problem, using the ideal subset of one-character words. And, indeed, the frequency of parafoveal word N + 1 yielded a significant interaction between preview and parafoveal load: Readers obtain parafoveal information from word N + 2 when word N + 1 is easy to process; this PB is significantly reduced for low-frequency words. Although such a result is compatible in principle with processing gradient models, none of the current models implemented a dynamical modulation of the perceptual span.

Parafoveal-on-Foveal Effects

Parafoveal-on-foveal (POF) effects are much weaker than PB effects. So far, there are indeed mostly failures to find POF effects in alphabetic languages in the boundary paradigm when measured on pre-boundary words (i.e., word N in our terminology; see Angele et al., 2008, for a review), but there are a few exceptions (Kliegl et al., 2007). Also, POF effects are routinely reported for corpus analyses (Kliegl et al., 2006; Risse et al., 2008). In contrast, for Chinese reading, POF effects have been reported consistently from word N + 1 (Yan et al., 2009; Yang et al., 2009, Exp. 1) but not word N + 2 (Yang et al., 2009, Exp. 2). Similar to their results, we observed both FFD and GD differences on word N due to the frequency of word N + 1 (i.e., a typical N + 1 frequency POF effect), with no evidence that preview types of word N + 2 influenced the fixation duration on word N. There was, however, some evidence for an effect on word N + 1 which has been interpreted as a delayed POF effect (Kliegl et al., 2007).

Although in alphabetic languages the reliability of POF effects is tenuous in boundary experiments, POF frequency effects of word N + 1 have been found very consistently in corpus analyses (Kennedy & Pynte, 2005; Kliegl, Nuthmann, & Engbert, 2006; Kliegl, 2007). SAS models such as E-Z-Reader do predict that parafoveal information can guide eye movements, as evident from skipping of frequent words N + 1. However, POF effects of N + 1-frequency on fixation durations on word N violate the assumption that lexical processing of N + 1 starts only after complete lexical access of word N (see also Wang et al., 2009). Alternatively, such lexical POF effects are thought to arise from mislocated fixations due to oculomotor error (Drieghe et al., 2008; Nuthmann, Engbert, & Kliegl, 2005; Rayner et al., 2003). Results from the present experiment do not rule out the possibility of such a mislocation account, but its viability still needs to be demonstrated with simulation. In contrast, POF effects are within the scope of GAG models and have been simulated in SWIFT (Engbert et al., 2005).

Conclusion

Due to visual acuity constraints, parafoveal processing signals are weak at best. We used simple, non-compound characters to maximize their detection probability and found evidence for preprocessing of word N + 2. Consequently, the generalizability to Chinese characters at large, which are mainly semantic-phonetic characters (Shu, Chen, Anderson, Wu, & Xuan, 2003) remains to be established. In general, however, Chinese script appears to be well suited to unravel the dynamical interplay of visual, attentional, and lexical processes during word recognition in natural reading.

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