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# Preview fixation duration modulates identical and semantic preview benefit in Chinese reading

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**Abstract** Semantic preview benefit from parafoveal words is critical for proposals of distributed lexical processing during reading. Semantic preview benefit has been demonstrated for Chinese reading with the boundary paradigm in which unrelated or semantically related previews of a target word  $N + 1$  are replaced by the target word once the eyes cross an invisible boundary located after word  $N$  (Yan et al., 2009); for the target word in position  $N + 2$ , only identical compared to unrelated-word preview led to shorter fixation times on the target word (Yan et al., in press). A reanalysis of these data reveals that identical and semantic preview benefits depend on preview duration (i.e., the fixation duration on the preboundary word). Identical preview benefit from word  $N + 1$  increased with preview duration. The identical preview benefit was also significant for  $N + 2$ , but did not significantly interact with preview duration. The previously reported semantic preview benefit from word  $N + 1$  was mainly due to single- or first-fixation durations following short previews. We discuss implications for notions of serial attention shifts and parallel distributed processing of words during reading.

**Keywords** Eye movement · Parafoveal processing · Semantic · Chinese

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## Introduction

The inspection time of each word during sentence reading strongly depends on the words' properties such as its length or frequency of occurrence in a certain language, suggesting that the duration of fixating a word reflects the time needed to process and lexically access its entry in the mental lexicon (for a review see Rayner, 2009). The spatial extent of visual processing during a fixation goes much further beyond the currently fixated word, extending at most up to 4 letters to the left and 14–15 letters to the right of fixation during reading of alphabetic languages (McConkie & Rayner, 1975; Rayner & Bertera, 1979) and 1 character to the left and 2–3 characters to the right of fixation during reading Chinese (C.-H. Tsai & McConkie, 1995; Inhoff & Liu, 1997, 1998). This area, which must be visible for a normal reading rate, is called the *perceptual span* (McConkie & Rayner, 1975). In principle, with a sufficiently short word to the right of a fixated word  $N$ , chances are that even the word beyond the next one (i.e., word  $N + 2$ ) may fall into the perceptual span. Whether information of word  $N + 2$  can be extracted during reading of alphabetic languages is currently a highly controversial discussion (Rayner, Juhasz, & Brown, 2007; Angele, Slattery, Yang, Kliegl, & Rayner, 2008; for positive results see Kliegl, Risse, & Laubrock, 2007; Risse, Engbert, & Kliegl, 2008; Risse & Kliegl, in press). Here we report a reanalysis of published data and demonstrate that semantic information extraction from words  $N + 1$  and  $N + 2$  during Chinese reading depends on preview duration. Preview duration of words  $N + 1$  or  $N + 2$  is defined as the time that the reader looks at word  $N$  before moving to words  $N + 1$  or  $N + 2$ .

### Evidence for and against semantic preview benefit in alphabetic scripts

The boundary paradigm (Rayner, 1975) has been extensively used to investigate what type of information is obtained from a parafoveal preview. In this paradigm, preview of a target word is deprived by presenting an alternative word (or nonword) that parafoveally occupies the position during pretarget fixations. During a saccade that crosses an invisible boundary located at the end of the pretarget word, the preview word is replaced by the correct word. If correct preview of the target word is provided in parafoveal vision compared to if it is denied, fixation durations on the target word are reduced when it is subsequently fixated. This *preview benefit* is consistently interpreted as evidence for preprocessing a neighbouring word  $N + 1$  during prior fixations on word  $N$ , integrating the parafoveal information across saccades, and thus facilitating its later foveal processing.

With manipulations of the information overlap between the preview and the target word, it has been shown that in Western alphabetic languages orthographic (Balota, Pollatsek, & Rayner, 1985; Inhoff, 1989; Rayner, 1975) and phonological codes (Ashby, Treiman, Kessler, & Rayner, 2006; Mielliet & Sparrow, 2004; Chace, Rayner, & Well, 2005) are extracted during preboundary fixations and facilitate word recognition of word  $N + 1$  when it is fixated. So far, there has been no such evidence of a benefit from a semantically related parafoveal preview (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Rayner, Balota, & Pollatsek, 1986; see also Rayner, White, Kambe, Miller, & Liversedge, 2003, for a review). One possible explanation for this null effect

is that phonology plays an important mediating role leading to a word's meaning being activated relatively late (Van Orden, 1987; Van Orden, Pennington, & Stone, 1990; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), when compared to some other languages such as Chinese, which we will elaborate below.

In contrast to the view of late semantic activation, evidence from fast priming studies suggests that semantic information facilitates recognition of a foveal target word during a narrow time window at a very early stage with prime durations of about 30 ms (Sereno & Rayner, 1992). In a recent study using a combination of the fast priming and boundary paradigm, Hohenstein, Laubrock, and Kliegl (2010) extended this research to investigate parafoveal semantic priming. Hohenstein et al. varied the duration of parafoveal semantic primes for word  $N + 1$ . They obtained a semantic preview benefit with a parafoveal prime duration of 125 ms, but not for shorter ones (Experiment 1 and 2). When the saliency of the parafoveal prime word was increased, the semantic preview benefit was significant with an 80-ms but not with the 125-ms parafoveal prime duration (Experiment 3). Thus, in addition to providing evidence for parafoveally processing semantic information in alphabetic languages, the results suggest that semantic preview benefit is time dependent with facilitation due to semantic relatedness of parafoveal preview only during a specific, possibly only early, time window.

### Chinese script and semantic preview benefit

Eye-movement control during reading Chinese shares many basic characteristics of alphabetic writing systems (Yan, Kliegl, Richter, Nuthmann, & Shu, 2010). However, there are also important differences, especially with respect to parafoveal processing of semantic information. Chinese script uses square-shaped characters with different levels of visual complexity as the basic writing units; they all occupy the same amount of horizontal extent. There are two important features that make Chinese script particularly well-suited for the demonstration of parafoveal semantic processing. First, in comparison with alphabetic languages, it is generally accepted that Chinese characters are mapped more closely to meaning than to phonology (see Hoosain, 1991, for a summary) whereas the contribution of phonological activation during identification is comparatively small (see Feng, Miller, Shu, & Zhang, 2001, for a review). Second, most Chinese words are only one or two characters long (Yu et al., 1985). Given that a Chinese character typically occupies the space of 3 letters in alphabetic languages (i.e., J. L. Tsai & McConkie, 2003), on average, word  $N + 1$  is closer to the point of fixation on word  $N$  in Chinese than in alphabetic languages.

Yan, Richter, Shu, and Kliegl (2009) investigated parafoveal processing of Chinese words in position  $N + 1$  by manipulating the first character in two-character words and found a reliable preview benefit for characters semantically related to the target. Yan, Kliegl, Shu, Pan, and Zhou (in press) used the same material as Yan et al., but they moved the target word to the  $N + 2$  position by inserting a high-frequency or low-frequency word in position  $N + 1$ . They reported an  $N + 2$  preview benefit (see also Yang, Wang, Xu, & Rayner, 2009), but only when the preview character was identical to the target character; the effect was larger with a high-frequency word  $N + 1$ . Importantly, there was no significant preview benefit

when the previewed character was semantically related to the target but there was a trend in this direction.

In the boundary paradigm the previews are always either available or denied for the entire duration of the fixation prior to the boundary. This raises the possibility that the failure to find a reliable semantic preview benefit for word  $N + 2$  in Chinese could be due to a dependence of this effect on a specific time window. Hohenstein et al.'s (2010) results suggest that parafoveal semantic information may facilitate processing as early as 125 ms. As preboundary fixation durations are usually much longer than 125 ms (and under the readers' control), these long previews may have masked a semantic preview benefit during a specific time window in alphabetic scripts.

### Sequential attention shift vs. processing gradient models

Statistically reliable evidence for semantic preprocessing of word  $N + 2$  provides important constraints for theoretical accounts of serial attention shift (e.g., Engbert & Kliegl, 2001; Reichle, Liversedge, Pollatsek, & Rayner, 2009) and processing gradient models of eye-movement control (e.g., Engbert & Kliegl, 2010; Engbert, Nuthmann, Richter, & Kliegl, 2005; Reilly & Radach, 2003, 2006). Serial attention shift (SAS) models like E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle et al., 2009; see Engbert & Kliegl, 2001, for a different variant) 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, semantic preview benefit is problematic for serial attention shift models (e.g., Reichle et al., 2009, for a review). On the other hand, processing gradient (PG) models such as SWIFT (Engbert et al., 2005) or Glenmore (Reilly & Radach, 2003, 2006) assume distributed lexical processing in the perceptual span. As a consequence of this principle, PG models generally allow semantic preprocessing for words  $N + 1$  and even for words  $N + 2$  as long as they are in the perceptual span. However, due to the acuity-related decrease of processing efficiency with eccentricity from the current fixation location, semantic preprocessing for word  $N + 2$  might be too weak to be detected in alphabetic languages. In Chinese, as a language in which the information is more densely packed, the semantic information extraction has been shown for word  $N + 1$  and may even be visible for word  $N + 2$  for an appropriate time window of preview.

### The present study

The current study reports a reanalysis of Yan et al. (2009) and Yan et al. (in press). In the boundary paradigm, preview duration of word  $N + 1$  and word  $N + 2$  is "controlled" by participants' fixations on the preboundary word  $N$ . When a saccade is executed that crosses the invisible boundary, the display change of word  $N + 1$  and word  $N + 2$  is triggered and terminates the parafoveal prime. Therefore, the variability of preview durations may act like different parafoveal prime durations and can be used as a covariate for the size and direction of various preview effects.

Using the data from the two prior studies, we focus on the size of various informative preview effects (i.e., identical, semantic, orthographic, and phonological relative to unrelated preview words) as a function of the preview single-fixation duration for parafoveal processing of word  $N + 1$  and  $N + 2$  in Chinese reading.

Method

Subjects

All participants of the experiments were native Chinese students from Beijing Normal University with normal or corrected to normal vision. For the eye-tracking experiments, 48 students were tested for Data Set 1 with a manipulation of word  $N + 1$  (Yan et al., 2009) and an independent sample of 74 students contributed to Data Set 2 with a manipulation of word  $N + 2$  (Yan et al., in press). Also, 51 students who did not participate in the two eye-tracking experiments were recruited for three norming studies of relatedness between previews and targets.

Material

Forty-eight simple non-compound characters were selected as targets, which served as the first character of word  $N + 1$  in Data Set 1 and the first character of word  $N + 2$  in Data Set 2. Each target character was embedded into a two-character target word, only the identity condition provided legal word-level preview. For each target character, four types of preview characters were selected for orthographically related, phonologically related, semantically related, and unrelated preview conditions. As shown in Table 1, there were no differences between the five preview types with respect to visual complexity as indexed by number of strokes

**Table 1** Means (standard deviations) of frequency (per million), number of strokes and relatedness ratings of target and preview characters

	Target	Preview				
		Identical	Orthographic	Phonological	Semantic	Unrelated
Example	永	永	水	用	久	向
Meaning	Forever	Forever	Water	Usage	Long	Towards
Pronunciation	yong3	yong3	shui3	yong4	jiu3	xiang4
Frequency	1,150 (1,728)	1,150 (1,728)	1,154 (1,435)	1,197 (1,757)	1,164 (1,721)	1,163 (1,573)
No. of strokes	5.0 (2.1)	5.0 (2.1)	4.8 (1.8)	5.1 (1.9)	5.5 (2.6)	4.9 (1.9)
Orthographic rating			<b>3.8 (0.8)</b>	1.6 (0.3)	1.5 (0.4)	1.6 (0.3)
Phonological rating			1.2 (0.3)	<b>4.3 (0.6)</b>	1.2 (0.2)	1.1 (0.2)
Semantic rating			1.2 (0.3)	1.2 (0.1)	<b>4.1 (0.6)</b>	1.2 (0.2)

Ratings set in bold signify that independent ratings matched the intended experimental manipulation



## Data analysis

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., 18% in Data Set 1 and 5% in Data Set 2). Analyses were based on right-eye fixations during first-pass reading. We distinguish between first fixation durations (FFDs; the first fixation on a word, irrespective of the number of fixations), single fixation durations (SFDs; cases in which a word was inspected with exactly one fixation), and gaze durations (GDs; the sum of fixations during the first reading of the word). Cases with FFDs shorter than 60 ms or longer than 600 ms were excluded (1% of all fixations in Data Set 1 and 2% in Data Set 2). Further, trials with regressions from word  $N$  or  $N + 1$  for Data Set 1 as well as from word  $N$ ,  $N + 1$  or  $N + 2$  for Data Set 2 were excluded (10% trials in Data Set 1 and 11% trials in Data Set 2). For the five preview conditions in Data Set 1, there were 1,052 observations in the LMM model for FFD and GD analyses and 769 observations for SFD analysis; for the four preview conditions in Data Set 2, there were 4,024 observations in the LMM model for FFD and GD analyses and 3,385 observations for SFD analysis.

Inferential statistics are based on planned comparisons for the related and the identity previews with the unrelated preview as reference. Estimates are based on a linear mixed model (LMM) with crossed random effects for subjects and items using the *lmer* program of the *lme4* package (Bates & Maechler, 2010) in the R environment for statistical computing and graphics (R-Core Development Team, 2010). Estimates larger than 2 SE (i.e.,  $t > 2$ ) are interpreted as significant. Analyses of residuals and inspection of duration distributions strongly suggested that log-transformation is required to meet LMM assumptions. Therefore, we used log-transformed durations for LMMs.

## Results

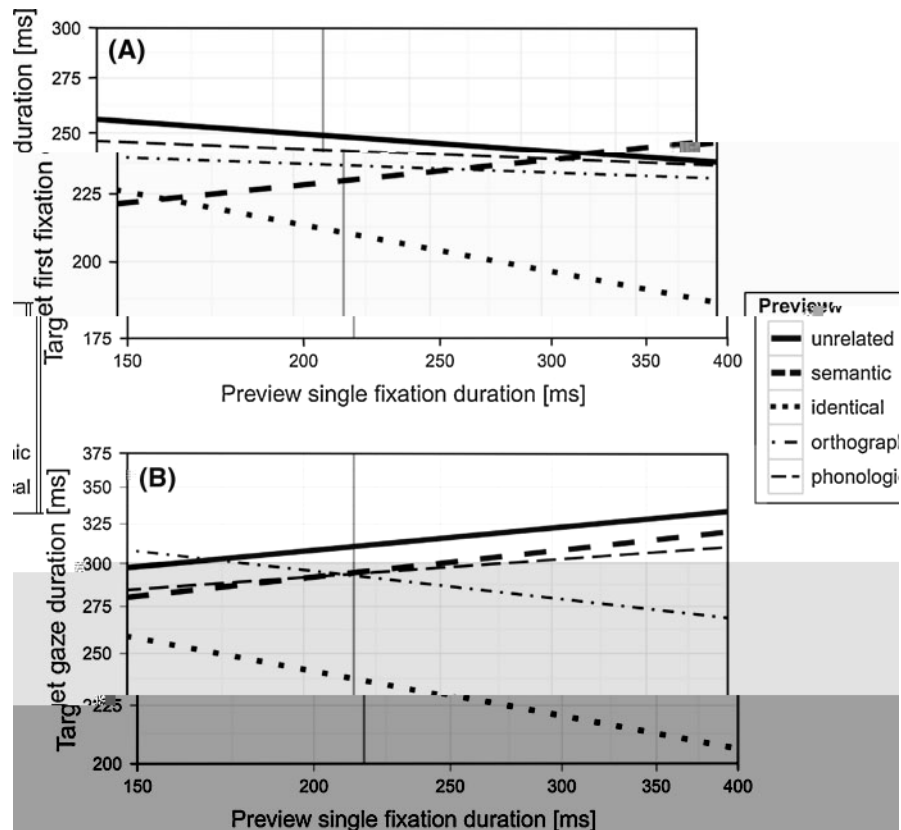
The main goal of the present research was to test whether the duration of the fixation prior to the display change in cases when only a single fixation is made on the preboundary word modulates preview benefit from semantically related parafoveal words in positions  $N + 1$  and  $N + 2$  in reading of Chinese. FFDs, SFDs, and GDs on word  $N + 1$  (Data Set 1) and  $N + 2$  (Data Set 2) were used as dependent variables. In the LMMs, these effects of interest translate into interactions between the continuous predictor of single-fixation duration on preboundary word  $N$  and planned comparisons of semantic, orthographic, phonological (only in Data Set 1), and identical preview with an unrelated preview as baseline (i.e., treatment contrasts with unrelated preview as reference category). Main effects were evaluated at the mean of the log preview SFD (i.e., the covariate was centered). Thus, the intercept represents the mean log FFD, mean log SFD, or mean log GD on the target word for the unrelated condition. Analyses using preview SFD as covariate yielded the clearest dissociation of effects, possibly because single-fixation cases carry few mislocated fixations (Nuthmann, Engbert, & Kliegl, 2005) and are reliable indicators of successful parafoveal word segmentation (Yan et al., 2010).

We note that similar trends (not always significant) were also present for FFDs and GDs on the preboundary word  $N$ . We also test the critical results in post-hoc comparisons for short and long preview durations, using the mean of the log-transformed single fixation duration as cut-off point.

Preview benefit for word  $N + 1$

*Identical preview benefit*

The main effect of identical preview was highly significant ( $b = -0.16$ ,  $SE = 0.03$ ,  $t = -6.1$ ;  $b = -0.17$ ,  $SE = 0.03$ ,  $t = -5.5$ ;  $b = -0.27$ ,  $SE = 0.04$ ,  $t = -7.2$ ; for FFD, SFD and GD analyses, respectively). In Fig. 2, the identical preview benefit corresponds to the difference between the unrelated (bold solid) and identical (bold dotted) lines. It is



**Fig. 2** Linear regression of first-fixation duration (a), and gaze duration (b) on word  $N + 1$  on single-fixation duration on word  $N$  for unrelated (bold-solid), semantic (bold-dashed), identical (bold-dotted), orthographic (simple dashed), phonological (simple dot-dashed) preview conditions using logarithmic scales for both axes. The vertical line indicates the mean log single-fixation duration on word  $N$ . Between-subject and between-item differences for dependent variable and covariance in the LMM were removed prior to regressions. Figure was generated with *ggplot2* (Wickham, 2009)

shown for FFDs (panel A) and GDs (panel B). The vertical line indicates the mean log preview duration (i.e., the value at which main effects are evaluated).

With FFD as dependent variable (Fig. 2a), the identical preview effect was remarkably large and also largely independent of preview duration (i.e., distance between identical and unrelated conditions is large and the hypothesis that the two lines are parallel cannot be rejected; interaction  $t$ -values for FFDs, also SFD,  $< 1$ ).

On 17, 30, 25, 34 and 29% (for identical, orthographic, phonological, semantic and unrelated preview conditions, respectively) of all valid trials, first fixations on target word were followed by refixations. With GD as dependent variable (Fig. 2b), the identical preview benefit significantly increased with preview duration ( $b = -0.28$ ,  $SE = 0.14$ ,  $t = -2.0$ , for the interaction of identical vs. unrelated preview and preview duration).<sup>1</sup> The increase in the preview benefit resulted from the divergence in GD for unrelated and identical previews; neither the numeric GD increase for the unrelated preview ( $t = 1.36$ ) nor the numeric GD decrease for the identical preview ( $t = -1.37$ ) was significant by itself.

The similarity between FFDs and GDs in slopes for the identical conditions (bold dotted lines in Fig. 2) suggests that refixation rate did not depend on preview duration. The divergence in slopes for the unrelated conditions (negative for FFDs and positive for GDs; bold solid lines in Fig. 2) suggests that refixation rate increased during preview. This was confirmed in post-hoc analyses of refixation rate, using a binary measure of fixating the target once or more than once as dependent variable in a generalized linear mixed model (GLMM): Refixation rate increased significantly during preview in the unrelated preview condition ( $b = 0.25$ ,  $SE = 0.10$ ,  $t = 2.5$ ), but refixation rate did not decrease significantly in the identical preview condition ( $b = -0.07$ ,  $SE = 0.11$ ,  $t = -0.6$ ). Traditionally, the unrelated preview condition serves as the baseline for the computation of the preview benefit. The increase in refixation rate with preview duration in this condition may be interpreted as evidence for a preview cost. This is a very important result because it suggests that classical preview benefits may arise in part as a consequence of *preview cost* associated with long previews of unrelated words.

### *Semantic preview benefit*

The main effect of semantic preview was also significant for FFDs and marginally significant for SFDs ( $b = -0.07$ ,  $SE = 0.03$ ,  $t = -2.7$ , and  $b = 0.06$ ,  $SE = 0.03$ ,  $t = -1.8$ , respectively) and there was a numeric trend for GDs ( $b = -0.06$ ,  $SE = 0.04$ ,  $t = -1.6$ ). These (tendencies to) main effects were strongly qualified by interactions with preview duration (i.e., preview SFDs;  $b = 0.16$ ,  $SE = 0.10$ ,  $t = 1.7$ , and  $b = 0.23$ ,  $SE = 0.12$ ,  $t = 2.0$ , for FFDs and SFDs, respectively; see Footnote 1). The dashed bold line (semantic preview) and the solid bold line

<sup>1</sup> We also tested the interaction between preview duration and preview benefits in a LMM with subgroup as two-level factor replacing the covariate (i.e., logarithm preview single fixation duration), which is more compatible with the traditional ANOVA route. In this analysis we failed to replicate the significant interactions (identical preview benefit in GD analysis:  $b = -0.09$ ,  $SE = 0.07$ ,  $t = -1.2$ ; semantic preview benefit:  $b = 0.08$ ,  $SE = 0.05$ ,  $t = 1.5$ ;  $b = 0.09$ ,  $SE = 0.06$ ,  $t = 1.5$ ; for FFD and SFD analyses, respectively). We present this also as evidence that not everything is significant in LMM (as is sometimes surmised).

(unrelated preview) in Fig. 2a shows that FFDs with semantic preview were as short as those for identical preview given a 150 ms preview duration, but were as long as those for unrelated preview with a preview duration of 400 ms. Thus, the semantic preview benefit differed from the identical preview benefit: the semantic preview benefit was large for short previews and vanished with increasing preview duration whereas identical preview benefit was present for all preview durations. The effects were not significant with GD as the dependent variable.

*Orthographic and phonological preview benefits*

There was a significant main effect for orthographic preview in FFDs ( $b = -0.06$ ,  $SE = 0.03$ ,  $t = -2.1$ ; SFDs:  $t = -1.7$ , GDs:  $t = -1.7$ ). There was no significant effect of the phonological preview condition (all  $t$ -values  $< 1.4$ ).

None of the interactions between orthographic or phonological preview and preview duration was significant, that is the slopes for the orthographic (dot-dash) and phonological (dashed) previews did not differ significantly from the one for the unrelated-preview baseline. In a follow-up LMM with identical preview as reference conditions, these slopes were not significantly different from this condition either (all  $t$ -values  $< 1.4$ ).

*Preview effects for grouped short and long previews*

*Identical preview.* As a further illustration of the significant interaction, we separated trials into two subgroups with a cutoff point of mean log preview SFD of 217 ms; the value at which the main effects in the above LMMs were evaluated (see Table 2). This criterion led to 572 observations for FFD and GD analyses as well as 420 observations for SFD analysis for the short preview group, and 480 observations for FFD and GD analyses as well as 349 observations for SFD analysis for the long preview group. Results indicated that identical preview benefit in GDs was significant in each of the subgroups and increased in effect size with

**Table 2** Means (standard errors) of first-fixation duration (FFD), single-fixation duration (SFD) and gaze duration (GD) on word  $N + 1$  from Data Set 1, broken down by mean log preview single-fixation durations

	No. obs	Identical	Orthographic	Phonological	Semantic	Unrelated
<i>Short preview</i>						
FFD	572	216 (9)	235 (10)	249 (9)	231 (9)	259 (7)
SFD	420	214 (10)	240 (12)	256 (11)	237 (11)	263 (8)
GD	572	260 (16)	307 (17)	322 (17)	308 (16)	332 (15)
<i>Long preview</i>						
FFD	480	219 (12)	255 (11)	254 (11)	254 (12)	262 (9)
SFD	349	218 (13)	246 (13)	257 (13)	259 (14)	259 (11)
GD	480	257 (23)	333 (23)	326 (23)	340 (23)	370 (20)

Means and standard deviations are computed across grand means

increased preview duration ( $b = 0.23$ ,  $SE = 0.05$ ,  $t = 4.7$  and  $b = 0.31$ ,  $SE = 0.06$ ,  $t = 5.2$  for short and long previews, respectively).

*Semantic preview.* The semantic preview benefit was also modulated by preview duration: It was significant for short previews ( $b = 0.10$ ,  $SE = 0.03$ ,  $t = 2.9$  and  $b = 0.10$ ,  $SE = 0.04$ ,  $t = 2.3$ ; for FFD and SFD analyses, respectively) but not for long ones (both  $t$ -values  $< .07$ ).

*Orthographic and phonological preview.* Orthographic preview benefit was significant for short previews,  $b = 0.09$ ,  $SE = 0.04$ ,  $t = 2.3$  and  $b = 0.09$ ,  $SE = 0.04$ ,  $t = 2.0$ ; for FFD and SFD analyses, respectively; both  $t$ -values were smaller than 1 for long previews. Note in the LMM this effect was significant as a main effect. The phonological preview benefit tended to be significant for long previews ( $b = 0.10$ ,  $SE = 0.06$ ,  $t = 1.7$  and  $b = 45$  ms,  $SE = 23$  ms,  $t = 1.9$ ; for analyses in log-transformed and original metrics, respectively) compared to short previews (both  $t$ -values  $< 0.7$ ).

Preview benefit for word  $N + 2$

#### *Skipping of word $N + 1$*

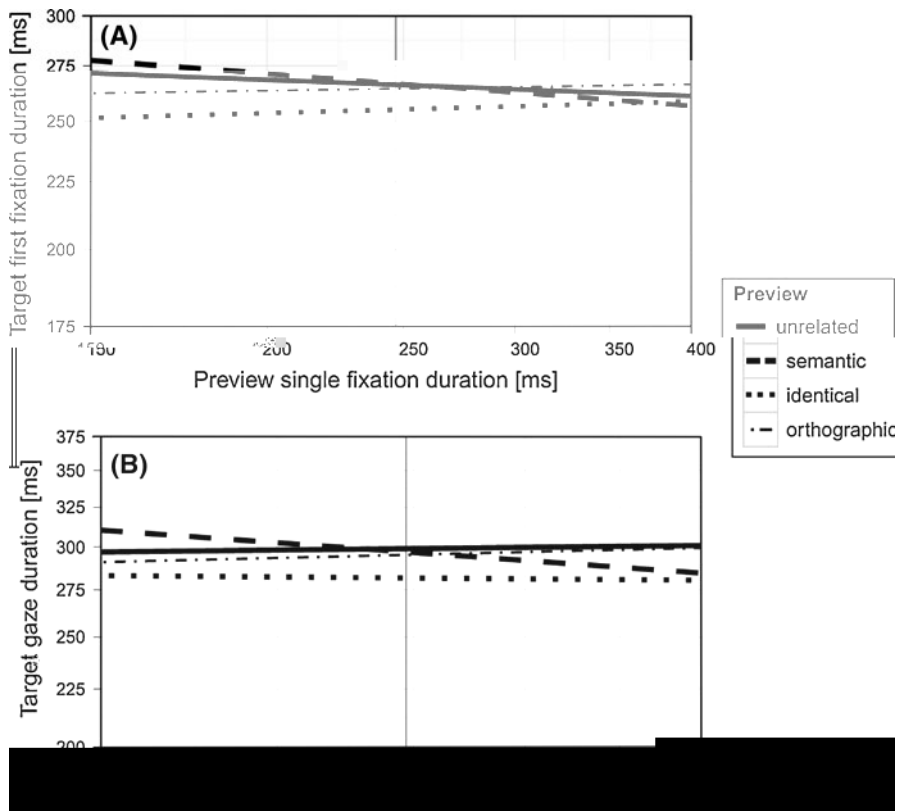
In the second data set with target words in position  $N + 2$ , all of the words in position  $N + 1$  were one character long. Consequently, there was a high skipping probability associated with this word (54%). It is well known that fixations after skipped words are longer than on average. In the present experiment skipping of  $N + 1$  increased FFDs by 23 ms, SFDs by 23 ms and GDs by 58 ms on target word  $N + 2$ . These effects were highly significant in the LMM ( $b = 0.09$ ,  $SE = 0.01$ ,  $t = 7.7$ ;  $b = 0.08$ ,  $SE = 0.01$ ,  $t = 8.2$ ;  $b = 0.18$ ,  $SE = 0.01$ ,  $t = 12.5$ ; for FFD, SFD and GD analyses, respectively). Skipping of word  $N + 1$ , however, did not interact with preview duration or preview conditions (all  $t$ -values  $< 1.4$ ).

#### *Identical preview*

In general, preview effects were much weaker for word  $N + 2$  than for word  $N + 1$  (compare Fig. 3 for word  $N + 2$  and Fig. 2 for  $N + 1$ ). The largest effect in this data set was again the main effect of identical preview ( $b = -0.05$ ,  $SE = 0.01$ ,  $t = -3.8$ ;  $b = -0.05$ ,  $SE = 0.01$ ,  $t = -3.7$ ;  $b = -0.07$ ,  $SE = 0.02$ ,  $t = -4.2$ ); for FFD, SFD and GD analyses, respectively, but none of the interactions with preview duration were significant (all  $t < 1$ ). In a follow-up LMM, FFDs, SFDs, and GDs after identical preview were also significantly shorter compared to semantic or orthographic preview (all  $t > 2.65$ ).

#### *Semantic preview*

Despite the strongly reduced preview modulation, the bold dashed line for semantic preview and bold solid line for unrelated preview represent a significant interaction



**Fig. 3** Linear regression of first-fixation duration (a) and gaze duration (b) on word  $N + 2$  on single-fixation duration on word  $N$  for unrelated (*bold-solid*), semantic (*bold-dashed*), identical (*bold-dotted*) and orthographic (*simple dashed*) preview conditions using logarithmic scales for both axes. The vertical line indicates the mean log single-fixation duration on word  $N$ . Between-subject and between-item differences for dependent variable and covariance in the LMM were removed prior to regressions. Figure was generated with *ggplot2* (Wickham, 2009)

between preview duration and semantic preview benefit for GD analysis ( $b = -0.11$ ,  $SE = 0.05$ ,  $t = -2.0$ ).<sup>2</sup> Again, we observed a crossover pattern, but this time the semantic preview effect was negative for shorter than average preview durations and positive for longer than average ones (i.e., semantic preview benefit; see Fig. 3b). This negative difference was not significant in the subgroup of short previews, but neither was the positive difference for long previews (see below). The interaction was not predicted. Therefore, the result is in need of independent replication before it is used for substantive interpretations.

<sup>2</sup> This interaction also reached significance in a LMM using a logic grouping factor ( $b = -0.06$ ,  $SE = 0.03$ ,  $t = -1.9$ ).

**Table 3** Means (standard errors) of first-fixation duration (FFD), single-fixation duration (SFD) and gaze duration (GD) on word *N* + 2 from Data Set 2, broken down by mean log preview single-fixation durations

Means and standard deviations are computed across grand means

	No. obs	Identical	Orthographic	Semantic	Unrelated
<i>Short preview</i>					
FFD	2,222	248 (5)	257 (4)	266 (5)	263 (6)
SFD	1,855	245 (5)	259 (5)	265 (5)	260 (6)
GD	2,222	267 (8)	281 (8)	293 (8)	286 (9)
<i>Long preview</i>					
FFD	1,802	259 (6)	275 (6)	271 (6)	270 (6)
SFD	1,530	259 (6)	274 (6)	273 (6)	272 (6)
GD	1,802	285 (9)	298 (9)	298 (9)	312 (9)

Orthographic preview

The main effect of orthographic preview and its interaction with preview duration were not significant (all *t*-values < 1.2).

Preview benefit for grouped short and long previews

Post-hoc breakdown of trials by mean log preview duration (i.e., 247 ms in original metric) did not reveal significant semantic or orthographic preview benefits for any of the groups.<sup>3</sup> As shown in Table 3, there was only a numerical trend of a semantic and orthographic preview benefit with long previews for GD analyses (semantic preview benefit: *b* = 0.04, SE = 0.02, *t* = 1.6; *b* = 0.02, SE = 0.02, *t* = 0.9; for trials with long and short previews, respectively. For analyses of orthographic preview benefit: *b* = 0.03, SE = 0.02, *t* = 1.4; *b* = 0.02, SE = 0.02, *t* = 0.7; for trials with long and short previews, respectively). The lack of significance in the post-hoc analysis is a consequence of the loss of statistical power associated with using a dichotomized factor derived from a continuous covariate of preview duration (e.g., Baayen, 2008).

Finally, the identical preview benefit was significant for both groups (*M* = 27 ms, *b* = 0.08, SE = 0.02, *t* = 3.2 and *M* = 19 ms, *b* = 0.06, SE = 0.02, *t* = 2.7; for trials with long and short previews, respectively), with a numerically larger effect for long previews.

<sup>3</sup> Split of trials by preview single-fixation duration at 240 ms led to balanced groups in number of observations and more representatively demonstrative results: For semantic preview benefit with long previews, No. obs = 1,958, *b* = 0.04, SE = 0.02, *t* = 1.8 and *b* = 17 ms, SE = 9, *t* = 2.0; for analyses in log-transformed and original metrics, respectively; for orthographic preview benefit with long preview, *b* = 0.03, SE = 0.02, *t* = 1.5 and *b* = 16 ms, SE = 9, *t* = 1.8; for analyses in log-transformed and original metrics, respectively. Identical preview benefit was also numerically larger for long (*b* = 0.08, SE = 0.02, *t* = 3.5 and *b* = 30 ms, SE = 9, *t* = 3.4; for analyses in log-transformed and original metrics, respectively) than for short previews (*b* = 0.06, SE = 0.02, *t* = 2.7 and *b* = 19 ms, SE = 8, *t* = 2.4; for analyses in log-transformed and original metrics, respectively). All other *t*-values were smaller than 1.

## Discussion

In alphabetic languages, studies using the boundary paradigm in a natural sentence reading task have so far failed to demonstrate preview benefit of semantically related parafoveal previews (see Rayner et al., 2003, for a review). Recently, such semantic facilitation effects were reported for an early time interval of parafoveal semantic priming (Hohenstein et al., 2010). Considering preview durations as a predictor for the size of different types of preview effects, the present study confirmed the notion of time-dependent parafoveal facilitation effects and extended it to sentence reading in Chinese. The most important results for previews of word  $N + 1$  were (a) that refixation rate increased with preview fixation duration in the unrelated condition, (b) that identical preview benefit in GDs increased with preview fixation duration, and (c) that semantic preview benefit in SFDs and FFDs occurred after short previews. The analyses of preview effects from word  $N + 2$  recovered the previously reported identical preview benefit. There was also a significant crossover interaction of semantic preview and preview duration. As the interaction was small and not expected, we will not attempt to interpret it.

### Unrelated preview cost

During unrelated preview trials, GDs increased numerically, but not significantly across preview duration. There was, however, a significant increase in refixation rate. Such an increase with preview duration likely reflects interference with processing of the target word due to earlier or ongoing processing of the unrelated preview word. The unrelated preview condition usually serves as the baseline for the computation of preview benefit. Such preview benefit, however, may in part be due to processing cost induced by processing of unrelated words. The relation between gaze duration, refixation rate, and preview duration deserves to be followed up in detail.

### Identical preview benefit

In the identical preview condition accumulation of information during preview is beneficial at all preview durations. For GDs on word  $N + 1$  identical preview benefit increased over preview duration. This increase in the difference between identical and unrelated previews was due to a numeric increase of unrelated GDs and numeric decrease of identical GDs; neither the identical nor the unrelated trends for preview duration was significant by itself. The fact that identical preview is facilitative for the entire duration of preview is in agreement with Inhoff, Radach, and Eiter (2006) and Yen, Radach, Tzeng, Hung, and Tsai (2009) who reported reduction of durations on target words either if the target word was parafoveally visible only for the initial 140 ms of pretarget fixations or only during the end of the preboundary fixation (i.e., after 140 ms until a saccade to word  $N + 1$  terminated parafoveal processing). The absence of a significant modulation effect of the preview time on identical preview benefit in a boundary paradigm reported by White, Rayner, and

Liversedge (2005) who partitioned their data on the median for participants and conditions could be due to reduced statistical power for dichotomized covariates.

The detection of the increase of preview benefit from word  $N + 1$  across preview duration reported here probably requires the use of a continuous measure of preview duration and statistically more powerful techniques (such as LMM) than were used

unrelated preview. Thus, a semantically related preview word changes from being functionally identical with the target word itself to being functionally unrelated to the target word.

### Orthographic and phonologic preview benefit

A time dependency analogous to the one observed for semantic preview benefit was also obtained for orthographic preview benefit with significant facilitation for short preview of word  $N + 1$ . Finally, in line with a relatively late stage of phonology activation in Chinese sentence reading (Feng et al., 2001), the phonological preview benefit for word  $N + 1$  was mainly observed in trials with long previews.

### Time course of parafoveal processing and attention

The time course of parafoveal processing has been discussed as an opportunity to test different assumptions on how attention relates to word processing during reading. Inhoff, Radach, and Eiter (2006) postulated that SAS models predict parafoveal (lexical) information uptake during late periods of preboundary fixations that is after complete processing of the preboundary word  $N$  and the consequent shift of attention to the subsequent word  $N + 1$ . In other words, SAS models may have difficulties to account for parafoveal effects during the beginning of the preboundary fixation.

There is another challenging result. The reduction of semantic preview benefit with long previews might be caused by a reduced perceptual span since long preboundary fixations could be an indicator of high processing difficulty (Henderson & Ferreira, 1990). However, given the fact that the identical preview benefit increased with preview duration, this perceptual span modulation assumption does not account for the current result. A more reasonable explanation is that the accumulated parafoveal semantic information eventually disrupted the processing of the target word. Yen, Tsai, Tzeng, and Hung (2008) reported a similar finding in their Experiment 2: when the prior fixation duration was short (i.e., less than 220 ms), the semantic (or morphological) preview benefit amounted to 19 ms. This effect reduced to 4 ms when the prior fixation duration was long.

As McDonald (2005) pointed out, if several words are processed in parallel, cumulative preview benefit could be expected to increase with the time a target word resides in the perceptual span. This argument, however, can only be applied to identical preview benefit because it assumes that integration across saccades is restricted to correct parafoveal information. In the boundary paradigm using non-identical previews, various kinds of “incorrect” parafoveal previews overlap with the later foveal target. We consider it as plausible that during preboundary fixations we accumulate not only positive evidence (which may later facilitate identification of the replaced target word) but also diverging evidence (which may interfere with target word identification). Therefore, as preview durations increase, facilitation of parafoveal preview may cancel and even result in disruptions.

We very much doubt that any of the currently available computational models, such as the E-Z Reader SAS model (Reichle et al., 1998; 2009; see Rayner, Li, & Pollatsek, 2007, for an adaptation for reading Chinese) or models built around the assumption of processing gradients, such as the SWIFT model (Engbert et al., 2005) or Glenmore (Reilly & Radach, 2003, 2006) are ready to reproduce such competition of lexical activations. With its well-defined linguistic processing

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