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Word Predictability Depends on Parafoveal Preview Validity in Chinese Reading

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Abstract

Research with alphabetic scripts shows that providing an invalid parafoveal preview eliminates or diminishes effects of contextual predictability on word identification, revealing that such effects depend on the interplay between top-down contextual expectations and bottom-up perceptual information. Whether similar effects are observed character-based scripts like Chinese is unknown. However, such knowledge would extend our understanding of contextual prediction in different writing systems. Accordingly, we conducted an eye movement experiment using the boundary paradigm to assess contextual predictability effects on the processing of target words with valid and invalid parafoveal previews. Interactions between predictability and preview validity were observed in early reading times but not word-skipping for target words. This suggests an interplay between top-down and bottom-up processes drives contextual processing in Chinese reading, but that word-skipping is not strongly mediated by contextual expectations in this script. We consider these findings in relation to differences between alphabetic and non-alphabetic writing systems.

Keywords Eye movements, Word predictability, Parafoveal preview, Chinese reading

Abstract = 150 words

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Total = 2996 words, Maximum = 3000 words

A word's contextual predictability has an important influence on eye movement control during reading, with lower fixation probabilities (and so higher word-skipping) and shorter reading times for high compared to low predictable words (see Staub, 2015). The effect in word-skipping suggests that word predictability can influence parafoveal processing (i.e., the pre-processing that occurs while the reader is still fixating the previous word), and therefore exerts a very early influence on word identification during reading.

Numerous studies with alphabetic scripts have examined this influence on parafoveal processing using the boundary paradigm (Rayner, 1975). In this, an invisible boundary is placed immediately before a target word in a sentence. The target word is shown at first either correctly (a valid preview) or incorrectly (an invalid preview) and is changed to the correct word once the reader's gaze crosses the invisible boundary. This is accomplished rapidly, during the time taken to make an eye movement, so that readers are unaware that a change has been made. In this way, the influence of contextual predictability and the validity of the parafoveal preview on the subsequent processing of the target word can be inspected. In one such study, Balota, Pollatsek, and Rayner (1985) observed effects of predictability on word-skipping and initial reading times for valid previews (e.g., cake) and to a lesser extent for orthographically-similar invalid previews (e.g., cahc). However, these effects were eliminated when invalid previews were orthographically-dissimilar and related (e.g., pies) or unrelated (e.g., bomb) to the target. Balota et al. took this to show that the influence of contextual predictability on word identification depends on the availability of parafoveal word infromation. Moreover, this finding has been replicated in numerous other studies with alphabetic languages (e.g., Choi, Lowder, Ferreira, Swaab, & Henderson, 2017; Juhasz, White, Liversedge, & Rayner, 2008; Schotter, Lee, Reiderman, & Rayner, 2015; Staub & Goddard, 2019; Veldre & Andrews, 2018; White, Rayner, & Liversedge, 2005).

Such effects have been interpreted in the context of computational models of eye movement control, such as E-Z Reader (e.g., Reichle, Pollatsek, Fisher, & Rayner, 1998). Within this model, word identification is a two-stage process requiring an initial familiarity check (called L1) followed by full lexical processing (L2). Contextual predictability is assumed to influence both stages. While the model assumes serial word identification, if the familiarity check for the currently-fixated word is finished before a program to move the eyes to the next word is completed, it is assumed that attention shifts to the next word along (in parafoveal vision) and a familiarity check for this word is initiated. The model therefore allows for an influence of contextual predictability on parafoveal processing of words, although the underlying mechanisms are unclear.

Several accounts have attempted to flesh out these mechanisms. White et al. (2005) explained the interactions between contextual predictability and parafoveal information using a modified version of interactive word recognition model proposed by McClelland and O'Regan (1981). White et al. hypothesized that while neither factor alone is sufficient to facilitate word identification, when combined they generate a detectable benefit. Therefore, when only contextual cues are available (i.e. an invalid preview), the predictability effect disappears. However, Staub and Goddard (2019) provided an alternative explanation based on Norris' (2006) Bayesian reader model. They argued that word identification comprises a balance between contextual expectations (providing a prior probability distribution over upcoming words) and perceptual evidence. When parafoveal information is unavailable (i.e., an invalid preview), early orthographic processing can only be conducted once the word is fixated and therefore in high-acuity foveal vision, so that perceptual evidence predominates. But when the preview is valid, orthographic processing can be initiated in low-acuity parafoveal vision so that context has stronger influence. Therefore, contextual predictability effects are minimal for invalid previews and stronger for words viewed parafoveally.

Whether such effects are specific to alphabetic scripts like English or also found for character-based scripts like Chinese is largely unknown, although such knowledge would provide valuable evidence about effects of contextual predictability across different writing systems. Chinese uses the logographic script in which text is created from a sequence of pictograms called characters, each of which occupies the same square area of space (Hoosain, 1992). Most words contain two (or more) characters although word boundaries are not demarcated using spaces or other visual cues (Li, Zang, Liversedge & Pollatsek, 2015; Zang et al., 2016). Context may therefore play an important role in Chinese reading by helping to delineate words in this naturally unspaced text. Moreover, several studies show effects of word predictability in early measures of processing, including word-skipping and forward saccade length (Liu, Guo, Yu, & Reichle, 2017; Rayner et al., 2005; Zhao et al., 2019), suggesting this can influence parafoveal processing. Conversely, Chinese has other characteristics that promote perceptual constraints on parafoveal processing. In particular, because the text is more densely-packed than in alphabetic scripts, more information is available parafoveally. Moreover, readers may even have foveal access to the next word (or words) in a sentence (Yang, Rayner, Li, & Wang, 2012). However, studies to date have not investigated effects of contextual predictability on parafoveal processing, so the nature of the interplay between these factors is unclear.

Accordingly, the present study addressed this question using the boundary paradigm. Participants read sentences in which target words had high or low cloze probability and previews were valid or invalid. We examined eye movements, including word-skipping and reading time measures sensitive to the early processing of words. The crucial question was whether we would observe an interplay between contextual predictability and preview validity similar to that in alphabetic scripts. Alternatively, we might find that either contextual predictability or parafoveal information predominates because of the specific characteristics of the Chinese writing system.

Method

Ethics Statement. The study was approved by the research ethics committee in the Academy of Psychology and Behavior at Tianjin Normal University and conducted in accordance with the principles of the Declaration of Helsinki.

Participants. Participants were 64 young adults aged 18-25years (*M* = 21) from Tianjin Normal University. Another eight participants took part in the experiment but were excluded from statistical analyses as they exhibited a high rate of display change detection. All participants were native Mandarin speakers, screened for normal acuity (> 20/40 in Snellen values) using a Tumbling E eye chart (Taylor, 1978).

Prior to conducting the experiment, statistical power was conducted using the simR package in R (Green & MacLeod, 2016) based on means and standard deviations for young adult participants in the study by Choi et al. (2017). The power to detect an interaction between word predictability and preview validity was assessed as sufficient (> 80%) for the sample size in the present experiment.

Stimuli and Design. Stimuli were 80 sentence frames containing a two-character target word in Chinese (see Table 1). Target words had high or low predictability from the prior sentence context, assessed using a cloze procedure with sentence fragments truncated immediately before the target word. Twenty-four young adults who did not take part in the experiment provided the next word in the sentence. A word was selected as highly predictable if more than 60% of participants guessed it to be the next word, and as less predictable if fewer than 20% guessed it to be the next word. The selected targets were always two-character words. High and low predictable target words differed in predictability but were matched for word and first character frequency and complexity (see Table 2). The sentences averaged 22 characters (range = 18-31 characters) and target words always appeared near the middle of sentences.

Tables 1 & 2

Sentence stimuli were presented using the boundary paradigm (Rayner, 1975), with valid and invalid previews. An invisible boundary was placed immediately prior to the target word. Valid previews were the high and low predictability two-character target words. Invalid previews were nonwords composed of two characters with very low character frequency and visually dissimilar to the target word (see Figure 1).

The sentences were divided into 4 lists. Each included the sentence frame with a valid or invalid preview of either the high or low predictable word, with an equal number of sentences in each condition. Across lists, each sentence appeared once in each condition and each list included an equal number of sentences in each condition. Each list also included 120 filler sentences and began with five practice sentences. Sixteen participants were randomly allocated to each list. The experiment therefore had a within-participants design with factors word predictability (high, low) and preview validity (valid, invalid).

Apparatus and Procedure. Stimuli were presented on a high-resolution 24-inch Benq LCD monitor (1920×1080 pixels) with a fast refresh rate (144Hz). The sentences were displayed in Song 34-point font as black text on a gray background. At 59 cm viewing distance, each character subtended about 1.2°, and so of normal size for reading. An Eyelink 1000 Plus (SR Research Ltd, Canada) eye tracker recorded right eye-movements during binocular reading at a sample rate of 1000Hz.

On arrival, participants were screened for acuity. They were then sat at the eye-tracker and instructed to read normally and for comprehension. Participants then completed a three-point horizontal calibration procedure (ensuring spatial accuracy of .30°or better). At the beginning of each trial, a fixation square equal in size to one character was presented on the left side of the screen. Once this was fixated, a sentence was presented across a single line with the first character replacing the square. Participants pressed a response key to terminate the display once they finished reading. The sentence was then replaced by a comprehension question on 25% of trials, which participants answered by pressing a response key. The experiment lasted about 40 minutes for each participant.

Results

Following standard procedures, fixations shorter than 80 ms and longer than 1000 ms were removed. Trials were also excluded if track-loss or error occurred (affecting 0.3% of trials), fewer than five fixations were made on a sentence (affecting 6% of trials), an eye-blink occurred when crossing the boundary or fixating a target word (affecting 2% of trials), or a display-change was triggered early or completed late (i.e., more than 2 ms following onset of the subsequent fixation; affecting 12% of trials). Participants who reported seeing a display change on more than 10% of trials were excluded (affecting 8 participants, who were replaced).

We analyzed standard word-level measures (Rayner, 2009). These include measures sensitive to the first-pass processing of target words, i.e., before a fixation to the right of the target word or a regression (backwards eye movement) from that word. These were word-skipping (SP, the probability of not fixating a word), first-fixation duration (FFD; length of the first fixation on a word), gaze duration (GD; sum of all first-pass fixations), and regressions-out (RO; probability of a regression from a word during first-pass). Total reading time is reported as a measure of later processing. Supplementary analyses include launch site distance (distance from the target word's left boundary to the launch site of the saccade ending in the first fixation on the target) and incoming-saccade length (ISL, length of the saccade resulting in the first fixation on the target) as additional fixed-effects factors.

Data were analyzed by linear mixed effects models for continuous variables and generalized linear mixed-effects model for binary variables (Baayen, Davidson, & Bates, 2008), using the glmer function in the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) in R (R Development Core Team, 2016). For all measures, a maximum random effects structure was used (Barr, Levy, Scheepers, & Tily, 2013) with word predictability, preview validity and their interaction as fixed factors, and participants and stimuli as crossed random effects. If the maximum random effects model did not converge, the model was reduced by first trimming the random structure for stimuli, starting with removal of random effect correlations, then random slopes. Contrasts of main effects and contrasts to examine interactions were defined using sliding contrasts (the contr.sdif function) in the MASS package (Ripley, Venables, Bates, Hornik, Gebhardt, & Firth, 2015). Reading times were log-transformed but, as results for log-transformed and untransformed models were similar, untransformed analyses are presented for transparency.

Accuracy answering comprehension questions that followed the sentences was high (> 80%) for all participants (*M* = 94%), indicating good comprehension. Mean eye movement measures are reported in Table 3 and statistical effects summarized in Table 4.

Tables 3 & 4

Main effects of word predictability were obtained in word-skipping, reading times (FFD, GD, TRT), and regressions out, such that skipping rates were higher, reading times shorter, and regressions fewer for high than low predictable words. Main effects of preview validity were observed in word-skipping, reading times and regressions-out, due to lower skipping rates, longer reading times and more regressions for invalid than valid previews.

Crucially, an interaction between word predictability and preview validity was observed in first-pass reading times (marginal in FFD, reliable in GD). The pattern was the same as for alphabetic scripts, so that predictability effects were found for valid previews (FFD, $b = 16$, $SE = 5$, $t = 3.09$; GD, $b = 21$, $SE = 8$, $t = 2.8$), but not invalid previews (FFD, $b = 3$, $SE = 5$, $t = 0.53$; GD, $b = 3$, $SE = 5$, $t = 0.59$). No interaction was observed in word-skipping or total reading times. The absence of an effect in word-skipping contrasts with effects in alphabetic languages. Consequently, we used Bayes factors (BFs; Vandekerckhove, Matzke, & Wagenmakers, 2014) to quantify this null interaction using the BayesFactor package (version 0.9.12-2; Morey, Rouder, & Jamil, 2015), estimating marginal likelihood using Monte Carlo sampling, and setting iterations to 100,000 and g-priors to 0.5. We compared models with and without an interaction using standard interpretative categories where BFs > 3 provides weak to moderate evidence and BFs > 10 provide strong evidence for one model over another. This showed that a model with no interaction was 14 times more likely to be correct than one with an interaction, confirming the absence of an interaction in conventional statistical analyses.

Effects of word predictability on parafoveal processing were likely to be mediated by the distance away of the fixation prior to a saccade to the target word. We therefore re-assessed effects with launch site distance and incoming saccade length included as dichotomous variables (specifying close launch sites as up to two characters from the target word and distant launch site as more than two characters away). These produced no significant threeway interactions for launch site distance or incoming saccade length in any measures. Moreover, interaction effects in GD approached significance with these factors included (launch site distance, $b = -23$, $SE = 12$, $t = -1.97$; incoming saccade length, $b = -21$, $SE = 11$, $t = -1.92$). Accordingly, these factors did not strongly mediate the interaction between word predictability and preview validity.

Discussion

The present experiment used the boundary paradigm to investigate the influence of parafoveal preview validity on word predictability effects in Chinese reading. The results showed standard effects of preview validity and replicated previous findings of word predictability (Rayner et al., 2005; Zhao et al., 2019). Importantly, the findings showed word predictability effects were mediated by preview validity, so effects were observed only for valid previews. This resonates with findings from alphabetic languages (Balota et al., 1985; Choi et al., 2017; Juhasz et al., 2008; Schotter et al., 2015; Staub & Goddard, 2019; Veldre & Andrews, 2018; White et al., 2005), suggesting that the interplay between word predictability and parafoveal processing is similar across writing systems. In particular, the findings show contextual effects depend on the availability of a valid preview, and so observed only when useful parafoveal information is available.

These findings are consistent with models of eye movement control, such as E-Z Reader, in which word predictability can influence early stages of a word's processing, including its parafoveal processing. They are also consistent with mechanisms proposed to account for effects of preview validity on contextual prediction (Staub & Goddard, 2019; White et al., 2005), suggesting that essentially the same mechanisms might apply in Chinese and alphabetic reading. The absence of an interaction effect in word-skipping suggests contextual effects may be weaker in Chinese than alphabetic languages. This may be a consequence of stronger parafoveal perceptual information in Chinese reading because text is densely-packed and so more information is available parafoveally (e.g., Yang et al., 2012). Consequently, contextual cues may be unable to affect the familiarity check sufficiently strongly or quickly to countermand a saccade program directed towards the target word and initiate a new program to skip this word. This may be investigated further in future research by examining effects for invalid previews that are visually similar to valid previews, which facilitate predictability effects in alphabetic languages (e.g., Balota et al., 1985). This might reveal if predictability effects are weaker, relative to parafoveal perceptual processes, in Chinese reading.

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Disclosure statement

The authors have no conflicts of interest.

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Table 1. An example of sentence stimulus.

High	Valid Preview	光在不同介质中的传播速度|**速度**是不一样的。
Predictability	Invalid Preview	光在不同介质中的传播培贯|**速度**是不一样的。
Low	Valid Preview	光在不同介质中的传播路径|**路径**是不一样的。
Predictability	Invalid Preview	光在不同介质中的传播稠籴|**路径**是不一样的。

Target words are shown in bold and vertical line indicates the invisible boundary. The high predictable word 速度 means “velocity”, and the low predictable word 路径 means “route”. The sentence translates as “The propagation velocity / route of light in various media is different”.

Table 2. Properties of target words

Variables	Word Predictability		Inferential Statistics	
Word predictability	High	Low	*t*	*p*
Word predictability	85%	1.5%	64	< .001
Word frequency (per million)	92	66	1.31	.19
First character frequency (per million)	790	759	.17	.87
Number of strokes (word)	15	15	.76	.45
Number of strokes (first character)	7.48	7.98	1.22	.23
Sentence plausibility	6.19	6.16	.28	.78

Table 3. Summary of Eye Movement Measures

Measure	Valid Preview		Invalid Preview		Preview effect	Predictability effect
	High Predictability	Low Predictability	High Predictability	Low Predictability		
Word-skipping (%)	41 (2)	37 (2)	23 (1)	21 (1)	17	3
First-fixation duration (ms)	229 (3)	245 (4)	292 (4)	293 (4)	56	9
Gaze duration (ms)	244 (4)	265 (5)	346 (6)	346 (6)	92	11
Regressions-out (%)	7 (1)	12 (1)	19 (1)	23 (2)	12	5
Total reading time (ms)	300 (8)	321 (7)	391 (8)	429 (9)	100	30

Table 4. Summary of Statistical Effects

Measure	Effect	*b*	CI	*SE*	*t/z*
Word-skipping	Word predictability	-.16	[-.32, -.01]	.08	-2.06*
	Preview validity	-1	[-1.15, -0.84]	.08	-12.46*
	Word predictability × Preview validity	.13	[-.18, 0.44]	.16	.83
First fixation duration (ms)	Word predictability	10	[3, 16]	3	2.69*
	Preview validity	54	[43, 65]	6	9.65*
	Word predictability × Preview validity	-13	[-27, 0]	7	-1.91+
Gaze duration (ms)	Word predictability	11	[1, 23]	6	2.11*
	Preview validity	88	[69, 107]	10	9.09*
	Word predictability × Preview validity	-23	[-42, -4]	10	-2.31*
Regressions-out	Word predictability	.41	[.17, .65]	.12	3.39*
	Preview validity	1.06	[.72, 1.40]	.17	6.14*

	Word predictability × Preview validity	-.35	[-.83, .13]	.25	-1.43
	Word predictability	30	[15, 44]	7	4.12*
Total reading time (ms)	Preview validity	100	[70, 130]	15	6.59*
	Word predictability × Preview validity	14	[-14, 42]	14	.99

Note * = $p < 0.05$