Eye Movements of Developing Chinese Readers:

Effects of Word Frequency and Predictability

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Abstract

The frequency and contextual predictability of words have a fundamental role in determining *where* and *when* the eyes move during reading in both alphabetic and non-alphabetic languages. However, surprising little is known about the how the influence of these variables develops, although this is important for understanding how children learn to read. Accordingly, to gain insight into their use during reading development, we examined the effects of orthogonally manipulating the frequency and contextual predictability of a specific target word in sentences on the eye movements of developing Chinese readers. The findings show that both factors influence eye movement behavior associated with the early processing of words during reading, but that effects of contextual predictability are mediated by the lexical frequency of words. We consider these effects in the context of visual and linguistic demands associated with reading Chinese and in relation to current models of eye movement control during reading.

Abstract = 150 words

Main text = 6024 words

Introduction

Skilled readers move their gaze along lines of text in a series of short eye movements, called saccades, separated by brief fixational pauses. Studies of children's eye movements reveal this behavior becomes more adult-like as reading skill develops, so that developing readers make increasingly longer forward eye movements, fewer and shorter fixations, and fewer regressions (i.e., backwards eye movements; for a review, see Blythe & Joseph, 2011). Moreover, while most studies showing this age-change in eye movement behavior have focused on alphabetic languages like English, essentially the same pattern is observed in Chinese (Yan, Liu, Liang, Liu, & Bai, 2015; Zang Liang, Bai, Yan, & Liversedge, 2013; Zhang, 2012; for a review, see Zang, Liversedge, Bai, & Yan, 2011). This suggests that changes in eye movement behavior during reading development are broadly similar across different writing systems. However, while these changes are indicative of the development of skilled reading, further work is needed to understand the underlying mechanisms.

Current models of eye movement control in reading, such as E-Z Reader (e.g., Reichle, Pollatsek, Fisher, & Rayner, 1998) and SWIFT (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005), emphasize the importance of frequency and predictably in determining how quickly words can be identified. Indeed, a fundamental assumption of the E-Z Reader model is that the process of lexical identification drives the forward progression of the eyes. E-Z Reader implements this as a two-stage process. In the first stage, frequency and predictability inform a familiarity check which assesses whether the current word is likely to be recognized imminently, whereupon the system initiates a saccade that carries the eyes forward in the sentence, while in the second stage these factors guide lexical access.

When readers fixate a word, the familiarity check and saccade-programming are initiated in parallel. The time taken to complete the familiarity check is influenced by both frequency and predictability. Once completed, lexical access begins, and this causes attention to shift to the next word (although gaze remains on the fixated word). Following this attentional shift, the system begins processing the next word parafoveally by initiating a new familiarity check. If this is completed before saccade-programming moves to a non-labile stage, the parafoveal word may be skipped (i.e., not fixated and the eyes move to fixate the next word along). Otherwise, a saccade will be initiated to shift gaze to the parafoveal word. How quickly the parafoveal word familiarity check can be completed is also influenced by frequency and predictability. Therefore, according to E-Z Reader, both factors play a fundamental role in determining how rapidly a word can be identified and *when* and *where* the eyes move. While less fully elaborated, SWIFT also incorporates the assumption that speed of lexical access is a function of frequency and predictability, and therefore that the two factors guide lexical identification during reading.

Consistent with both models' predictions, numerous experiments with skilled readers show high frequency words are read faster and skipped more often than low frequency words (Inhoff & Rayner, 1986; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner & Duffy, 1986; Rayner, Sereno, & Raney, 1996; Reichle & Drieghe, 2013). Similarly, more predictable words are read faster and skipped more often than less predictable words (Balota, Pollatsek, & Rayner, 1985; Bélanger & Rayner, 2013; Drieghe, Rayner, & Pollatsek, 2005; Kretzschmar, Schlesewsky, & Staub, 2015; Rayner et al., 2004; Rayner, Slattery, Drieghe & Liversedge, 2011; Rayner & Well, 1996; Reichle & Drieghe, 2013). Moreover, while research primarily has been conducted in alphabetic scripts, effects are similar in Chinese (e.g., Guo, Zang, Bai, & Yan, 2011; Li, Bicknell, Liu, Wei, & Rayner, 2014; Lu, Bai, & Yan, 2008; Yan, Tian, Bai, & Rayner, 2006).

Word frequency is considered to influence early stages of lexical processing, although is unclear whether predictability exerts a similarly early influence, although understanding the relative timing of these effects is important for development of theoretical models. Therefore, some studies have examined the conjoint influence of frequency and predictability in skilled reading. Many studies report additive effects in reading times for words in alphabetic languages (Altaribba, Kroll, Sholl, & Rayner, 1996; Ashby, Rayner, & Clifton, 2005; Bélanger & Rayner, 2013; Gollan et al., 2011; Kretzschmar et al., 2015; Lavigne, Vitu, & d'Ydewalle, 2000; Miellet, Sparrow, & Sereno, 2007; Rayner, Binder, Ashby, & Pollatsek, 2001; Rayner et al., 2004; for a review, see Staub, 2015) and Chinese (Guo et al., 2011; Lu et al., 2008). Such effects are generally taken as showing independent influences of frequency and predictability, most likely because predictability effects occur later in reading. However, other studies report interactive effects, so that predictability influences an early stage of lexical processing (Hand, Miellet, O'Donnell, & Sereno, 2010; Inhoff, 1984; Sereno, Hand, Shahid, Yao, & O'Donnell, 2018). Similarly, while some studies show additive effects of these variables on word-skipping (Bélanger & Rayner, 2013; Drieghe et al., 2005; Kretzschmar et al., 2015; Reichle & Drieghe, 2013), others show interactive effects, although the patterns of effects are not consistent. For instance, a study in English (Gollan et al., 2011) and one in Chinese (Guo et al., 2011) report larger predictability effects for low than high frequency words, while two studies in English (Hand et al., 2010; Rayner et al., 2004) report larger predictability effects for high than low frequency words. Despite this inconsistency, the findings show that frequency and predictability can jointly influence word-skipping.

However, while the influence of these variables has been investigated extensively with skilled readers, few studies have investigated effects in developing readers. Several studies in alphabetic languages report frequency effects on reading times for words (i.e., shorter reading times for higher frequency words) for readers aged 6 to 11 years (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Joseph, Nation, & Liversedge, 2013; Huestegge, Radach, Corbic, & Huestegge, 2009; Tiffin-Richards & Schroeder, 2015; Rau, Moll, Snowling, & Landerl, 2015; Valle, Binder, Walsh, Nemier, & Bangs, 2013), without reporting word-skipping. By comparison, hardly any studies have investigated frequency effects in developing Chinese readers, and those that have either used an unusual reading paradigm in which words remained visible only briefly following fixation (Zhang, 2012) or failed to control for predictability (Chen & Ko, 2011). A likely reason for the scarcity of such research is the absence of a Chinese corpus of written word frequencies for children. Because of this, researchers must use frequency estimates from adult corpora, which is problematic (Huestegge et al., 2009; Joseph et al., 2013).

Similarly, little is known about the influence of word predictability on the eye movements of developing readers. There are no studies in Chinese and only one recent study in English (Johnson, Oehrlein, & Roche, 2018). This showed shorter reading times for more predictable words for readers aged 6-12 years, with the effect emerging early in the eye movement record (in word-skipping and first-pass reading times) only for participants with strong decoding abilities. No studies to date have manipulated frequency and predictability orthogonally. However, as developing readers will take time to acquire familiarity with printed reading material, they may rely more on context when identifying lower frequency words as compared to skilled readers (Stanovich, 1986).

Such effects may be pronounced in Chinese because of the visual and linguistic characteristics of its writing system. The basic morphemic units in this language are box-like pictograms called characters (Hoosain, 1991, 1992). A single character will sometimes correspond to a word, although most words are formed by two (and sometimes more) adjacent characters, and boundaries between words are not marked using spaces or other visual cues (Zang et al., 2011). Variables such as frequency and predictability therefore may provide important cues to word boundaries in Chinese reading (Li, Rayner, & Cave, 2009), and the acquisition of these cues will be crucial to developing readers. Such investigations are also important for the construction of developmental models of eye movement control. Only one such model exists to date, based on E-Z Reader (Reichle et al., 2013). Simulations in this model suggest child and adult readers primarily differ in their rate of lexical processing, although these did not assess frequency and predictability effects. Understanding the influence of these variables is therefore important for the further model development.

Accordingly, the present experiment examined effects of word frequency and predictability on the eye movements of developing Chinese readers. We selected readers from Grade 5 of primary school (aged 11-13 years), as children in this age group will have acquired the basic skills underpinning Chinese reading (Xue, Shu, Li, Li, & Tian, 2013). Participants read sentences containing a specific target word, and its frequency and predictability was manipulated orthogonally using age-appropriate measures of frequency and independent assessments of predictability. If the two factors affect the early lexical processing, we should observe shorter reading times for high compared to low frequency words and for more compared to less predictable words. In addition, if these factors influence parafoveal processing, we may observe higher skipping of high compared to low frequency words, and for more compared to less predictable words. Finally, the findings will reveal whether these influences are additive or interactive.

Method

Ethics Statement

The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Research Ethics Committee at Tianjin Normal University. Participants' legal guardians gave informed consent and participants assented to take part in the experiment.

Participants

Participants were 44 Grade 5 children aged 11 to 13 years (M = 11.5 years) from a primary school in Tianjin. A power analysis was conducted using the simr package for R

(Green & Macleod, 2016). No previous study with the same design exists for developing readers, so we based estimates of frequency and predictability effects from a recent adult study (Staub & Goddard, 2019). The analysis suggested at least 28 participants are required to achieve 80% power (Cohen, 1962). Most previous developmental eye-movement studies have used smaller or similar-sized samples (Blythe et al., 2009, Experiment 1, N = 12 children, Experiment 2, N = 16 children; Johnson et al., 2018, N=48; Joseph et al, 2013; N = 22 children; Huestegge et al., 2009, N = 21 children; Rau et al., 2015, 25 matched pairs of German/English speaking children; but see Tiffin-Richards & Schroeder, 2015, N = 75 children; Valle et al., 2013; N = 90 children). The present study therefore used a larger sample size than most comparable studies and should have sufficient power to detect key effects. All participants were native Chinese speakers with normal or corrected vision, and none had a diagnosed visual or reading impairment. Each participant received a small gift for taking part. Reading skill was assessed as part of a larger project using standard tests of reading comprehension (Xie, Zhang, Wu, & Nguyen, 2019) and reading fluency (Li & Wu, 2015; Xue et al., 2013). Participants were selected from Grade 5 as this age-group would be expected to have basic metalinguistic knowledge (reading fluency, vocabulary, comprehension skills) required to read and understand sentences (Xue et al., 2013).

The comprehension test consisted of a passage entitled "Searching for Food", followed by 15 questions (1 sequencing question, 7 multiple-choice questions, and 7 open-ended questions). Participants read silently then answered the questions; with scores summed to produce a comprehension score. The reading fluency test consisted of 100 sentences, some containing obvious violations of common knowledge. Participants read as many sentences as they could within three minutes while judging whether each sentence contained a violation. Fluency was calculated as the sum of characters evaluated correctly within three minutes.

To ensure our sample were reading appropriately for their age, we compared their test performance against a pool of 320 Grade 5 children from two different primary schools in Tianjin. This showed no comprehension difference between our sample and the larger pool, but a significant difference in fluency. This discrepancy may be due to differences in the teaching methods in the schools contributing to the larger pool. Students in one school received speed-reading training as part of their language training, which may have affected fluency scores. When this group was removed from the larger pool, fluency no longer differed significantly from our sample on either test (see Table 1). Our sample is therefore comparable to a larger pool of students who did not receive specialist training.

[Table 1]

Materials and Design

To create a set of age-appropriate stimuli, we selected 25 pairs of high and low frequency two-character words from an adult Chinese corpus (Cai & Brysbaert, 2010). The pairs were matched for complexity (i.e., number of character strokes). To ensure the stimuli were age-appropriate, 20 Grade 5 children who did not participate in the experiment provided familiarity ratings. To do this, each pair was presented along with 5 other words with intermediate lexical frequencies. Participants ranked the relative familiarity of these words on a 7-point scale (1 = highly unfamiliar, 7 = highly familiar). The results showed that the high frequency word in each pair was always judged as more familiar than the low frequency word (high frequency words = 4.55, low frequency words = 2.90, $t(24) = 5.72$, $p < .0001$). This showed that adult word frequency counts provided an effective proxy for children's word familiarity in our experiment. Note, however, that although frequency and familiarity are highly correlated, these can show different effects (Gernsbacher, 1984). It therefore would be valuable for future research to have a corpus of Chinese word frequency statistics. Each word pair was embedded interchangeably in two sentence frames. The high frequency word was more predictable in one frame and the low frequency word more predictable in the other (see

Figure 1). Frequency and predictability were therefore manipulated orthogonally.

[Figure 1]

Predictability was assessed using a cloze procedure. Another group of 30 Grade 5 children were shown each sentence frame truncated immediately before the target word and asked to write the next word in the sentence, and these completions were used to assess the target word predictability. Mean cloze probability for higher predictability words was 57% for high-frequency words and 42% for low-frequency words. For lower predictability words, cloze frequencies were 1% for high-frequency words and 0.4% for low-frequency words. These were analyzed using a 2 (high vs low frequency) x 2 (higher vs. lower predictability) ANOVA. The results showed cloze probability was greater for higher than lower predictability words ($F(1,24) = 210.05$, $p < .001$), with a marginal main effect of frequency ($F(1,24) = 4.24$, $p = .051$), and a marginal interaction ($F(1,24) = 4.10$, $p = .054$). This suggests the we had an effective measure of word predictability (although note that the higher predictability words might not be considered to be as highly predictable compared with stimuli in previous adult studies and resemble the medium-predictability words used by Sereno et al., 2018). In addition, variation in word predictability across the high and low frequency conditions could reflect the relative difficulty of generating contexts that make lower frequency words as predictable as higher frequency words, given that higher frequency words are easier to access lexically. An additional 30 Grade 5 children rated the sentence naturalness using a 5-point scale (1 = entirely natural, 5 = entirely unnatural). This was analyzed using a 2 (frequency) x 2 (predictability) ANOVA. The results showed sentences were rated as equally natural across conditions (*M*s < 1.9; *Fs* < 3.27, *p*s >.10; Table 2 summarizes the word and sentence characteristics).

[Table 2]

The experiment used a within-participants design with factors word frequency (high, low) and predictability (higher, lower). Two counterbalanced lists of 50 experimental sentences were created so each included all 25 pairs of high and low frequency words in either higher or lower predictability contexts[1]. Each target word was seen an equal number of times in each condition across the experiment. Sentences in each list were presented in randomized order intermingled with 22 filler sentences and beginning with six practice sentences.

Apparatus and Procedure

Participants' right eye movements were recorded during binocular reading using a high-resolution Eyelink 1000 Plus eye-tracker (.001° RMS spatial error, 1000 Hz; SR Research inc., Toronto, Canada). Sentences were displayed on a high-definition 19-inch ViewSonic P225f monitor as black-on-white text in 20-point Song font. At 70cm viewing distance, each character subtended approximately 1°.

Participants took part individually. At the start of the experiment, the procedure was described and the participant instructed to read normally and for comprehension. The eye-tracker was then calibrated to their eye movements using a 3-point horizontal procedure. For all participants, spatial accuracy was better than .20°. Thereafter, calibration was checked between trials and the eye-tracker recalibrated as necessary to maintain the same high spatial accuracy. At the start of each trial, a fixation square equal in size to a character space was presented on the left side of the screen. Once the participant fixated this location, a sentence appeared on the screen, with its first character replacing the square. The participant pressed a response key on finishing reading each sentence. On 30% of trials, a yes/no comprehension question was presented following the sentence and participants responded by pressing one of two response keys. For each participant, the experiment lasted approximately 20 minutes.

Results

Prior to analyzing data, a standard procedure pooled short adjacent fixations and removed short (< 80 ms) or long (> 1200 ms) fixations, as well as fixations more than three standard deviations from the global mean (affecting < 1% of fixations). Participants responded with at least 80% accuracy (M = 94%) on comprehension questions that followed the sentences, indicating good sentence comprehension.

We examined standard eye movement measures informative about first-pass reading (time spent processing a word on its first encounter, prior to a fixation to its right or a regression from that word) and later processing of target words (Rayner, 2009). Word-skipping (SP) is the probability of not fixating a word in first-pass reading and informative about the parafoveal processing. For this analysis, we excluded saccades launched more than three character from a target word as readers were unlikely to obtain useful preview information about the target word prior to this saccade. First-fixation duration (FFD) is the length of the first fixation on a target word during first-pass reading, and single-fixation duration (SFD) the length of the fixation for words receiving one first-pass fixation. Gaze duration (GD) is the sum of all first-pass fixations on a target word and regressions-out (RO) the probability of a backwards saccade from a word during first-pass reading. Regression-path duration (RPD), the sum of all fixations from the first fixation on a word during first-pass reading until the reader's gaze moves past that word to the right including time spent re-reading, provides a measure of integration difficulty (Liversedge, Paterson, & Pickering, 1998). Total reading time (TRT), the sum of all fixations on a word, is informative about overall reading difficulty. Finally, regressions-in (RI), the probability of a regression back to the target word, shows how often a word is re-inspected.

Data were analyzed by linear mixed-effects models (Baayen, Davidson, & Bates, 2008) using the lmer function from the lme4 package (Bates, Mächler, & Bolker, 2011) within R (R Development Core Team, 2014). Data for continuous variables were log-transformed (Baayen et al., 2008), and data for discontinuous variables analyzed using generalized linear models. For each dependent measure, a model was constructed with frequency and predictability as fixed factors, using the contr.sdif (MASS) function (Venables & Ripley, 2002). Contrasts were specified as 0.5/-0.5 for high/low frequency words and higher/lower predictability words, such that the intercept corresponded to the grand mean and fixed-effects corresponded to main effects. Participants and items were specified as random factors. A full random structure was specified for participants and items (Barr, Levy, Scheepers, & Tily, 2013). If this model did not converge, we trimmed it until it converged, by first removing correlations between factors, then interactions first for items then participants, then slopes[2]. To ensure reduced models were not a poorer fit, we compared these against a full model using a $\chi 2$ test of model fit (Tiffin-Richards & Schroeder, 2018). If the models did not differ significantly, we used the reduced model as the final model. Table 4 shows mean target word data, Table 5 summarizes statistical effects, and Figure 2 illustrates effects of word frequency and predictability.

[Table 3 & 4; Figure 2]

Overall word-skipping averaged 19%, comparable to skipping rates for developing readers in previous alphabetic (Blythe & Joseph, 2011) and Chinese (Yan et al., 2015; Zang et al., 2013; Zhang, 2012) studies. Analyses of word-skipping showed main effects of frequency and predictability, due to higher skipping for high than low frequency words (marginally significant), and for higher compared to lower predictability words. An interaction effect was due to a predictability effect (higher skipping rates for more predictable words) for low (7.5% effect) but not high (0.8% effect) frequency words.

First-pass reading time measures showed a main effect of word frequency only in gaze duration, which were shorter for high frequency words. All first-pass reading time measures (FFD, SFD, GD) showed main effects of predictability, such that fixation times were shorter for more predictable words. There also were interactions, which planned contrasts showed were due to effects of predictability for high frequency (FFD = 22ms, SFD = 24ms, GD = 45ms) but not low frequency (FFD = 11ms, SFD = 10ms, GD = 13ms) words. A frequency effect in regressions-out reflected more regressions from low frequency words. Measures of later processing produced main effects of frequency in regression-path and total reading times, such that high frequency words had shorter reading times. There was also a main effect of predictability (marginal for RPD and RI, significant for TRT), such that higher predictability words had shorter reading times and were regressed to less often. No other effects were significant.

One concern might be that interaction effects between predictability and frequency in word-skipping and reading times might reflect differences in predictability levels for high and low frequency words. Accordingly, to address this, we conducted additional analyses in which predictability was assessed as a continuous rather than a dichotomous variable, based on a word's log-transformed cloze predictability (see Smith & Levy, 2013). We used linear mixed-effects models for reading times, and generalized linear models for word-skipping, with frequency as a dichotomous variable and predictability specified as the cloze value for each word, centered and log-transformed. These produced main effects of word frequency in early (GD) and late (RPD, TRT) measures, main effects of predictability in early (SP, GD) and later (TRT) measures, and interactions between word frequency and predictability in word-skipping and GD (see Table 5). The pattern to these interactions was consistent with analyses with predictability included as a categorical variable (see Figure 3). Consequently, the additional analyses suggest the interaction effects were not due to differences in predictability levels across high and low frequency words.

[Table 5; Figure 3]

Individual Difference Effects on Eye Movement Behavior. Pre-tests administered to participants assessed reading fluency, comprehension and vocabulary. These allowed us to assess effects of linguistic proficiency on eye movements. To do so, we included scores from each test as additional fixed-factor variables in linear-mixed effects models (and generalized linear models for discontinuous variables). The results showed main effects of each factor on eye movements, due to lower word-skipping, longer reading times and fewer regressions for lower reading fluency or comprehension scores (*t/z*s > 2.32), and longer reading times for lower vocabulary scores ($t > 2.54$). Moreover, an interaction between vocabulary and word predictability in single-fixation durations ($\beta = 0.05$, $SE = 0.02$, $t = 2.06$) was due to larger predictability effects for participants with lower vocabulary scores (note single first-pass fixations occurred on 59% of trials, with a similar proportion for readers with higher and lower vocabulary scores). This suggests developing readers with weaker linguistic knowledge rely more heavily on word predictability, consistent with evidence from research with adult readers showing less-skilled readers make greater use of context (Ashby et al., 2005). An interaction between fluency and word frequency in total reading times ($\beta = 0.06$, $SE = 0.03$, $t = 2.08$) additionally showed participants with lower fluency produced larger word frequency effects, most likely because they re-read lower frequency words more often compared to more fluent readers (see Barnes, Kim, Tighe, & Vorstius, 2017). Finally, three-way interactions between comprehension, frequency and predictability were significant in word-skipping ($\beta = 0.78$, $SE = 0.31$, $t = 2.53$) and regressions-out ($\beta = 0.57$, $SE = 0.27$, $t = 2.13$). This effect was due to participants with lower comprehension scores skipping words that were both less predictable and of lower frequency less often compared to other words. The regression effect was due to participants with lower comprehension scores making more regressions from these less predictable, low frequency words compared to other words. This provides further evidence that poorer proficiency readers make greater use of context, especially when words are hard to decode. No other effects yielded significance (*t*s < 1.9). The results show individual differences in reading proficiency can modulate eye movements, although research is needed to understand underlying mechanisms (e.g., Reichle et al., 2013).

Discussion

The experiment reported here is the first to investigate conjoint effects of word frequency and predictability on the eye movements of developing readers. The study was conducted in Chinese, a naturally-unspaced language in which readers may be especially reliant on cues provided by frequency and predictability to delineate words (Li et al., 2009). Our findings show that developing Chinese readers use frequency and predictability to identify words during reading. Moreover, use of these cues develops sufficiently rapidly for children in Grade 5 (aged 11-13 years) to use them effectively.

The results revealed influences of frequency and predictability on word-skipping and reading times. As expected, word-skipping was higher and reading times shorter for high than low frequency words and for higher compared to less predictable words. These findings concur with data from skilled readers in Chinese (Guo et al., 2011; Li et al., 2014; Lu et al., 2008; Yan et al., 2006) and alphabetic languages (Balota et al., 1985; Bélanger & Rayner, 2013; Drieghe et al., 2005; Inhoff & Rayner, 1986; Kretzschmar et al., 2015; Rayner & Duffy, 1986; Rayner et al., 1996, 2004, 2011; Reichle & Drieghe, 2013). Moreover, the finding that frequency effects emerged early, in first-pass reading, is broadly consistent with previous developmental studies (Blythe et al., 2009; Huestegge et al. 2009; Joseph et al., 2013; Rau et al., 2015; Tiffin-Richards & Schroeder, 2015; Valle et al., 2013; for a review, see Blythe & Joseph, 2011). Finally, our findings provide novel evidence that frequency can influence word-skipping, revealing that developing readers can use this cue during parafoveal processing to guide where to move the eyes. Although participants in previous developmental studies were from a younger age-group (6-11 years) than the present experiment (11-13 years), Chinese children typically begin formal schooling a little later (6-7 years) compared to children in the UK and Germany (where previous studies were conducted), so these age-groups are likely to be broadly comparable.

Our findings show also that predictability influenced word-skipping and reading times. The effects were broadly comparable with the only previous developmental study of predictability effects (Johnson et al., 2018). However, it is notable that, in this previous study, effects were found in word-skipping and a reading time measure associated with early lexical processing only for participants with good decoding abilities. Participants in the present experiment were drawn from a broad sample of children with typical reading abilities. Analyses that included offline assessments of reading proficiency nevertheless revealed a relationship between reading proficiency and eye movement behavior such that lower proficiency readers made greater use of predictability, especially when words were harder to decode (e.g., of lower frequency). This contrasts with these previous findings. However, this may reflect the specific challenges in recognizing words in unspaced Chinese text. In particular, because of their poorer lexical skills, less proficient readers may rely especially heavily on predictability to facilitate word segmentation, especially when words are more difficult to identify. Further work is required to test this and establish how developing readers learn to segment words in unspaced text. The present findings nevertheless demonstrate that frequency and predictability cues are used early in reading development.

The present findings also showed interactive effects of these factors on word-skipping and reading times for words, revealing a conjoint influence of frequency and predictability on an early stage of lexical identification (see Staub, 2015). Our findings are in line with other studies showing interactive effects (e.g., Hand et al., 2010; Inhoff, 1984; Sereno et al., 2018), although some studies show additive effects in alphabetic scripts (Altaribba et al., 1996; Ashby et al., 2005; Bélanger & Rayner, 2013; Drieghe et al., 2005; Gollan et al., 2011; Kretzschmar et al., 2015; Lavigne et al., 2000; Miellet et al., 2007; Rayner et al., 2001; Rayner et al., 2004; for a review, see Staub, 2015) and Chinese (Guo et al., 2011; Lu et al., 2008). This includes research by Lu et al. (2008), who reported additive effects of frequency and predictability in reading times by skilled readers (without reporting word-skipping), whereas we show interactive effects in both reading times and word-skipping by developing readers. This differential pattern may reflect developmental changes in the influence of frequency and predictability. Understanding the relationship between these factors is important for the development of computational models of eye movement control, including E-Z Reader and SWIFT (Engbert et al., 2005; Reichle et al., 1998). These current models predict that frequency and predictability have an early influence on lexical processing, but with debate over whether effects are additive or interactive. Similarly, a developmental model based on E-Z Reader (Reichle et al., 2013) incorporates the assumption that both variables influence word identification, but presently does not specify whether effects are additive or interactive. Therefore, as we detail below, our findings may be important in providing insights into the relative timing of the influence of these variables.

First, our findings show predictability effects on word-skipping only for low frequency words, with more skipping when these words are more predictable. This suggests predictability effects on skipping are mediated by ease in lexically identifying parafoveal words. High frequency words are likely to be more easily identified parafoveally, and so decisions to skip these words may not be strongly affected by predictability (i.e., skipping effects for these words may be at ceiling). Low frequency words, by comparison, will be less easily identified parafoveally, unless strongly predicted from prior context, and this may account for the interaction effect. Second, we observed a complex pattern of effects in reading times, such that the relative influence of frequency and predictability changed across the time course of processing. We first observed an interactive effect in early processing measures (FFD, GD), due to predictability effects on reading times for high frequency words only. By comparison, measures of later processing (RPD, TRT) showed predictability effects on reading times regardless of frequency. Moreover, the effect in RPD was even suggestive of a larger predictability effect for low frequency words. The indication, therefore, is that predictability had an early and sustained influence on word identification, that emerged earliest during fixational processing for higher frequency words and influenced processing of both high and low frequency words later in the eye movement record. This pattern of effects might reflect how easily words, once fixated, can be identified in unspaced Chinese text. In particular, as high frequency words are likely to be identified more easily, and therefore more quickly, this might result in facilitation of their identification by predictability early during fixational processing. However, as low frequency words are likely to be harder to identify in unspaced text, and so likely to be recognized more slowly, predictability effects may emerge more slowly for these words and exert an influence later during processing, once word segmentation has taken place. Interaction effects in early reading time measures appears contrary to Stanovich and West's (1981) account that describes larger effects of context for more difficult words (i.e., lower frequency words). It should nevertheless be clear from the discussion above that this apparent interaction represents a difference in the time course of effects for high and low frequency words, rather than larger effects for high frequency words. Crucially, the effects we observed in later reading time measures show that, ultimately, predictability influences processing of both high and low frequency words. Moreover, analyses including individual differences in reading proficiency showed larger predictability effects for lower frequency words for poorer proficiency readers, consistent with Stanovich and West's more general account.

An issue this nevertheless raises is why word predictability influences skipping rates for low frequency word, and so influence parafoveal processing of these words, yet has a relatively late influence on the fixational processing of low frequency words. One possibility is that this might reflect variation in the ease with which some low frequency words can be processed parafoveally, perhaps due to individual differences in word familiarity or the influence of another factor, such as orthographic familiarity. As a result, those low frequency words that are easier to identify parafoveally may also benefit from contextual predictability, which might help explain why an interaction effect is observed in word-skipping. By comparison, low frequency words that are not skipped are likely to remain more difficult to identify compared to higher frequency words when fixated, potentially explaining why predictability effects emerge more slowly during fixational processing for low than high frequency words. Of course, this explanation is speculative and further work is needed to more fully understand factors affecting parafoveal processing in Chinese reading, which appears to include word frequency and predictability but may also be influenced by the properties of individual characters in words, including their frequency of usage and visual complexity (see, e.g., Lin, et al., 2018; Wei, Li, & Pollatsek, 2013; Zang, Zhang, Bai, Yan, Angele, & Liversedge, 2018).

The present experiment reveals that developing Chinese readers use information about word frequency and predictability to guide decisions about when and where to move their eyes. It is also the first developmental study to show an interactive influence of these variables on word identification, affecting word-skipping and reading times for words. However, as we investigated these effects in an unspaced, character-based language (i.e., Chinese), where such cues may be vital to segmenting word boundaries (e.g., Li et al., 2009), it will be important to establish if effects are similar in spaced alphabetic languages. There are also several other limitations to the present research. First, the participant group were Grade 5 readers who would be expected to have acquired the basic skills required for Chinese reading. These exhibited adult-like sensitivity to cues provided by frequency and predictability. It is therefore essential to investigate effects in younger groups to more clearly understand the acquisition of these cues. We also investigated effects for two-character target words. Words in Chinese comprise one or more characters and, while two-character words are most common, their identification requires morphological processing skills not required for one-character words. Consequently, an important extension to this work will involve examining the influence of frequency and predictability on the identification of one-character words by developing readers. Our manipulation of word predictability was also not exceptionally strong (although still effective) and there are good arguments to investigate a broader range of predictability effects (including low, medium and high predictability words) to more fully understand this variable's influence (see, e.g., Sereno et al., 2018). Finally, Johnson et al. (2018) revealed that word predictability effects differs for children with varying decoding abilities. Our findings shed some light on this relationship in developing Chinese readers. However, it will be important to assess this systematically to understand differences in the use of lexical and contextual cues by children with specific reading difficulties, to tailor interventions that might improve their reading performance. The findings we report also are theoretically important for the future development of models of eye movement control. Current models of skilled reading predict that frequency and predictability influence the early processing of words. However, models of reading development are in their infancy and for now only applicable to alphabetic languages. The present findings will help the development of these models and their extension to non-alphabetic languages like Chinese. Crucially, by providing a framework for understanding how skilled reading develops, such models can form the basis for interventions to support developing readers.

Footnote

1. Participants did not see an equal number of target words in each condition. We therefore repeated the data analyses reported here with a balanced dataset created by removing the extra word pair that unmatched the number of items per condition. The same pattern of effects was found, therefore, we decided to keep the original dataset.

2. Models with a maximum random structure were used for all reading times measures (SFD, GD, RPD, TRT). However, the random structure of models was trimmed to (1 + frequency × predictability | pp) + (1 + frequency + predictability |stim) for first-fixation duration; and trimmed to (1 + frequency | pp) + (1|stim) for measures of word-skipping, regressions-in and regressions-out.

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Data files and related resources are available from the University of Leicester online Figshare repository: https://leicester.figshare.com/s/979dd64534e3350ef379

Conflict of Interest

No potential conflict of interest was reported by the authors.

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Figure Legends

Figure 1 Example sentence stimulus in each word frequency and predictability condition.

Figure 2. Eye movement measures for target words as a function of word frequency and predictability

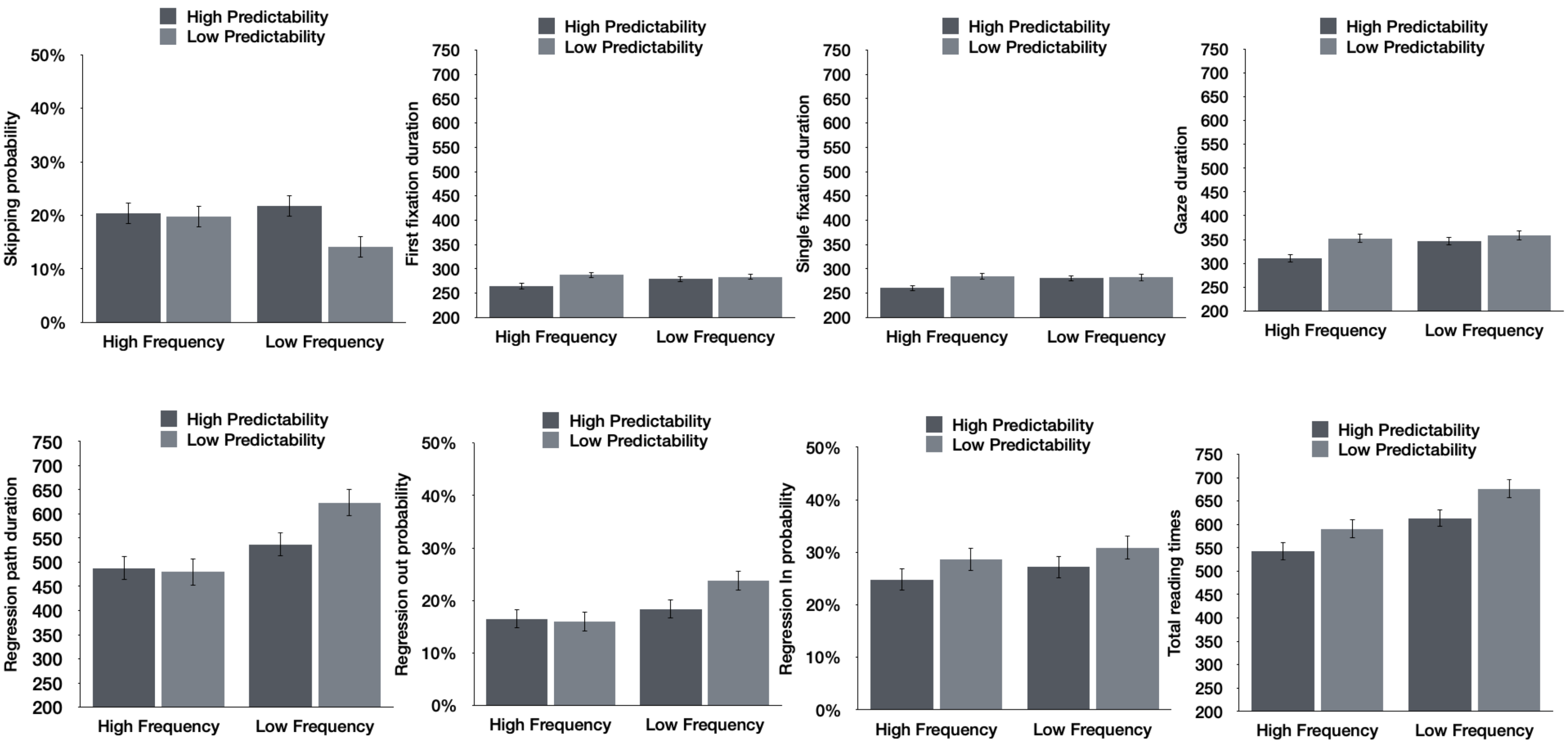
Figure 3. Eye movement measures for target words as a function of word frequency and predictability when word predictability is a continuous variable specified in terms of log cloze predictability.

Figure 1.

Conditions	Sentences
High Frequency - High Predictable	校门口站着一位年过花甲的老人正在等孙子放学。 An aging man who is over 60 years old are standing at the school gate and waiting for his grandson.
High Frequency- Low Predictable	这位渴望重见光明的老人最终决定接受手术治疗。 The aging man who was longing to see again finally decided to have an operation.
Low Frequency- High Predictable	这位渴望重见光明的盲人最终决定接受手术治疗。 The bland man who was longing to see again finally decided to have an operation.
Low Frequency- Low Predictable	校门口站着一位年过花甲的盲人正在等孙子放学。 A bland man who is over 60 years old are standing at the school gate and waiting for his grandson.

Note. Target words are shown underlined but were shown normally in the experiment. Sentences are shown translated into English.

Figure 2.



Note. Error bars show the Standard Error of the Mean.

Figure 3.

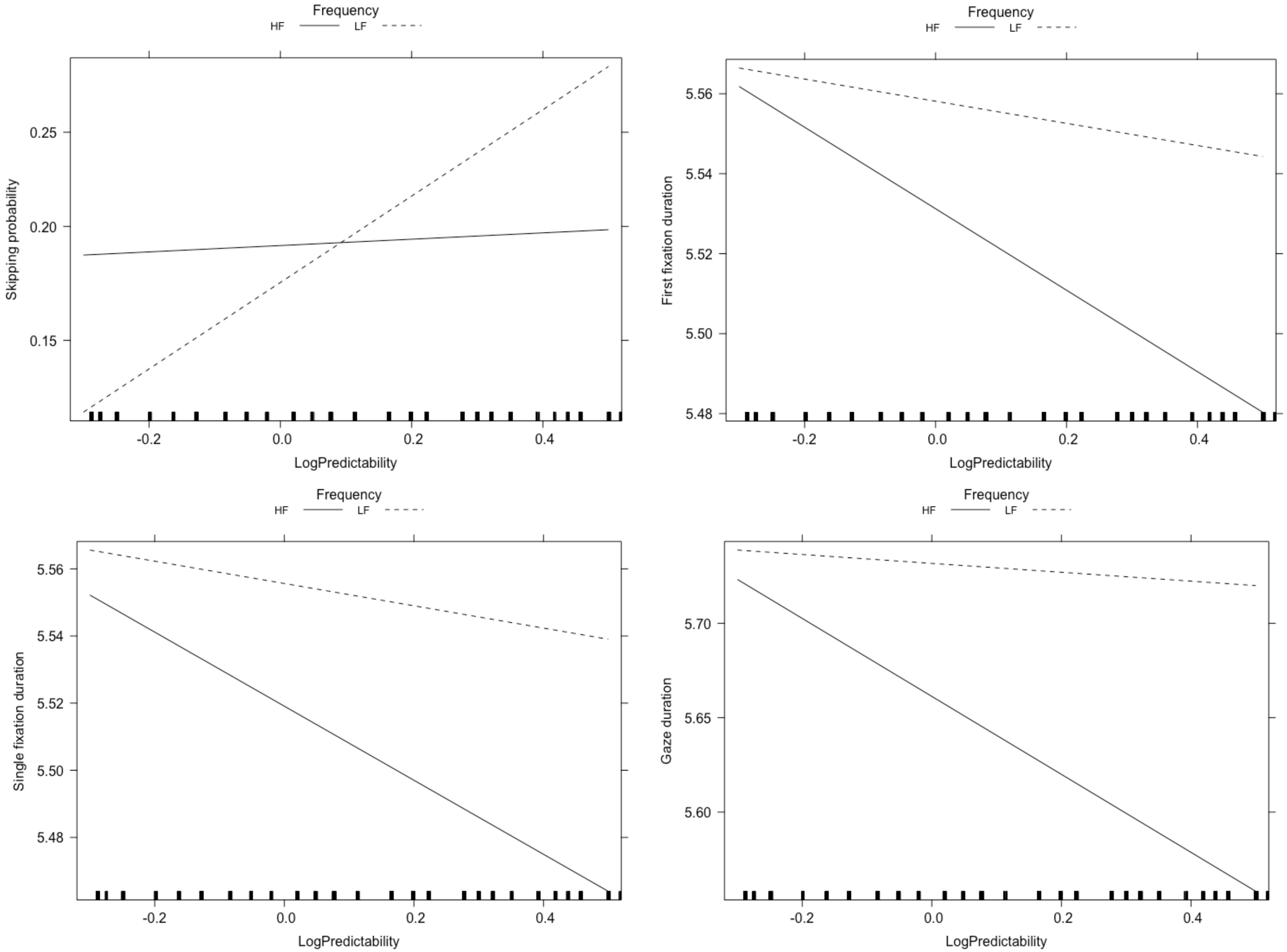

Frequency
HF
LF
Skipping probability
First fixation duration
Single fixation duration
Gaze duration
LogPredictability

Table 1. Children's Performance on Standardized Reading Tests.

Reading Tests	Reading Comprehension	Reading Fluency
Present Study	11.4 (2.8)	384 (216)
Normative 1	11.8 (3.0)	521 (368)
One-sample t test	t (43) = 0.96, p > .05	t (43) = 11.5, p < .001
Present Study	11.4 (2.8)	384 (216)
Normative 2	11.8 (2.9)	380 (158)
One-sample t test	t (43) = 0.95, p > .05	t (43) = 0.05, p > .05

Note: Standard deviation are shown in parenthesis. Normative 1 is the pool of 320 children from two school and Normative 2 is the pool of 265 children when 54 students who received speed-reading training as part of their language teaching are removed.

Table 2. Target Word and Sentence Characteristics

	High Frequency		Low Frequency	
	High Predictability	Low Predictability	High Predictability	Low Predictability
Frequency (per million)	131.4 (151.6)		11.2 (11.5)	
Word familiarity	4.6 (1.0)		2.9 (1.1)	
Number of first character strokes	6.8 (1.9)		6.6 (2.9)	
Number of second character strokes	6.7 (3.0)		6.2 (2.6)	
Stroke number of the whole word	13.5 (3.3)		12.9 (3.5)	
Predictability (%)	56.9 (24.9)	1.0 (2.5)	42.7 (23.8)	0.4 (2.0)
Sentence naturalness	1.8 (0.4)	1.9 (0.3)	1.8 (0.3)	1.9 (0.4)

Note: Standard Deviations are shown in parentheses.

Table 3. Eye Movement Measures in Each Word Frequency and Predictability Condition

	High Frequency		Low Frequency	
	High Predictability	Low Predictability	High Predictability	Low Predictability
Skipping probability (%)	21.2 (2.1)	20.5 (2.1)	22.6 (2.2)	15.1 (1.8)
First-Fixation Duration (ms)	268 (6)	290 (6)	281 (5)	292 (7)
Single-Fixation Duration (ms)	263 (6)	287 (7)	283 (6)	292 (8)
Gaze Duration (ms)	316 (9)	360 (9)	360 (10)	373 (11)
Regressions Out (%)	17.7 (1.8)	17.8(1.8)	19.4 (1.9)	24.3 (2.0)
Regression Path Duration (ms)	488 (25)	480 (21)	537 (27)	623 (30)
Regression In (%)	25.4 (2.1)	28.9 (2.2)	27.5 (2.2)	31.4 (2.2)
Total Reading Time (ms)	547 (17)	591 (17)	640 (22)	715 (23)

Note: Standard Errors of the Mean are shown in parentheses.

Table 4. Summary of Statistical Effects

Fixed effect		SP	FFD	SFD	GD	RO	RPD	RI	TRT
Intercept (global mean)	*b*	-1.57	5.54	5.54	5.69	-1.61	5.98	-0.97	6.22
	SE	0.24	0.02	0.03	0.03	0.15	0.04	0.10	0.05
	t/z	-6.42	220.30	203.66	164.08	-10.43	139.36	-9.54	136.29
Frequency	*b*	-0.32	0.03	0.04	0.07	0.35	0.15	0.12	0.14
	SE	0.17	0.02	0.03	0.03	0.14	0.04	0.12	0.04
	t/z	-1.87~	1.25	1.50	2.28*	2.44*	3.76***	1.07	3.92***
Predictability	*b*	-0.44	0.05	0.05	0.07	0.13	0.08	0.19	0.12
	SE	0.15	0.02	0.02	0.03	0.13	0.04	0.11	0.03
	t/z	-2.98*	2.62*	2.21*	2.61*	1.04	1.93~	1.77~	4.00***
Frequency x Predictability	*b*	-0.64	-0.08	-0.09	-0.14	0.39	0.05	-0.04	-0.01
	SE	0.30	0.04	0.05	0.05	0.26	0.10	0.22	0.10
	t/z	-2.14*	-2.13*	-1.89~	-2.64*	1.47	0.56	-0.20	-0.10
Planned Contrasts		SP	FFD	SFD	GD				
High Frequency: Low vs. High Predictability	*b*	-0.13	0.10	0.10	0.14				
	SE	0.30	0.03	0.03	0.03				
	t/z	-0.45	3.22***	3.37**	4.14***				
Low Frequency: Low vs. High Predictability	*b*	-0.62	0.01	0.01	-0.01				
	SE	0.26	0.02	0.03	0.04				
	t/z	-2.37*	0.46	0.30	-0.11				

Note. SP=Skipping probability; FFD=First-fixation duration; SFD: Single-fixation duration; GD=Gaze duration; RO=Regression out probability; RPD=Regression path duration RI=Regression in probability; TRT=Total reading times. ***$p < .001$, **$p < .01$, *$p < .05$. ~$p<0.1$.

Table 5. Summary of Statistical Effects: Cloze Predictability Factor included as a continuous variable (centered and log-transformed).

Fixed effect		SP	FFD	SFD	GD	RO	RPD	RI	TRT
Intercept (global mean)	*b*	-1.50	5.54	5.54	5.70	-1.50	5.97	-0.95	6.22
	SE	0.24	0.03	0.03	0.03	0.13	0.04	0.10	0.04
	t/z	-6.25	218.64	204.86	163.93	-11.20	144.47	-9.80	137.59
Frequency	*b*	-0.11	0.03	0.04	0.07	0.27	0.15	0.10	0.14
	SE	0.14	0.02	0.02	0.02	0.13	0.03	0.11	0.03
	t/z	-0.77	1.46	1.71~	3.04**	2.09*	4.51***	0.89	4.75***
Predictability	*b*	0.71	-0.06	-0.07	-0.12	-0.26	-0.11	-0.38	-0.20
	SE	0.26	0.03	0.04	0.04	0.27	0.08	0.21	0.05
	t/z	2.68**	-1.95~	-1.72~	-2.59*	-0.97	-1.39	-1.83~	-3.73**
Frequency x Predictability	*b*	1.22	0.07	0.08	0.18	-0.14	0.03	0.03	0.04
	SE	0.53	0.07	0.08	0.08	0.48	0.12	0.42	0.10
	t/z	2.31*	1.12	0.99	2.18*	-0.31	0.21	0.06	0.34
Planned Contrasts									
High Frequency:	*b*	0.01	-0.10	-0.10	-0.21				
Low vs. High Predictability	*SE*	0.39	0.04	0.05	0.05				
	t/z	0.03	-2.38*	-2.26*	-3.89***				
Low Frequency:	*b*	1.23	-0.02	-0.03	-0.01				
Low vs. High Predictability	*SE*	0.49	0.05	0.06	0.07				
	t/z	2.53*	-0.42	-0.42	-0.20				

Note. The random structure was (1|pp) + (1+ LogPredictability|stim) for reading times measures (FFD, SFD, GD, RPD, TRT) , (1|pp) + (1|stim) for FFD and for all dichotomous variables (SP, RO, RI). SP=Skipping probability; FFD=First-fixation duration; SFD: Single-fixation duration; GD=Gaze duration; RO=Regression out probability; RPD=Regression path duration RI=Regression in probability; TRT=Total reading times.

$^{***}p < .001$, $^{**}p < .01$, $^{*}p < .05$. ~$p<0.1$.