Initial landing position effects on Chinese word learning in children and adults

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Abstract

We adopted a word learning paradigm to examine whether children and adults differ in their saccade targeting strategies when learning novel words in Chinese reading. Adopting a developmental perspective, we extrapolated hypotheses pertaining to saccadic targeting and its development from the Chinese Reading Model (Li & Pollatsek, 2020). In our experiment, we embedded novel words into eight sentences, each of which provided a context for readers to form a new lexical representation. A group of children and a group of adults were required to read these sentences as their eye movements were recorded. At a basic level, we showed that decisions of initial saccadic targeting, and mechanisms responsible for computation of initial landing sites relative to launch sites are in place early in children, however, such targeting was less optimal in children than adults. Furthermore, for adults as lexical familiarity increased saccadic targeting behavior became more optimized, however, no such effects occurred in children. Mechanisms controlling initial saccadic targeting in relation to launch sites and in respect of lexical familiarity appear to operate with functional efficacy that is developmentally delayed. At a broad theoretical level, we consider our results in relation to issues associated with visually and linguistically, mediated saccadic control. More specifically, our novel findings fit neatly with our theoretical extrapolations from the CRM and suggest that its framework may be valuable for future investigations of the development of eye movement control in Chinese reading.

Keywords: saccadic targeting, word learning, children, Chinese reading

Introduction

Children develop their vocabularies at an extremely high rate in the primary school period, and a significant amount of vocabulary development occurs through the derivation of word meanings from context during natural reading (Fukkink, 2005; Nagy, Anderson, & Herman, 1987). Several recent studies have examined the cognitive processes underlying children's novel word learning (aged 7 to 11 years) during reading by using eye tracking (e.g., Blythe, Liang, Zang, Bai, Yan, & Liversedge, 2012; Joseph & Nation, 2018; Liang, Blythe, Zang, Bai, Yan, & Liversedge, 2015). Eye tracking is a method that is well established as a means of investigating reading behavior by measuring when and where the eyes fixate on text as written language is processed naturally. This approach is widely used to investigate the time course of learning via naturalistic reading, by indexing the incremental changes in moment-to-moment reading behavior as readers experience novel words over multiple exposures (see Elgort, Brysbaert, Stevens, & Van Assche, 2018; Joseph, Wonnacott, Forbes, & Nation, 2014; Joseph & Nation, 2018). All the studies investigating novel word learning listed above measured fixation durations on novel words fixated by children (often compared to adults) with a view to quantifying the time required for those novel words to be successfully identified within the context of a sentence. And this line of research has demonstrated that, consistent with age-related research investigating normal reading, during novel word learning, children's eye movements exhibit developmental characteristics that change with chronological age and improved reading skill. For example, as chronological age increases, children make shorter and fewer fixations on novel words, and fewer regressions back to the novel words in order to reinspect them (e.g., Blythe et al., 2012). Whilst the word learning studies mentioned above have all examined issues of when children move their eyes as they process novel words, to date, no study of novel word learning has investigated the question of where readers target their initial saccades as novel words are encountered and recognized. Of course, much is known regarding how readers of alphabetic languages target their saccades to words that are established in memory. Upcoming word units are visually, and to some extent linguistically, processed in the parafovea, and in alphabetic languages, saccades are targeted to (roughly) just left of their center. The importance of the spaces between words for efficient saccadic targeting has long been established (e.g., Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner, 2009; Rayner, Fischer, & Pollatsek, 1998). However, the question of where saccades are targeted is not so straightforward in unspaced languages like Chinese. The lack of overt word boundary demarcation in Chinese makes the question of saccadic targeting of particular interest. Quite how readers identify the location to which they wish to target a saccade in relation to the constituent characters and words of the upcoming text is currently unclear. Furthermore, the extent to which a Chinese reader must be familiar with the words they are processing in order to efficiently target saccades is also unknown. Thus, given current debate concerning the nature of saccadic targeting in unspaced languages like Chinese, and the absence of understanding of how this relates to a reader's familiarity with words, in the present study we investigated saccadic targeting in relation to novel word learning in Chinese reading in both adults and children.

Children's saccadic targeting in familiar word reading

For the reading of alphabetic languages, such as English and German, children in their early years of reading (around 7 years old) are able to use adult-like saccadic targeting strategies for highly efficient text processing (Joseph, Liversedge, Blythe, White, & Rayner, 2009; McConkie, Zola, Grimes, Kerr, Bryant, & Wolff, 1991; Vitu, McConkie, Kerr, & O'Regan, 2001). Both child and adult readers target their initial fixations to a position slightly left of the word center, which is referred to as “Preferred Viewing Location” (PVL, Rayner, 1979). Children can also adjust their saccadic targeting to the upcoming word by processing word length information in the parafovea: initial landing positions tend to be further into a word as word length increases (Blythe & Joseph, 2011; Joseph et al., 2009). Moreover, like adults, children are more likely to refixate a word following an initial fixation distant from the word center compared to cases where the initial fixation is close to the word center (Blythe & Joseph, 2011; Joseph et al., 2009; Vitu et al., 2001). Children engaged in alphabetic language reading are able to target their saccades quite efficiently at a relatively young age (approximately 7 years, see Blythe & Joseph, 2011), which may be, at least partially, attributable to the presence of word spacing that demarcates word boundaries. It appears that children, like adults, perceive word boundaries (i.e., spaces) in parafoveal vision and use this information to facilitate saccade target selection. In fact, when spaces between words are artificially removed in English reading, saccadic targeting becomes less efficient: the peak of the PVL curve shifts towards the beginning of the word (Paterson & Jordan, 2010; Perea & Acha, 2009; Rayner et al., 1998; Sheridan, Rayner, & Reingold, 2013).

In contrast to alphabetic languages like English, there are no spaces between words in written Chinese, which means that visual word boundary cues are not present for children (and adults) to use for successful saccadic targeting during reading. Thus, it is an issue of some intrigue as to how Chinese children develop the ability to target their saccades as they read. Zang et al. (2013) provide significant insight into this issue. In their study, they compared the saccadic targeting strategies of children (8- to 9-year-olds) and adults when they read familiar words naturally. Arguably, the most important finding from this study was that, although the children’s linguistic processing ability was far less than that of adults, they still targeted their initial saccades to upcoming words as effectively as adults, being most likely fixate towards a word center when a single fixation was made on a word, and initially fixating towards the beginning of a word when two or more fixations were made on that word (see also Zang et al., 2013). Similar basic saccadic targeting behavior in children and adults in both Chinese and English reading implies that the mechanisms underlying decisions of where to target the eyes in familiar word reading attain developmental maturity early, and are quite basic in nature.

Beyond this, recent studies have demonstrated that ongoing lexical processing difficulty influences where readers of Chinese move their eyes in reading (Liu, Reichle, & Li, 2015, 2016; Wei, Li, & Pollatsek, 2013). A very well-established variable that is known to directly influence processing difficulty in reading is lexical frequency. Frequency has been shown to play an important role in determining where to move the eyes in Chinese reading for adult readers. Adults tend to target their eyes further into high than low frequency words (Liu et al., 2016; Wei et al., 2013). Similar findings have also been reported in studies of alphabetic reading like English (e.g., Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006), Finnish (i.e., Hyönä, Yan, & Vainio, 2018) and Uighur (i.e., Yan, Zhou, Shu, Yusupu, Miao, Krügel et al., 2014). These findings are very relevant to the present study in which we investigate how children and adults target saccades to novel words that are extremely unfamiliar to them. Given that novel words are essentially equivalent to extremely low-frequency words that a reader may not have yet encountered, then it is quite reasonable to suggest that such words would pose substantial processing difficulty (Chaffin, Morris, & Seely, 2001; Chu & Leung, 2005; Lowell & Morris, 2014), particularly for children (see Blythe et al., 2012). If this is the case, then it raises another fundamental question, namely, where do Chinese readers (both children and adults) target their saccades when encountering novel words in reading. The present study will focus on this issue.

Processing-based strategy of saccadic targeting in Chinese reading

A recent dominant account associated with how Chinese readers target their saccades in reading is called the processing-based hypothesis which was developed by Li and his colleagues (2013, 2015). Central to this hypothesis is the view that Chinese readers first make an implicit estimation of the number of characters/letters that they can process to the right of the current fixation and then they target their next saccade just to the right of those characters/letters. In this way, the reader positions their point of fixation on the immediately adjacent novel information in the sentence. By this account, saccade targeting is dynamically adjusted in a manner that reflects the demands of ongoing foveal and/or parafoveal processing; the more difficult the foveal and/or parafoveal processing, the shorter the saccade into upcoming text.

The processing-based account of saccadic targeting provides a reasonable explanation for the following empirical findings. First, the properties of the fixated word that are known to affect lexical processing also affect where readers target their next saccade, for example, saccades tend to land further into long than short words (e.g., Wei et al., 2013; Zang et al., 2018), high than low frequency words, (e.g., Liu et al., 2016, 2019a, 2019b; Rayner et al., 2006; Wei et al., 2013; Yan et al., 2014), and morphologically-simple compared with morphologically-complex words (e.g., Hyönä et al., 2018; Yan et al., 2014). Furthermore, the influence of word frequency on saccadic eye movements is modulated by the amount of parafoveal information that is extracted prior to a saccade such that saccades leaving a high-frequency word are longer than those leaving a low-frequency word (when a valid preview is available). However, this effect decreases when a preview is invalid (see Liu et al., 2015). These findings above collectively suggest that foveal and/or parafoveal processing plays an important role in saccadic targeting, at least for unspaced Chinese reading. The more characters Chinese readers are able to process to the right of fixation, the further they will subsequently send their eyes forward in the text. Thus, easier-to-process foveal words allow for more parafoveal processing of upcoming words, which in turn results in a longer saccade from that word.

The processing-based account of saccadic targeting might also offer an explanation of how the PVLs and their associated distributions come to be established in Chinese reading. As reported by Yan et al. (2010) and Zang et al. (2013), PVLs exist in Chinese reading and these vary systematically as a function of how many times a word is fixated. Saccades are directed towards the center of an upcoming word which is fixated just once, whilst towards the beginning of the upcoming word if it is fixated two or more times. Yan et al (2010) provided the following explanation to account for how Chinese readers choose to target their initial saccades towards a word beginning or a word center in reading. They proposed that the nature of the PVL depend on whether or not a word is successfully segmented prior to it being fixated, with saccades being directed by default towards the center of a word when that word has been successfully parafoveally segmented, whilst towards a different location, its beginning, when the rightward boundary has not been successfully identified (i.e., complete segmentation has not occurred). An alternative explanation is, that the eyes may fixate at the center or the beginning of the upcoming word by chance (see Li et al., 2011; Zang et al., 2018). Since word perception is more efficient when a saccade lands towards the center of a word (O'Regan, 1981; O'Regan & Lévy-Schoen, 1987), the word can be processed with a single fixation in this situation. In contrast, when a saccade lands in a non-optimal position (e.g., towards a word's beginning), word identification is less efficient, and refixations are necessary. To date, empirical investigations have been unable to determine which of these alternative explanations is correct. Nonetheless, it is important to note that both explanations do suggest that saccade targeting in Chinese reading is directly affected by the efficacy of online visual and lexical processing that occurs in both parafoveal and foveal vision. Such theoretical claims fit with the central basic assumption of the processing-based saccadic targeting account.

Recently, Li and Pollatsek (2020) reported an integrated model of word processing and eye movement control in Chinese reading (the Chinese Reading Model, CRM) in which a processing-based strategy plays a central role. They used their model to successfully simulate a range of eye-movement control phenomena in relation to Chinese reading (e.g., word frequency effect, word length effect, word predictability effect, preview effect and saccadic targeting). Although our experiment was conducted prior to the publication of the CRM, the model is clearly very directly theoretically relevant, and for this reason, we felt it was necessary to generate predictions on its basis. The aspects of Li and Pollatsek's paper that are most relevant for present purposes concern their simulations of saccadic targeting in Chinese reading. Given that Chinese is comprised of strings of characters presented in a uniformly spaced manner, Li and Pollatsek (2020) argue that the character is the naturally salient unit that forms the basis for saccadic target selection. To further explain, the CRM assumes that where to move the eyes in reading is directly determined by a character-activation map, within which there is a unit corresponding to each of the upcoming character positions in the sentence. Activations for these character units are initially set to 0, and the activations of characters that have already been fixated and fully recognized have activations of 1. On any particular fixation, the activation units corresponding to characters to the right of fixation (and actually, the fixated character and its predecessor) are updated synchronously within the activation map in line with the degree to which the characters in those positions are activated (we assume that this means the extent to which they are parafoveally processed). When a decision to move the eyes is made, the character activation map is searched sequentially until a character unit is encountered that has an activation value greater than a threshold (specified as a free parameter in the model). The character corresponding to this activation unit is selected as the target for the saccade. Furthermore, the CRM also stipulates that the degree to which the character that is selected as the saccade target is parafoveally processed will determine how far a saccade will be targeted to the right within that character (i.e., the greater the extent to which a target character is processed, the further to the right within that character the fixation on that character will land).

The issue of saccadic targeting in the CRM is further complicated by the fact that the word identification module and the eye movement control module that comprise the model have an interactive relationship. The activation of a character unit in the character activation map can be influenced both by gradual delivery of information concerning a character's identity based on parafoveal processing, as well as that character's likelihood of being a potential constituent of a set of possible words – presumably something akin to a candidate set within the word processing module. The important point to note here is that both character level and word level factors impact on the decision of the parafoveal character to which saccades should be targeted. Via this account, the model successfully simulated two current and important findings associated with saccade targeting in Chinese reading; first it showed that saccade length was affected by the frequency and length of the currently fixated word (see Wei et al., 2013); second, it successfully showed that the length of a saccade leaving a word was affected by the frequency of the upcoming word, and that this effect itself was modulated by the preview validity of that upcoming word (see Liu et al., 2015).

The CRM has already made an important contribution in explaining and providing understanding regarding how eye movement control occurs during reading of unspaced Chinese text. However, we note that the feasibility of the model has, as yet, been assessed on the basis of empirical findings from skilled adult readers. Perhaps unsurprisingly, given its recency, the model has not been evaluated in relation to how it might account for changes in eye movement behavior that occur as new words are acquired. Of course, any model of eye movements and reading should, ultimately, explain how eye movement behavior changes as newly acquired words become increasingly familiar to the reader with exposure and experience. Quite an amount has already been learnt about the differences in eye movement behavior that exist between beginning readers (i.e., children who can read simple sentences but who have limited reading experience and proficiency) and much more skilled adult readers (for reviews, see Blythe & Joseph, 2011; Zang, et al., 2011). There is also an increasing literature demonstrating differences in eye movement behavior for words that are less compared with more familiar to readers (see Bai et al., 2013; Blythe et al., 2012; Joseph et al., 2014; Liang et al., 2015, 2017). Accordingly, in the present study, we attempted to consider (and, to some degree, evaluate) the utility of the processing-based account that is central to the CRM from a developmental perspective. More specifically, we investigated whether this account might readily provide an explanation of how children and adults target their saccades to novel words during a period of cumulative learning.

The present study

We adopted a paradigm adapted from our previous studies (see Bai et al., 2013; Blythe et al., 2012; Liang et al., 2015, 2017), in which we presented participants with 8 exposures each to a two-character pseudoword (a novel target word) embedded within a sentential context which we required them to read normally. From each exposure to a novel word in a sentence, participants were able to learn some background information and some of the semantic characteristics of the pseudowords. All the sentences that contained the same pseudoword were presented sequentially, thereby allowing us to assess the influence of change with cumulative experience. Furthermore, we assessed effects of word learning in two participant groups, children (aged 9-10 years) and adults. Thus, our study allowed us to assess effects of increased exposure to novel words on eye movement behavior in reading in participant groups for which processing was less (children) or more (adults) efficient. It was in this way that we investigated how efficiency of processing influenced eye movement behavior in reading as a means of evaluating the processing-based account which is central to the CRM in relation to saccadic targeting in Chinese readers.

Our objective in this experiment was to consider the claims of the CRM in the context of adult novel word reading, and then to consider how the scope of the model might be extended, in principle, to account for data relating to how less experienced readers, namely children (9-10 years), processed novel words during natural reading. To do this, we followed two lines of enquiry in our experiment. The first broad issue of investigation concerned whether there were any general differences in saccadic targeting to novel words between children and adult readers. Assuming that the CRM offers a veridical characterization of reading in both adults and children, then we anticipated that any such differences would reflect relative immaturity in the nature of mechanisms and underlying representational structures, and efficiencies of parafoveal processing with respect to the identification of the parafoveal saccadic target (i.e., the particular character in the perceptual span) in children relative to adults.

In line with recent empirical findings in respect of children's parafoveal processing (8-10 years, see Pagán, Blythe & Liversedge, 2016; Tiffin-Richards & Schroeder, 2015), and on the basis of the theoretical account offered by the CRM, there are good reasons to believe that variation might exist between children and adults, and that this might influence basic decisions as to where to target the eyes to novel words in reading. Effective parafoveal processing is a hallmark of skilled reading, and is a necessity for effective saccadic targeting. It is well documented that children under 10 years old have a reduced perceptual span (i.e., a reduced parafoveal processing extent, see Häikiö, Bertram, Hyönä, & Niemi, 2009; Rayner, 1986), and that they are less efficient in respect of the extraction of useful visual and linguistic information from parafoveal text than are adults (for a review, see Reichle, Liversedge, Drieghe, Blythe, Joseph, White et al., 2013). Given this, and given the theoretical stipulations of the CRM, we are able to form some basic, very testable, predictions regarding how children will target saccades to novel words relative to adults. First, if the perceptual span is reduced in children relative to adults, then children should process fewer characters to the right of fixation than adults, and those characters should be processed less effectively. Within the CRM, information about the nature of upcoming characters in the perceptual span feeds directly into the eye movement control module where it directly activates character units in the character-activation map. Thus, these character units reflect upcoming character positions that are potential targets of a saccade. If, as we have argued, children have a reduced perceptual span and are less effective in their extraction of information from the parafovea than adults, there should be three consequences with respect to the pattern of fixation landing positions on the novel target words in our experiment. First, given the reduced extent of parafoveal processing, the distribution of fixations on target words for children should be shifted to the left of that observed for adults. Second, reduced efficiency in parafoveal information extraction in children relative to adults should result in reduced activation levels for the character units in the character-activation map in the eye movement control module. As a result, any landing position distributions that we observe for adults should be comparable, but relatively less accurate in children (reflecting generally lower activations in each of the character units in the character-activation map in children relative to adults). Third, we anticipated that landing positions on our target words would be influenced by the location from which saccades were launched, but this effect would be reduced in children relative to adults. This issue, again, links to a core assumption of the CRM, as we stated earlier, that parafoveal processing is important in saccadic targeting in Chinese reading. Launch distance is generally accepted to be a modulatory influence on the amount of parafoveal information extracted from an upcoming target word prior to it being fixated; a more distant launch site yields reduced parafoveal preview relative to a closer launch site (Hand, Miellet, O'Donnell, & Sereno, 2010; Li, Liu, & Rayner, 2015; Slattery, Staub, & Rayner, 2012; Whitford & Titone, 2014). According to the CRM, when a saccade to a word is launched from a near site, more visual and linguistic information regarding the upcoming character units will be extracted whilst they lie in the parafovea. Consequently, closer launch sites will lead to increased activations for character units in the character-activation map in the eye movement module, and the CRM specifies that increased activations for upcoming words causes saccades to be targeted further into those words. Thus, we predicted a relationship between launch sites and landing positions in respect of upcoming words such that saccades targeted from closer locations to the upcoming word would land further into those words than saccades targeted from further away. To reiterate, we anticipated that any such relationship would be greater in magnitude for adults relative to children due to adults' more proficient parafoveal processing.

It is also the case that according to the CRM, there should be differences between children and adults in relation to foveal processing effects for the novel words in our study. It is generally accepted that foveal processing difficulty is increased for novel compared to more familiar words, and that readers make longer initial fixations, refixations and more regressions back to novel compared with familiar words (Chaffin et al., 2001; Lowell & Morris, 2014). These effects that reflect increased foveal processing difficulty occur both as a consequence of less efficient processing prior to the word's direct inspection (i.e., it was processed less effectively when it was in the parafovea), as well as the increased difficulty the word poses in respect of full lexical identification and its interpretation in relation to sentential context after it has been directly fixated (see Reichle et al., 2013). These predictions (at least up to the point of full lexical identification) are entirely consistent with CRM stipulations (and indeed, processing-based accounts more generally), and therefore, we predict that first fixation durations, and gaze fixation durations on novel words will be significantly longer in children than in adults. To reiterate, at a theoretical level, any such differences will very likely reflect immaturity and reduced efficiency in the mechanisms and processes associated with the lexical identification of words in children relative to adults.

In our second line of enquiry, we investigated the nature of incidental word learning and how this affects saccadic targeting in Chinese reading, that is, how word learning occurs during natural reading in a cumulative and incremental manner (see Godfroid, Ahn, Choi, Ballard, Cui, Johnston et al., 2018; Hulme, Barsky, & Rodd, 2019; Joseph & Nation, 2018; Joseph et al., 2014). This issue again links to our assessment of how the CRM might be extended to allow for consideration of saccadic targeting to, and foveal processing of, novel words in children relative to adults. First, we assessed how saccadic targeting to novel words changes across a period of cumulative learning in children and adults. In relation to the acquisition of novel words, whilst representations of the orthographic forms are rapidly instantiated and learnt following limited exposures (one or two exposures, see Godfroid et al., 2018; Nation, Angell, & Castles, 2007; Nation & Castles, 2017; Share, 2004), in order for a more fully elaborated understanding of word meaning to develop, multiple exposures are necessary (see Joseph, et al., 2014; Nation et al., 2007; Tamura, Castles, & Nation, 2017). There is a wealth of literature demonstrating that the number of exposures to novel words is a robust predictor of successful instantiation of a representation for that word in memory (e.g., Elgort & Warren, 2014; Godfroid et al., 2018; Pigada & Schmitt, 2006; Pellicer- Sánchez, 2016; Webb, 2007). Recent experiments have shown a strong negative relation between the number of exposures to a word and all standard temporal eye movement measures of processing (including first fixation duration, gaze duration and total reading time on novel words, see Godfroid et al., 2018; Joseph et al., 2014). That is, when learning novel items over multiple encounters, a clear word familiarity effect emerges with respect to the decision of when to move the eyes in reading. This effect is quite analogous to the frequency effect observed for the reading of familiar words in many eye movement studies. Indeed, it seems likely that the frequency effect observed in adults derives from changes in familiarity due to increased levels of exposure with words over time. Consistent with this suggestion are findings from studies with children in the early stages of learning to read through to adults (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Huestegge, Radach, Corbic, & Huestegge, 2009; Hyönä & Olson, 1995; Tiffin-Richards & Schroeder, 2015).

Given this context, and given the account offered by the CRM, we can make concrete theoretical predictions in relation to cumulative exposure effects for both saccadic targeting to novel words and foveal processing effects associated with them. As noted earlier, the frequency of an upcoming word influences the decision of where to move eyes, with a clear tendency for initial fixation positions to be shifted rightwards for words with increased frequency (see Hyönä et al., 2018; Li, Bicknell, Liu, Wei, & Rayner, 2014). Also, as we have noted, it is specified within the CRM that the frequency of the upcoming word affects saccadic targeting such that saccades will land further to the right in high compared with low frequency words. Thus, on the assumption that the familiarity of a novel word increases with exposure, and the degree of exposure is a proxy (at least in respect of the earliest stages of a new word becoming established in the mental lexicon) of eventual lexical frequency effects, then we might expect that landing positions on novel words should on average shift to more rightward positions with increased exposure. And, given that adults are more effective learners than children, any such effects should be more pronounced in adults than children.

Finally, let us consider predictions in relation to cumulative exposure effects for foveal processing in children and adults in the context of the CRM theoretical framework. Again, it is important to acknowledge the centrality of influences of word frequency on foveal lexical processing and eye movement control decisions within the CRM. It is also important to reiterate that the familiarity of a novel word increases with exposure and is likely reflective of eventual lexical frequency effects that exist once novel words are lexically established. Note also that the time spent (foveally) processing a word is inversely related to its frequency. Thus, on the basis of theoretical specifications derived from the CRM, we predicted that foveal processing difficulty (as indexed by first and single fixation duration and gaze duration measures) would occur for the earliest encounters with novel words, but that such processing difficulty should reduce with increased exposure to the words. The clear theoretical linkage to the CRM here is in relation to the important role that lexical frequency plays in eye movement control and reading, and how a word's lexical frequency derives (developmentally) from the level of cumulative exposure a reader experiences with it.

Method

Participants

A total of 76 participants took part in the experiment: 38 adults (24 females, 14 males; mean age 20.8 years, range 19-24 years) and 38 children who were in the third grade of Jinnan Experimental Primary School (19 females, 19 males; mean age 9.6 years, range 9-10 years). All participants were native Chinese speakers with normal or corrected-to-normal vision, and no known reading difficulties.

The sample size was selected to be comparable to our previous studies testing children and adults that have explored novel word learning in Chinese reading (see Liang et al., 2015, 2017). The means and standard deviations from these studies were used to approximate effect sizes and the necessary sample sizes computed to ensure adequate power. For example, first fixation durations, gaze durations, and total fixation durations from the two studies suggest that the average effect size (d) for the main effect of word familiarity in children and adults is 0.44. Using this estimate, G-Power calculations approximated that a sample size of 34 is necessary to test word familiarity effects in each age group. Our sample size of 38 participants in each age group ensured that the power in the present study exceeded the minimum required.

Materials and design

Twenty-seven two-character pseudowords were constructed as novel words. All the characters that constituted the pseudowords had relatively low visual complexity and high frequency. The mean number of strokes of all constituent characters of pseudowords was 8.6 (range = 3 to 15), and the frequencies of all selected characters were higher than 100 per million (mean = 309 per million, based on the data from the corpus of SUBTLEX-CH, Cai & Brysbaert, 2010). Due to previous evidence showing that the positional frequencies of constituent characters of novel words plays an important role in word learning both for skilled adult readers and less-skilled child readers (see Liang et al., 2015; Liang et al., 2017), in the present study, we controlled the initial and final characters that made up the novel words to ensure they had a roughly equal likelihood of being the first, or the second character of a two-character word (mean = 50%, ranging from 46% to 55%).

Two precautions were taken to ensure that the pseudowords were genuinely novel. First, we ensured that all the novel words adopted in this experiment did not appear in the Contemporary Chinese Dictionary (2005). Secondly, with the goal of ensuring that the phonological forms of pseudoword stimuli would not be mistaken with phonological forms of real words, a list of the *pinyin* counterparts for each of the pseudowords (including their tones) and *pinyin* forms for 27 two-character high frequency words (as distractors) were presented on a piece of paper. Fifteen undergraduates were asked to try their best to write down the pairs of characters that they considered were consistent with the *pinyin* forms that formed real words (or to leave the response sheet blank if they felt there was no appropriate corresponding word). Participants did not produce any real word responses in relation to the *pinyin* pseudoword forms. This held for all the items in our stimulus set.

Each pseudoword was assigned to be a word representing an imaginary member of a real-world semantic category (e.g., animals, fruits, modes of transport, etc.). In total, there were 9 semantic categories, each containing 3 pseudowords. Fifteen undergraduates were instructed to rate the degree of association between the pseudowords and its pre-specified semantic category using a scale from 1 (very unlikely to be a member) to 4 (very likely to be a member). The mean score was 1.04 (SD = 0.07), indicating that the pseudowords were very unlikely to be regarded as a member of their pre-specified semantic category. This procedure excluded the possibility that a reader's prior knowledge about a pseudowords' likely semantic category membership might influence the manner in which a pseudoword might be learnt.

For each pseudoword, we constructed eight sentence frames that provided background information and characteristics associated with the meaning of the pseudoword in relation to its semantic category (see Table 1 for an example). All the stimuli in the present study are available through the Open Science Framework (https://osf.io/rztwx/). The sentences were 13 or 14 characters long, with a mean length of 13.5 characters. The target words were never presented as the first or the last word in a sentence. We undertook two prescreen procedures to assess naturalness and sentence difficulty. In order to avoid any influence of the inclusion of a pseudoword on the naturalness and difficulty judgments that participants provided, we replaced the pseudoword with a real word in the sentences. The real word was always a candidate member in the same semantic category as the pseudoword it replaced. Fifteen undergraduate participants rated the naturalness of the sentences using a scale from 1 (very unnatural) to 5 (perfectly natural). We tested undergraduate participants in this pre-screen because we were confident that they would fully understand how to make such judgments. Each sentence received a minimum score of at least 3 and the mean naturalness score was 4.46 (SD = 0.30), indicating that all the sentences appeared quite natural to read. Another 15 undergraduates and 15 children in grade 3, were instructed to rate the difficulty of the sentences using a 5-point scale (a score of "1" meant the sentence was very difficult to read, and a score of "5" meant the sentence was perfectly easy to read). The mean difficulty rating was 4.34 (SD = 0.30) for children and 4.2 (SD = 0.46) for adults. A *paired-t test* showed that the mean difficulty ratings were not significantly different in children and adults ($t(26) = 0.78$, $p > 0.05$).

In addition to our experimental sentences, we also constructed a set of comprehension questions that were to be used in the eye tracking experiment to ensure that readers were reading effectively for comprehension. For three of the sentences in each set of 8 experimental sentences, there was a yes/no comprehension question. Additionally, we set a multiple choice semantic category question for each novel word to check whether the readers had effectively learnt the pseudoword's category membership. Participants received the multiple choice question after 3of the 8 sentences in the learning phase. They always received the multiple choice question after the final sentence in the learning phase, and one also after two of the earlier learning sentences. We ensured that multiple choice presentations appeared equally often across participants over the second to the seventh learning sentences (i.e., the second learning sentence, the third, the fourth, etc). Each multiple choice question included four options of different semantic categories, 2 of which were categories used in the experiment, whilst 2 were categories that were not included in the experiment. The probability of each semantic category appearing in all the options was equal.

Table 1. Illustration of example stimuli and the procedure of the experiment.

Learning phase	Exposure	Sentences and translations
Phase 1	1	花园里的环米特别的鲜艳夺目。 Huanmi in the garden is particularly bright and colorful.
	2	充足光照是环米生长的基本条件。 Sufficient sunshine is the basic condition for the growth of huanmi.
	3	水养或盆栽的环米都不需要施肥。 Huanmi*s* growing in water or soil, do not to be fertilized.
	4	十月到腊月是环米开花的好季节。 From October to December, is the good season for huanmi to bloom.
Phase 2	5	富丽端庄的环米的花瓣不容易脱落。 The petals of delicate huanmi are not to easy to fall off.
	6	适合红色环米生长的土壤呈酸性。 The soil suitable for the growth of red huanmi is acidic.
	7	所有盆栽的环米都不需要定期浇水。 All potted huanmi do not need to be watered regularly.
	8	生长在山上的环米是一种药材。 Huanmi growing on the hills is one kind of medicinal materials.
Semantic choice question		请问：“环米”属于以下哪个类别？ (Question：Which category does huanmi belong to?) A) 动物(animal) B) 植物(fruit) C) 书本(book) D) 家具(furniture)

Apparatus

Participants' eye movements were recorded using a SR Research EyeLink 1000 eye tracker (sampling rate = 1000Hz) as they read sentences from a computer monitor at a viewing distance of

75 cm. Sentences were presented in black, Song font size 18 (25×25 pixels), on a 19-inch DELL monitor with a 1024 × 768 pixel resolution. Each character covered 0.74° of horizontal visual angle. Although participants read binocularly, only data from the movements of the right eye were analyzed.

Procedure

Participants were seated in front of the eye-tracker and were instructed to lean on chin and forehead rests to minimize head movements. A three-point horizontal calibration and validation were performed until maximum error was less than 0.2 deg. Recalibration and revalidation were conducted when necessary (i.e., when error increased beyond 0.2 deg). Each trial started with a fixation box (0.74 deg × 0.74 deg) at the location of the first character of the sentence. The sentence was presented on the screen once the participants successfully fixated the box. Participants were asked to click the left button of the mouse to end the display when they had finished reading each sentence.

Participants were informed that the sentences would contain some words that they might not know, and they were instructed to read and understand the sentence carefully, and as normally as they could. Two sets of 8 practice items were presented before the formal experiment to make sure that the participants were familiar with the experimental procedure. Next each of the sets of 8 experimental stimuli were presented in turn. Each set of eight sentences containing the same novel target word were presented in succession (i.e., they were presented in a blocked format). Participants were also required to use the mouse to click within pre-defined regions on the screen to provide the answers to the comprehension questions and to make their semantic category judgments when questions appeared on the screen. The experiments were split into four short sessions in order to avoid participants becoming fatigued and there was a break for participants to have a rest between each session. Each session lasted approximately 20 minutes.

Results

All participants scored 78% or higher on comprehension questions which followed 81 of the experimental sentences. Although the difference in scores between children and adults was significant, $t(74) = 5.37$, $p < 0.001$, the mean scores were high overall for both adults (91.6%) and children (85.9%), indicating that both groups of participants understood the sentences well even though each sentence contained an unknown word.

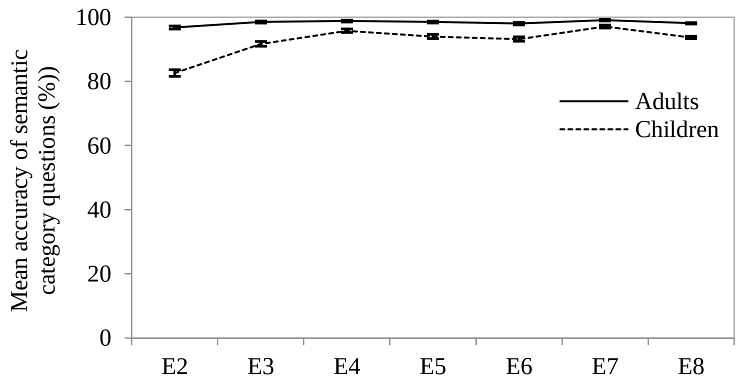

Figure 1. Mean accuracy for semantic category questions as a function of number of exposures in children and adults.

Performance on the four-choice semantic category questions, overall, was good in both groups of readers with high accuracy for each (see Figure 1; adult mean = 98.2%, children mean = 92.9%), though accuracy was higher for adults than children, $t(74) = 10.19$, $p < 0.001$. We also assessed change in response accuracy to the semantic category questions pertaining to the novel words over the learning episodes (2-8) for both adults and children. Adult’s semantic category accuracy was high from the outset (96%) and this level of performance maintained across the exposures (i.e., a ceiling effect for the adults). The children showed a slightly different pattern of performance. Initially, whilst accuracy was high at the outset, it was not as high as that observed for adults (82%), however, performance increased over the next two successive exposures before plateauing at ceiling performance. Across all exposures, children performed, on average, slightly below adults (see Figure 1). These results indicate that, compared with adult readers, children need more exposures to acquire aspects of meaning and semantic category information associated with a novel word acquired through natural reading.

Skipping rate and fixation duration analyses

Our primary objective in the current study was to examine saccadic targeting in relation to novel word learning during reading in children and adults. However, for completeness, we also briefly report results based on skipping rate and fixation duration analyses. Recall that a word's familiarity to the reader plays a critical role in the formation of oculomotor commitments within the CRM. This suggestion stems directly from the view that a reader's familiarity with a word increases with exposure and the degree of exposure is likely reflective of that word's eventual lexical frequency. Given that the time spent processing a word is inversely related to its frequency (for reviews, see Clifton et al., 2016; Rayner, 2009), we predicted that the degree of foveal processing difficulty that the reader might experience (as indexed by first fixation duration, gaze duration and total fixation duration measures) would be greater for the earlier encounters and should reduce as exposure to a novel word increases.

We conducted analyses of eye movement data for the target word across exposures. We report skipping rate, first fixation duration, gaze duration, and total reading time on novel words. These data are summarized in Figure 2. We excluded (a) fixations longer than 1200ms and shorter than

80ms (accounting for 0.7% of the eye movement data in total), and (b) trials for which blinks and tracker loss occurred on the target (accounting for 0.7% of the eye movement data in total).

Data were analyzed in the R computing environment (R Development Core Team, 2013) using linear mixed models (Baayen, Davidson, & Bates, 2008; Jaeger, 2008). We were interested in how eye movements on novel words changed across successive exposures reflecting novel word learning for child and adult readers. To explore this, we included fixed effects of *Exposure* (exposure sentence number: 1-8), *Age Group* (adults vs. children) and random effects of participants and items (novel words). We used linear mixed-effects models for continuous variables (i.e., data for the measures of first fixation duration, gaze duration and total fixation duration) and generalized mixed-effects models for binary variables (i.e., data for the measure of skipping rate) in which the participants and items were considered as random effects (Baayen et al., 2008). We began our analyses with the full random structure for the models (e.g., Barr, Levy, Scheepers, & Tily, 2013) that included slopes for the main effects and their interactions. The random structure was systematically simplified when failure to converge occurred, first by removing correlations between random effects, and then by removing their interactions. For each contrast we report beta values (*b*), standard error (*SE*), and *t* or *z* statistics. *T* or *z* values greater than 1.96 were considered significant at the 5% level. We performed log transformation of fixation duration data (i.e., three reading time eye movement measures) to reduce distribution skewing (Baayen et al., 2008). Our dataset and the R script used to analyze it are available through the Open Science Framework (https://osf.io/rztwx/).

Table 2 shows the results for these models. For the analyses of skipping rate, we found a reliable effect of *Exposure*, showing that as novel words became more familiar to the readers, they were more likely to be skipped in sentence reading. As noted, this effect is somewhat akin to word frequency effects observed for word skipping in normal Chinese reading (for a review, see Zang et al., 2011). Neither the effect of *Age group*, nor the interaction between *Age group* and *Exposure* were reliable, providing no evidence to indicate that skipping familiarity effects differed between children and adults across exposures.

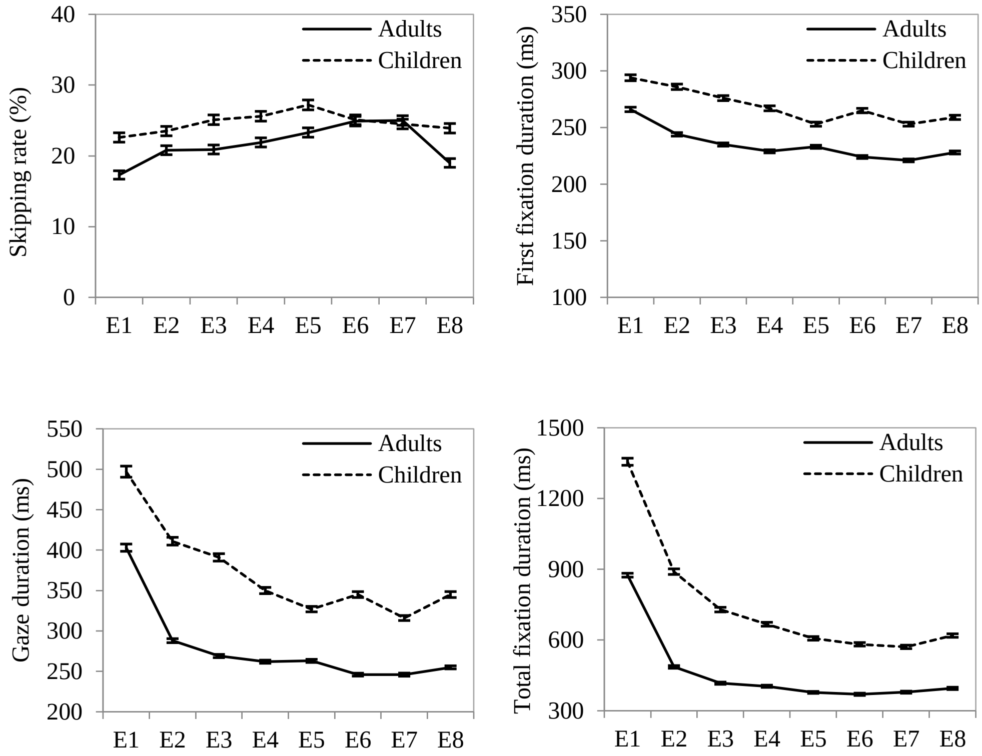

Figure 2. Skipping rate, first fixation duration, gaze duration, and total fixation duration on novel words over exposures in children and adults. Error bars represents standard errors.

Table 2. Results of models examining the effect of exposures, and age group on skipping rate and reading time eye movement measures.

		b	*SE*	*t/z*
Skipping rate	Intercept	-1.45	0.11	-13.74
	Age group	0.31	0.19	1.60
	Exposure	0.02	0.009	2.72
	Age group * Exposure	-0.03	0.02	-1.48
First fixation duration	Intercept	5.52	0.02	286.94
	Age group	0.10	0.04	2.67
	Exposure	-0.02	0.002	-7.72
	Age group * Exposure	0.001	0.003	0.20
Gaze duration	Intercept	5.80	0.03	177.67
	Age group	0.21	0.06	3.50
	Exposure	-0.04	0.004	-10.42
	Age group * Exposure	0.002	0.006	0.37
Total fixation duration	Intercept	6.58	0.04	160.88
	Age group	0.49	0.07	6.99
	Exposure	-0.09	0.007	-13.59
	Age group * Exposure	-0.009	0.008	-1.12

For the remaining three reading time eye movement measures (first fixation duration, gaze duration and total reading time), we found a reliable effect of *Age Group,* such that children made longer fixations than adults when processing novel words in sentence reading. This is consistent with the findings reported by Blythe et al. (2012), showing a basic age-related difference when processing novel words in natural reading. There was a reliable effect of *Exposure*, whereby both adults and children exhibited a clear downward reading time trend with increased exposures. This change was comparable between adults and children (there were no reliable interactive effects) and particularly pronounced during the earliest exposures to the novel word after which the effect flattened out. These results are consistent with the very basic stipulations of the CRM whereby decisions of when to move the eyes are determined by foveal processing difficulty. Processing difficulty was reduced in adults relative to children (due to adults' more proficient reading capability), and in relation to increased exposure to novel words (the words were acquired more readily by adults and became more familiar more rapidly, and therefore, they were easier to process). These results are also consistent with the findings from existing studies that demonstrate familiarity effects in novel word learning (e.g., Godfroid et al., 2018; Hulme et al., 2019; Joseph et al., 2014, 2018). Finally, the present results also illustrate how the most substantial improvements in word learning occur during the earliest exposures to a novel word (see Godfroid et al., 2018; Hulme et al., 2019). As can be seen from all of the data presented in Figures 1 and 2, based on eye movement indices of reading performance, the most dramatic changes occur within the first 4 or 5 exposures to a novel word, with exposures beyond this producing far less by way of improvement. Of course, here we are not suggesting that 4-5 exposures to a novel word are sufficient that a child might develop a fully specified semantic representation of word meaning. However, it does appear that after this level of exposure children (and to a greater extent, adults) feel comfortable to read and interpret novel words on the basis of a relatively shallow understanding of their meaning and the sentential context within which they appear. To us, this seems to be a good example of children "reading to learn" (Fukkink, 2005; Nagy, Anderson, & Herman, 1987; see also Blythe, 2014).

Initial landing position analyses

We turn next to the results that are the primary focus of our investigation, namely, the landing position data that reflect saccadic targeting to novel words. Recall that, in line with the CRM, we predicted that adults would target their initial saccades further into novel words than children, and that the distribution of landing positions for adults would lie to the right of that of the children.

These predictions arose due to the increased extent of the adults' perceptual span and their more proficient parafoveal processing relative to children.

We computed initial landing positions in relation to the number of characters from the beginning of the novel word. For our landing position distribution analyses, we defined each half character in the horizontal direction from the beginning to the end of the novel words as a zone (see Zang et al. 2013). In these analyses, therefore, each novel two-character word contained four zones (zone1: 0-0.5 char; zone 2: 0.51-1.0 char; zone 3: 1.01-1.50 char; zone 4: 1.51-2.0 char), with a value of 1 indicating the middle of a two-character novel word. We used linear mixed-effects models for continuous variables (i.e., data for mean initial landing positions) and generalized mixed-effects models for binary variables (i.e., data for initial landing position distributions) in which the participants and items were considered across random effects (Baayen et al., 2008).

Mean initial landing positions and corresponding distributions

In this section, we first report the comparisons of mean initial landing positions in children and adults on the basis of the entire initial fixation data set. For these analyses, given the theoretical specifications of the CRM, and the robust influence of launch distance on initial landing positions on words that has previously been demonstrated (see Engbert & Krügel, 2010; Hyönä et al., 2018; McConkie, Kerr, Reddix, & Zola, 1988; Nuthmann, Engbert, & Kliegl, 2005), we incorporated *Launch Distance* into the model as a covariate.

Based on the extremely different patterns of initial landing positions in single and multiple fixation cases, and based on the types of analyses that have been reported previously in the literature (see Yan et al., 2010; Zang et al., 2013), we also undertook further analyses in which we split the data set accordingly. Again, we incorporated *Launch Distance* into these analyses as a covariate and we report the age-related differences in mean proportions of single fixations. Note that the proportions of multiple fixation cases were the counterpart proportions to the single fixation cases (and, therefore, we do not report these). In these split analyses, we also report the age-related differences in mean initial landing positions for each data set separately. We also depict the distributions of initial fixations on novel words in single and multiple fixation cases, in order to determine whether the basic landing position distributions that have been reported for known words (Yan et al., 2010 & Zang et al., 2013) also occur for novel words.

For the proportion of single fixation cases, there was a reliable effect of *Age Group* (b = -0.99, SE = 0.16, t = -6.23). Adult readers made more single fixations on the novel words relative to children, indicating that adults process the novel words in sentence reading more proficiently than children. When we considered the entire data set of initial fixations on the target words, we found that adults initially fixated further into a novel word relative to child readers (b = -0.16, SE = 0.04, t = -3.79) (see Table 3). When we split the data into single and multiple fixation cases, we obtained similar patterns of results (single fixation cases: b = -0.10, SE = 0.03, t = -3.07; multiple fixation cases: b = -0.16, SE = 0.06, t = -2.43). On the assumption that word identification is more efficient when readers fixate more towards the middle of a word than towards its beginning, these results strongly suggest that child readers were less effective in targeting their initial fixations to more optimal positions within novel words relative to adults. Note also that these patterns of results for children and adults are very similar to those reported for known words (Yan et al., 2010; Zang et al., 2013), indicating that given 8 exposures to a novel word, based on mean initial landing position data, average saccadic targeting performance in reading is actually quite similar to that for words that are very well established in the mental lexicon. Perhaps the main point to note in relation to these landing position data is that the results are entirely consistent with the theoretical predictions we formed on the basis of the CRM.

Table 3. Number of observations, mean landing positions (in characters) for initial fixations (i.e., first fixations irrespective of the number of fixations on a word), single fixations, and first fixations in multiple fixation cases, as well as the proportion of single fixations in children and adults.

	Children	Adults
Mean initial fixation position	0.91(0.52)	1.03(0.55)
Number of observations	5262	5667
Single fixation position	1.04(0.49)	1.10(0.52)
Number of observations	3121	4412
Proportion of single fixations	59.3%	77.9%
First fixation position in multiple fixation cases	0.71(0.51)	0.81(0.60)
Number of observations	2141	1255

In relation to the distributions of initial fixation locations in single and multiple fixation cases, as can be seen in Figure 3a and 3b, broadly, children and adults showed similar patterns, though with some minor age-related differences. The distributions of initial landing positions for single fixation cases took the form of an inverted U-shape relationship, with more initial fixations landing towards the center of a novel word, and less towards the word beginning and word ending. In multiple fixation cases, the distribution of initial landing positions showed a negative curvilinear relationship, with more initial fixations towards the word beginning, fewer towards the word center, and fewest towards the end of the word (see Figure 3b). Again, these patterns for novel words were highly similar to those observed for known words as reported by, for example, Zang et al. (2013), indicating that the basic decisions regarding where to target initial saccades to known and novel words are quite similar during Chinese reading. The alignment of the present results with those for known word reading provide confidence in the suggestion that patterns of eye movements that occur when children (and adults) are developing their vocabulary via learning of new words embedded in texts (i.e., when they are reading to learn, Fukkink, 2005; Nagy et al., 1987; see also Blythe, 2014), do not differ radically from eye movements observed when reading text formed of words that are already well known.

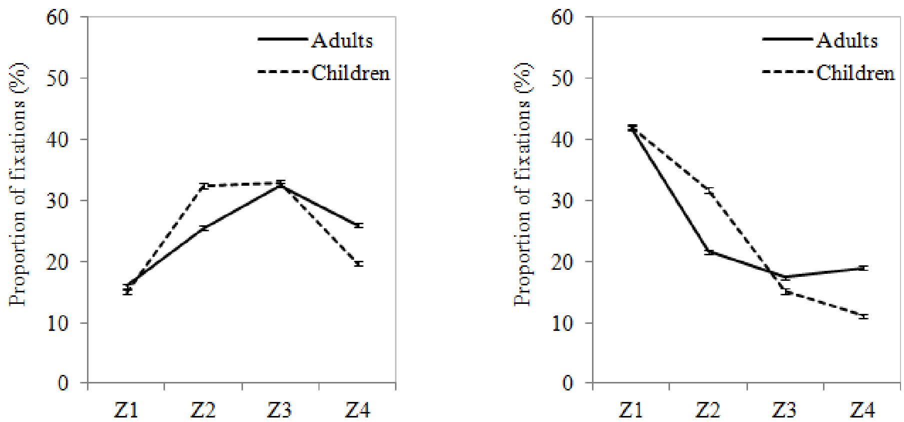

Figure 3a. Initial landing position distributions for single fixation cases

Figure 3b. Initial landing position distributions for multiple fixation cases

Figure 3. The distributions of initial fixations in children and adults.

Table 4. Fixed effect estimates for the distributions of initial fixations as a function of initial fixation zones in children and adults.

		Zone 1			Zone 2			Zone 3			Zone 4		
		b	*SE*	*Z*	*b*	*SE*	*Z*	*b*	*SE*	*Z*	*b*	*SE*	*Z*
The distribution of single fixation cases	Intercept	-3.46	0.10	-33.58	-1.45	0.07	-19.37	-0.21	0.05	-3.97	-0.24	0.10	-2.46
	Age group	-0.007	0.12	-0.06	0.41	0.10	4.14	-0.03	0.07	-0.43	-0.61	0.15	-4.00
	Launch distance	0.96	0.04	23.77	0.33	0.03	11.04	-0.35	0.03	-12.21	-0.76	0.04	-20.51
The distribution of first fixations in multiple fixation cases	Intercept	-1.69	0.14	-12.33	-0.45	0.10	-4.69	-1.34	0.11	-11.71	-1.19	0.18	-6.52
	Age group	0.20	0.20	1.03	0.48	0.13	3.65	-0.19	0.15	-1.24	-0.96	0.30	-3.21
	Launch distance	0.75	0.05	15.03	-0.45	0.05	-8.98	-0.22	0.06	-3.76	-0.43	0.07	-6.43

With respect to the age-related differences in initial landing position distributions in single and multiple fixation cases (see Table 4), the adults' initial fixations were less likely to land in zone 2, and more likely to land in zone 4 relative to child readers. The proportions of initial landing positions in zones 1 and 3 did not differ in children and adults. These results demonstrate that adult readers tended to make initial fixations further from the word beginnings compared with children, irrespective of whether they made a single, or multiple, fixations on a novel word. To be clear, whilst the nature of the landing position distributions (both for single and for multiple fixation situations) did not change between children and adults, the position of the entire distribution relative to the word did. Exactly as per the predictions of the CRM, there was a rightward translation in the distribution for adults relative to children. Thus, whilst the unique and quite distinct saccadic targeting characteristics associated with single as compared with multiple fixation situations that have been established in the literature are in place in children (as well as adults), it also remains the case that general differences (holding across all fixations) exist between children and adults. It appears that the saccadic control system in children is developed and refined in relation to the extent that quite different targeting parameters are applied contingent on whether an upcoming word receives a single, or multiple fixations. However, at a more general level, immaturity remains in relation to the development of the saccadic targeting system in children relative to adults, and overall therefore, targeting is more restricted in children than adults, and this might be due to their less efficient parafoveal processing.

Initial landing position effects as a function of launch distance

We conducted post hoc analyses of initial landing position data in relation to launch distance as a metric of parafoveal preview. These analyses are necessarily post hoc as it is impossible to experimentally manipulate launch site during natural reading. We wished to assess whether launch site distance modulated initial landing positions on novel words in children and adults' Chinese reading. The perceptual span is the area of effective vision from which useful information can be obtained during a fixation in reading (see Rayner, 1975). In Chinese reading, it extends 1 character to the left of the fixated character and up to 3 characters to the right (Inhoff & Liu, 1998; Yan, Zhou, Shu, & Kliegl, 2015). Given this, we categorized launch site as being either near (initial saccades launched from 0-1 characters to the left of a novel word), or far (initial saccades launched from 1-2 characters to the left of a novel word). We adopted these categories of launch site because they captured the majority of our data set with conditionalized data accounting for 70.9% of total initial landing position data[1]. Recall that, we predicted that readers would have a more effective preview of the upcoming novel word when saccades were targeted from near relative to far launch sites, and consequently, on average, readers should land further into the novel words when they launched their saccades from nearer than from more distant sites. Also, any such effect should be more pronounced and distinct in adults relative to children due to less efficient parafoveal processing in children.

[1] We also carried out analyses treating *Launch Distance* as a continuous variable. These analyses showed comparable effects to those reported here in which *Launch Distance* was dichotomized. Both sets of analyses showed robust interactive effects between *Age Group* and *Launch Distance* over all three data sets (all initial fixations, the single fixation data set, and the first of multiple fixations data set). Given the consistency between the two sets of analyses, and given that the dichotomized analyses were statistically, slightly more clear cut, we present the dichotomized analyses here (though to see the continuous analyses in full please visit https://osf.io/rztwx/). Additionally, note that we restricted our analyses to those saccades that were initiated from a two-character pre-target region (near launch sites from the character adjacent to the target, and distant launch sites from the second character from the target). We did this because we wished to consider saccades in children for which the launch and target characters fell within their perceptual span (which is known to be reduced relative to that of adult Chinese readers).

Table 5 shows the mean initial landing positions as a function of launch distance in children and adults. For the analyses of all initial fixation data (see Table 6), we found two main effects of *Age Group* (b = -0.24, SE = 0.05, t = -5.31) and *Launch Distance* (b = 0.28, SE = 0.01, t = 25.80). Initial fixations tended to land further into a novel word for adults than children, and for saccades launched from near than more distant sites. The interaction between *Age Group* and *Launch Distance* was also significant, b = -0.14, SE = 0.02, t = -6.49. In line with the theoretical predictions we formed on the basis of the CRM, both children and adults targeted initial saccades further into novel words when saccades were launched from near relative to far sites, but this effect was larger for adults (mean difference = 0.30) than for children (mean difference = 0.17). To us, this finding suggests that generally in the saccadic targeting system in reading, the mechanisms that capture contingencies between the target of initial saccades onto words and their relation to the position from which a saccade is launched are in place by the age of 9 years, that is, they are in place by a fairly young age.

Table 5. Mean initial landing positions as a function of launch distance (characters) and number of observations in children and adults.

	Children		Adults	
	Far	Near	Far	Near
All initial fixation positions	0.86(0.53)	1.03(0.47)	1.03(0.53)	1.33(0.46)
Number of observations	1944	1967	2246	1592
Single fixation position	1.02(0.47)	1.18(0.43)	1.11(0.48)	1.39(0.40)
Number of observations	1067	1194	1714	1281
First fixation position in multiple fixation cases	0.66(0.52)	0.81(0.46)	0.77(0.59)	1.09(0.58)
Number of observations	877	773	532	311

Table 6. Fixed effect estimates for mean initial landing positions in single fixation cases and multiple fixation cases as a function of launch distance.

		b	*SE*	*t*
All initial fixation positions	Intercept	1.11	0.02	44.43
	Age group	-0.24	0.04	-5.29
	Launch distance	0.26	0.02	15.06
	Age group * Launch distance	-0.13	0.03	-3.90
	Contrast 1 [a]	-0.35	0.02	-22.44
	Contrast 2 [b]	-0.21	0.02	-13.87
Single fixation position	Intercept	1.19	0.02	61.64
	Age group	-0.16	0.03	-4.51
	Launch distance	0.24	0.02	13.68
	Age group * Launch distance	-0.14	0.03	-4.00
	Contrast 1 [a]	-0.32	0.02	-19.83
	Contrast 2 [b]	-0.17	0.02	-9.37
First fixation position in multiple fixation cases	Intercept	0.93	0.03	26.89
	Age group	-0.24	0.06	-3.81
	Launch distance	0.25	0.03	9.15
	Age group * Launch distance	-0.14	0.06	-2.53
	Contrast 1 [a]	-0.32	0.03	-9.43
	Contrast 2 [b]	-0.19	0.02	-8.23

[a] Refers to the comparison of the initial landing position distributions launched from far versus near sites for adult readers; [b] Refers to the same comparisons for child readers.

Familiarity and initial landing positions during novel word learning

Finally, we examined whether the initial saccadic targeting to novel words changed with increased exposure to those words. Recall again that the CRM specifies that word frequency influences where the eyes will be targeted in relation to upcoming words, and we therefore predicted that initial landing positions should land further into a novel word as readers become more familiar with it via increased exposure to it. We also predicted that any such effect should be more pronounced in adults than children due to adults' more effective learning and more proficient parafoveal processing.

To ensure that we had a sufficient amount of data in each learning phase for meaningful analyses, we categorized the first four learning exposures for each novel word as being in *Learning Phase 1* (exposures 1 to 4), and the second four learning exposures as being in *Learning Phase 2* (exposures 5 to 8)[2]. We included fixed effects of *Learning Phase* (learning phase 1 vs. learning phase 2), *Age Group* (adults vs. children) and random effects of participants and items (novel words) in our LMMs. Again, as in our earlier analyses, we included launch distance in our model as a covariate.

Table 7 shows the mean initial landing positions on novel words in the two learning phases in children and adults. When considering all the initial landing position data, the effect of *Age Group* (b = -0.16, SE = 0.04, t = -3.80) was significant, showing that initial saccades were further into a novel word in adults (M = 1.04) than children (M = 0.91). The effect of *Learning Phase* was marginal (b = 0.03, SE = 0.02, t = 1.93), showing that there was a tendency for initial saccades to land further into a novel word in *Learning Phase 2* (M = 0.99) relative to *Learning Phase 1* (M = 0.96). The interaction of *Age Group* and *Learning Phase* was not significant (b = -0.02, SE = 0.02, t = -0.84).

[2] We also carried out analyses treating *Exposure* as a continuous variable. We observed quite similar patterns of results when *Exposure* was treated as continuous as when it was treated as a dichotomized variable. As with the dichotomized analyses, the interaction between *Age group* and *Exposure* was not significant for the analyses of the data set comprised of all initial fixations; also, this effect was statistically robust in our analysis of first fixations of multiple fixation cases. For our analyses of the single fixation cases, the interactive effect was marginal (t = 1.63) rather than fully significant when *Exposure* was treated as dichotomized (for the full set of analyses please visit https://osf.io/rztwx/).

Table 7. Mean initial landing positions as a function of learning phase (characters) and number of observations in children and adults.

	Children		Adults	
	Phase 1	Phase 2	Phase 1	Phase 2
All initial fixation positions	0.90(0.52)	0.92(0.53)	1.02(0.55)	1.05(0.55)
Number of observations	2656	2606	2901	2766
Single fixation position	1.05(0.47)	1.03(0.49)	1.08(0.51)	1.11(0.53)
Number of observations	1427	1694	2099	2313
First fixation position in multiple fixation cases	0.73(0.51)	0.70(0.52)	0.85(0.61)	0.73(0.59)
Number of observations	1299	912	802	453

For single fixation cases, there was an effect of *Age Group* (b = -0.10, *SE* = 0.03, t = -3.03), with initial fixations landing further into a novel word in adults than in children. There was no effect of *Learning Phase* (b = 0.01, *SE* = 0.01, t = 0.84), but there was an interaction between *Age Group* and *Learning Phase* (b = -0.05, *SE* = 0.02, t = -2.30). Adults' initial fixations tended to land closer to the word beginnings in *Learning Phase 1* than *Learning Phase 2* (b = -0.03, *SE* = 0.02, t = -1.98); while mean initial landing positions did not differ in the two learning phases for child readers (b = 0.02, *SE* = 0.02, t = 1.12). These results demonstrate that, for adult readers, when making single fixations on novel words, there was an influence of increased familiarity on saccadic targeting, but there was no evidence that a similar effect occurred in the children. These results indicate that with exactly the same degree of exposure to novel word stimuli, the influence of that increased exposure is substantially greater in adults than children. There are two possible reasons why this might be the case. First, in children relative to adults, a greater degree of exposure to novel words may be required for a comparable level of familiarity with those novel words to develop. If this suggestion is correct, then a critical issue concerns how indices, or representations, of familiarity (which will ultimately, presumably, be reflected in frequency metrics) are captured and develop during reading development. The second possibility is that the level of familiarity that develops across exposures to novel words in the current experiment is similar in both adults and children. However, the influence that such familiarity has on the computation of oculomotor metrics may be reduced in children relative to adults. If this is the case, then the issue of focus concerns the nature of change in oculomotor control mechanisms during reading development.

For multiple fixation cases, we observed an effect of *Age Group* (b = -0.14, SE = 0.06, t = -2.28), no effect of *Learning Phase* (b = -0.04, SE = 0.02, t = -1.72), and an interaction between the two factors (b = 0.08, SE = 0.04, t = 2.09). For adult readers, initial fixations were nearer to the beginnings of novel words in *Learning Phase 2* than *Learning Phase 1* (b = 0.10, SE = 0.03, t = 3.35), while as with the single fixation landing position data, such a difference did not occur for child readers (b = 0.006, SE = 0.02, t = 0.28). Clearly, as novel words became more familiar, when making two or more fixations on them during first pass reading, adult readers targeted their initial fixations closer to the word beginnings, before making a refixation on that word, whilst there was no evidence for comparable effects in children.

To us, it is worth considering the results from all three sets of analyses together (i.e., the analyses of the overall initial fixation data set, the single fixation analyses, and the analyses of the initial fixation data when two or more fixations are made on a word) in relation to our predictions and the theoretical account offered by the CRM. Initially, it might appear that the results from these three sets of analyses do not meet our predictions perfectly. Recall that we predicted that adults would target their saccades further into the novel words than children and that any such effect would be modulated by learning phase with reduced effects in the first compared to the second learning phase. Clearly, this pattern of effects did not occur when we analyzed the entire initial fixation set. However, the pattern did occur exactly as we predicted when we considered only the single fixation data. Saccades landed further into words in the second compared to the first learning phase in adults, with a far lesser such effect in children. Furthermore, a counterpart effect in exactly the opposite direction occurred when we considered the data set comprised of the first of multiple fixations on a word (i.e., saccades were targeted closer to the word beginning in adults in the later learning phase relative to the earlier learning phase with little by way of a similar effect in children). The directionally opposite counterpart effects across the analyses of the split data sets clearly produced a cancellation of observable differences in the overall analyses. Further, on the assumption that when readers make a single fixation on a word, the optimal position for a fixation is towards, or even slightly beyond its center (see Figure 3a), then presumably the single fixation analyses reflect more optimized saccadic targeting in the second compared with the first learning phase. This is exactly the pattern of effects that we observed for the adult participants (with little evidence of any such effects for the children). And we also know that when readers make two or more fixations on a word, then the preferred position at which to fixate the word is towards its beginning (see Figure 3b). Consistent with the suggestion that increased familiarity with words produced more optimized saccadic targeting, we found that in adults for refixation cases, their initial saccades were targeted even closer to word beginnings in the second relative to the first learning phase. Again, there was no evidence of such an effect in children. These differential patterns of saccadic targeting that are documented for single and multiple fixation cases on words naturally fall out of the word identification and corresponding word segmentation processes that operate in the CRM. Thus, if this interpretation is correct, then whilst the analyses of the entire data set provide little evidence of change with increased familiarity, the more detailed analyses of the data split into single versus multiple fixation categories provide results that appear to be quite consistent with the theoretical specifications of the CRM. To summarize, since in Chinese reading the preferred landing site on words is the word beginning in multiple fixation cases and the word center in single fixation cases (Yan et al., 2010; Zang et al., 2013), our three sets of analyses together suggest that as novel words become more familiar, adult readers modified saccadic targeting such that initial fixations moved slightly closer to preferred landing sites in order for optimized word processing in relation to different inspection patterns.

Discussion

In the present experiment, we adopted a relatively naturalistic approach to the investigation of the acquisition of novel Chinese written words in children and adults. Our objectives with this approach were to focus on potential differences in saccadic targeting that might exist between children relative to adults, and to assess how familiarity with novel words modulated any such effects. Based on our understanding of the recently developed CRM, we generated theoretical predictions in relation to differences between children and adults in foveal and parafoveal processing and how such processing differences (linked to changes in word familiarity) subsequently influenced saccadic targeting. We also explored for the first time the relationship between launch site and landing position effects during reading in children. Again, the theoretical motivation for these analyses derived directly from the stipulations of the CRM. Overall, our four lines of results were quite consistent with the predictions of the CRM and our experiment represents one of the first assessments of the model allowing for consideration of how it sits within a developmental context, and how it might operate in relation to novel word learning in Chinese reading.

Let us start by considering a very fundamental aspect of the results, namely, differences between adults and children in respect of when to move the eyes in Chinese reading. Here, the CRM stipulates that the decision of when to move the eyes is directly influenced by the time that is needed to process the fixated word, and the rate of activation of the fixated word is a primary driving force behind successive eye movements. Given that children are less skilled readers than adults, that is, they are less proficient in their linguistic operations relative to adults (see Reichle et al., 2013), we anticipated that children would take longer to process all the words, but particularly the novel words in our sentences relative to adults. Of course, such a prediction is very unsurprising and meets with a significant body of existing published evidence (see Blythe, 2014 for a review). Nonetheless, this prediction is very clear and our results based on the analyses of reading time measures were entirely aligned with the CRM, demonstrating that at a very basic level, the CRM can be, in principle, extended to offer an interpretive framework for (1) age-related differences in eye movement control during reading, and (2) processing of novel words in a natural reading situation.

We might also have expected to observe increased skipping rates in adults relative to children, however, basic word skipping differences were not significant in the present study. This is very likely due to the fact that our target words were novel and (certainly at the start of our experiment) completely unfamiliar. Thus, this result is actually quite unsurprising, and more importantly, as we discuss below, the word skipping measure did reflect sensitivity to increased familiarity as the novel words were repeatedly encountered through the course of the experiment.

Beyond basic processing time differences between adults and children, we obtained robust familiarity effects for our novel words that were quite comparable in nature between children and adults. The more familiar a novel word became to the reader, then the easier it was to process (shorter reading times) and the more likely it was to be skipped. Thus, entirely in line with the CRM, increased exposure to a novel word increases familiarity (which we consider to be formative in relation to a word's lexical frequency), resulting in reduced time necessary for it to be processed and identified. Importantly, the pattern of developing familiarity across exposures to novel words was very comparable between adults and children (though note, again, that overall, adults were more proficient than children), suggesting that the mechanism by which familiarity develops is very likely the same in adults and children. That is to say, there appears to be no qualitative difference in the mechanistic processes by which novel words are acquired in adults relative to children. Based on our interpretation and extension of the CRM to issues of development, such an assumption would be entirely reasonable given its specification of the role of word identification in relation to oculomotor commitments in reading. In our view, the CRM would require that novel words would be acquired by children and adults according to the same mechanistic process, albeit that process would operate less proficiently in children than adults. Again, these aspects of our results fit quite neatly with the specifications of the CRM.

Next, let us turn our attention to issues of where the eyes are targeted during reading. Here, the CRM stipulates that the saccadic targeting mechanism is processing-based, that is, decisions as to where to target saccades are made on the basis of how effectively upcoming characters and words are processed in the parafovea. The more effectively a word is parafoveally processed, the further the initial saccade will land into that word. On this basis, we used the CRM to formulate three predictions concerning age-related differences in initial saccadic targeting behavior between children and adults. First, given that children's parafoveal processing is less-mature, and therefore less proficient than adults', we predicted that at a general level, children might target their initial saccades less far into a novel word than adults and our mean initial landing position results were entirely in line with this prediction. Thus, our results offer support for a further basic and general prediction in relation to developmental differences that we derived from the CRM.

The second prediction related to saccadic targeting differences between children and adults that we derived from the CRM concerned the modulatory influence of saccadic launch site on landing positions. This relationship is well established for adult readers, but has never been systematically examined in relation to children's reading. As indicated earlier, according to the CRM, decisions concerning where to target the eyes are significantly influenced by the degree to which parafoveal text can be effectively processed, and parafoveal processing (as well as foveal processing in children is less proficient than in adults. Thus, a direct prediction of the CRM is that any modulatory influence of launch site on landing positions would be much greater in adults than children. Consistent with the predictions of the CRM, we found that initial saccades landed further into novel words when they were launched from near than when they were launched from more distant sites both for children and adults. However, this effect was greater in adults (0.27 character spaces for single fixation cases and 0.32 character spaces for multiple fixation cases) compared to children (0.16 character spaces for single fixation cases and 0.15 character spaces for multiple fixation cases). Our finding that adults adjust initial saccadic targeting to novel words on the basis of launch site distance to a greater degree than children supports the core assumption of the CRM that parafoveal processing plays a critical role in saccadic targeting in reading and that its reduced proficiency in children results in a reduced modulatory influence.

The third prediction that we derived from the CRM in relation to saccadic targeting was also related to differences between adults and children in their proficiency of parafoveal processing, and in particular, how with increased exposure to a novel word, its increased familiarity, might lead to more effective parafoveal processing which in turn might result in more pronounced initial landing position effects. As previously noted, it is well established in the literature that different patterns of landing position distributions are obtained in both children and adults when overall landing position data sets are split according to whether the initial fixation on an upcoming word is a single fixation, or instead is the first of multiple fixations on a word (Zang et al., 2013). In single fixation cases, readers optimally target towards the word center, whereas when initial fixations are the first of multiple fixations on the word, initially saccades are targeted to a word's beginning. If, as the CRM stipulates, there is a tight linkage between how effectively parafoveal words are processed and how saccades are subsequently targeted to those words, then as the familiarity of parafoveal words increases any saccadic targeting differences (in single and the first of multiple fixation cases) might become more pronounced. And beyond this, any such effects should be greater in adults than children given the differences in the proficiency of their parafoveal processing that we have already established. Again, our findings offered strong support for the CRM in that we observed the characteristic distributions of fixations for each category of initial fixation for both adults and children, but more importantly, these effects were greater in adults than children, presumably reflecting differences in parafoveal processing proficiency, and these effects became more pronounced in adults than children as the familiarity of the novel words increased. In our view, all of these effects are consistent with theoretical predictions that we might derive from the CRM when we adopt a developmental perspective and to this extent, in our view, the CRM provides a valuable theoretical framework not only for the consideration of eye movement control in adult Chinese reading, but also in relation to developmental differences in reading performance that exist between children and adults. Of course, we fully recognize that future work involving formal simulations by the CRM model will be necessary to establish the specific parameters that best fit the data from the current and future studies investigating these detailed aspects of eye movement control in children and adults. However, to our mind, the CRM does seem to offer significant explanatory power for the current, novel findings in relation to both adults and children.

Beyond these considerations, the fact that we found two important aspects of initial saccadic targeting behavior to be similar in children and adults is noteworthy and requires discussion. First, the distributions of initial landing positions on novel words were quite comparable in children and adults, with an inverted U-shape relationship when making single fixations and with a negative curvilinear relationship when making two or more fixations on novel words. Second, both children and adults were sensitive to launch site information when making initial fixations on novel words, such that they tended to target their initial saccades further into a novel word when saccades were launched from near relative to far sites. The similarity in these aspects of initial saccadic targeting behavior suggests that mechanisms for the basic decision of where to move the eyes in reading, and for computations of the relationship between launch sites and initial landing sites are fundamental, and are in place at a relatively young age in child readers. Note, however, that although there appears to be significant comparability in these relatively low level aspects of saccadic targeting in adults and children, we strongly suspect that not all aspects of saccadic targeting behavior will be similar. In particular, we consider that it is likely that saccadic targeting behavior associated with higher order aspects of language processing will be far less efficient and effective in children relative to adults. For example, consider a situation where an extended text, say a 15 sentence paragraph, is read and the reader makes a series of regressive saccades from the current sentence back to words and sections of text in previous sentences in order to coherently interpret the current sentence. Often such saccades are made on the basis of a mental representation of the spatial layout of the text in relation to linguistic content (see Inhoff, Kim, & Radach, 2019). Such eye movement behavior may often occur, for example, when ambiguity occurs, or a referring expression is encountered, or when an inference is necessary for text coherence. It is our contention that in these circumstances, it is likely that saccadic targeting behavior will differ between children and adults. We consider that this is likely because the low level saccadic targeting behavior that is comparable in adults and children is mediated, very largely, by visual processes, whereas saccadic targeting that subserves discourse interrogation is driven to a significant degree by linguistic processing. Low level eye movement control necessary for effective vision (see Findlay, Brown, & Gilchrist, 1997) is ordinarily active from birth (see Schöpf, Schlegl, Jakab, Kasprian, Woitek, Prayer et al., 2014), and oculomotor mechanisms and saccadic behavior required for effective vision are actually in place prior to birth (see Schöpf et al., 2014). Clearly, processing associated with linguistic interpretation that, arguably, very likely drives higher order aspects of saccadic targeting develops more slowly, and it is therefore likely that efficacy differences in such performance will occur. Further research is required to better understand the development of the relationship between different aspects of linguistic processing and saccadic targeting behavior, but at a theoretical level, we feel that the broad distinction we make here might be useful in guiding theorizing of such development into the future.

A final related point is also, perhaps, worth discussing. Traditionally, initial saccadic targeting decisions like those investigated in the present study are considered to be primarily influenced by visual characteristics of text, for example, word length and word spacing, see Hyönä & Bertram, 2011; Juhasz et al., 2008; O'Regan, 1979; Rayner, 1979). It is probably fair to say that, historically, the strength of argument for such factors affecting where to move the eyes has largely been driven by the broad recognition that word spaces, as visual markers, are a critical cue to word boundaries in English and other alphabetic languages. And the fact that during the early decades of eye movement research investigating reading, the vast majority of such studies focused on reading of English and other alphabetic languages. However, the comparatively recent increase in research investigating reading of unspaced non-alphabetic languages like Chinese has led to relatively well-established theoretical assumptions and premises being challenged. What is increasingly clear is that if a language affords an opportunity for some type of cue to be utilized in relation to the (visual and linguistic) units over which to operationalize parafoveal and foveal processing, as well as saccadic targeting (e.g., word spacing), then readers will capitalize on this and use it to guide processing decisions (e.g., Morris et al., 1990; Pollatsek & Rayner, 1982; Rayner et al., 1998). However, if a language does not offer such a cue (e.g., a lack of spaces in an unspaced language like Chinese), then that cue will carry little, or no, influence on decision formation, even when it is artificially introduced to text to provide meaningful information in respect of appropriate segmentations within a sentence (see Zang et al., 2013 for a good example of such a situation).

Let us return to the issue of how decision making develops in relation to saccadic targeting in the reading of unspaced languages (like Chinese). Several recent studies investigating reading in unspaced languages have shown that saccadic targeting might be influenced by language-specific factors (Kasisopa, Reilly, Luksaneeyanawin, & Burnham, 2013; Sainio, Hyönä, Bingushi, & Bertram, 2007). For example, in the reading of Thai (an unspaced, alphabetic language), position-specific frequencies of word boundary characters are generally considered as one critical determinant in saccadic targeting (Kasisopa et al., 2013). Also, a study on Japanese reading shows Hiragana and Kanji characters guide the eyes differentially (Sainio et al., 2007). In fact, even in spaced languages, some orthographic and linguistic factors also contribute to the decision of where to moves eyes in reading, such as orthographic regularity (in English and Finnish reading, see Hyönä, 1995; White & Liversedge, 2004), morphological structure (in Finnish and Uighur reading, see Hyönä et al., 2018, and Yan et al., 2014), and word frequency (in English, Finnish, and Uighur reading, see Hyönä et al., 2018; Rayner et al., 2006; Yan et al., 2014). These findings provide robust evidence that, in addition to visual factors such as word length and word spacing, higher-order factors also contribute to the guidance of saccades in reading. This suggestion also ties in quite neatly with the specifications of the CRM wherein word identification and word segmentation commitments, along with subsequent saccadic targeting decisions occur as part of a single process with no reference to visual demarcation cues. To be clear, we are suggesting here that there may be significant language specificity with respect to the computational systems that regulate saccadic targeting across languages. Alternative sources of information that influence decisions of where to move the eyes may be differentially weighted in the decision formation contingent on the nature of the orthography. And most pertinent to the present study, we can see that spacing appears to have a markedly different influence over such decisions in, say, English relative to Chinese reading.

In conclusion, the present study provides insight into saccadic targeting in children and adults during novel word learning in Chinese reading. We considered the specifications of the CRM from a developmental perspective and generated a series of theoretical predictions on this basis. Taken together, our results indicated that the systems controlling saccadic targeting showed differential maturity in children relative to adults. Broadly, mechanisms for the basic decisions of initial saccadic targeting, and mechanisms responsible for computation of initial landing sites relative to launch sites are in place early in children. However, mechanisms controlling initial saccadic targeting relative to launch sites and lexical familiarity appear to operate with functional efficacy that is developmentally delayed. Altogether the present findings fit neatly with our extrapolations of the CRM, suggesting that its framework and mechanistic account offer significant potential for future research investigating development of eye movement control in Chinese reading.

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