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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 44(44)

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Publication Date
2022

Peer reviewed

Does word boundary information facilitate Chinese sentence reading in children as beginning readers?

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Abstract

Written Chinese sentences consist of a series of characters without word boundary information. Here we examined whether word boundary information facilitated Chinese sentence reading comprehension in children as beginning readers. Primary grade 2-3 children read age-appropriate sentences with either spacing or shading contrast to mark word boundaries and answered related comprehension questions. Compared with regular sentences without word boundary information, spacing significantly impaired comprehension accuracy and reduced eye movement consistency during reading as measured in entropy, and the decrease in accuracy was associated with decrease in consistency of eye gaze transitions during reading. This result suggested that the performance impairment may be related to disturbances to their immature visual routine for reading that may be inconsistent with the provided word boundary information. In contrast, using shading contrast did not change children's reading performance or eye movement consistency. These findings have important implications for ways to facilitate reading development in children.

Keywords: Chinese sentence reading, word boundary, eye movement, EMHMM

Introduction

Words are the basic units for understanding sentences, and word processing skills are associated with sentence comprehension performance (Perfetti, 1985; 2007). For alphabetic languages such as English, spaces are used to help readers identify words in a sentence. In contrast, in some other languages, word boundary information in a sentence is either absent or less clear. For example, in Chinese, there is no word boundary indicator in written sentences, whereas in Arabic, word boundary information is sometimes less salient. It remains unclear whether providing clearer word boundary information in written sentences of these languages will facilitate reading comprehension. Some previous studies have attempted to examine this issue in adult readers. For instance, Leung et al. (2021) showed that in Arabic, adult readers had shorter fixation duration and longer saccade amplitude in reading Arabic sentences with double spacing between words than regular sentences; however their sentence reading time did not differ between the two conditions. Consistent with this finding, in Chinese reading, Bai et al. (2008) used spacing to mark word boundaries and found that participants had shorter fixation duration, longer saccade length, more progressive saccades, a larger number of fixations, and more regressive saccades than reading regular sentences with no spacing; however their reading time did not differ between the two conditions. In another experiment, they used background color contrast (grey and white) to highlight word boundaries instead of using spacing. They found no difference in either reading time or eye movement measures when reading in this condition as compared with regular sentences. These findings suggested that adult readers with abundant reading experience may have developed expertise in identifying word boundaries, and thus adding word boundary information during reading does not change their performance in reading time, although adding spacing did change their eye movement behavior.

In contrast, children learning to read may have poorer ability to identify word boundaries than adults, and thus word boundary information may be helpful. Lin and Lin (2017) examined spacing effect in 5th grade Chinese children, who were intermediate readers. They found that for typically developing children without reading difficulties, reading texts with spacing increased reading time per word as compared with reading regular texts with no spacing. This result suggested that spacing may impair intermediate readers' reading performance. However, in contrast to typically developing children, children with reading difficulties had shorter reading time per word when reading texts with spacing than regular texts after receiving some training in reading spaced texts. This result suggested that using space to mark word boundaries in Chinese reading may help intermediate readers with reading difficulties.

For beginning readers in Chinese, Zang et al. (2013) compared 3rd grade children and adults in reading regular and spaced texts in Chinese. They showed that both 3rd grade children and adults had shorter fixation duration and shorter

In J. Culbertson, A. Perfors, H. Rabagliati & V. Ramenzoni (Eds.), *Proceedings of the 44th Annual Conference of the Cognitive Science Society*.

reading time per word when reading spaced texts than regular texts; however, the difference in reading time per word was greater in 3rd grade children than in adults. This result suggested that using spacing to mark word boundaries may make young children's reading more efficient. Note however that Zang et al. (2013) did not examine comprehension accuracy. Thus, it remains unclear whether word boundary information facilitates young beginning readers' reading comprehension. Also, previous eye movement studies focused on summary statistics of local eye movement behavior, such as fixation duration and frequency of regressive saccades. These measures could not adequately capture changes in overall eye movement planning behavior due to word boundary information. We speculated that providing word boundary information during sentence reading, especially when using spacing, might interfere with their eye movement planning and visual routines for reading, resulting in decrease in eye movement consistency. This may affect their reading performance including comprehension accuracy.

To test this hypothesis, we conducted an eye tracking study of Chinese sentence reading with primary grade 2 and 3 beginning readers. We examined how using spacing (i.e., spacing condition) or shading contrast (black and grey; highlighting condition) to mark word boundaries influenced children's reading performance in both reading time and comprehension accuracy, and eye movement behavior including summary statistics and eye movement consistency. To quantify participants' eye movement consistency during reading, we used a machine-learning model-based approach, Eye Movement analysis with Hidden Markov Models (EMHMM; Chuk et al., 2014). In this approach, an individual's eye movement pattern was summarized using an hidden Markov model (HMM) in terms of regions of interest (ROI) and eye gaze transition probabilities among the ROIs. Thus, it takes both where the participant looks and the *order* of where the participant looks into account. We then use entropy of the HMM to quantify the participant's eye movement consistency during reading (e.g., Hsiao, Chan et al., 2021; Hsiao, An et al., 2020). Entropy is a measure of predictability; higher entropy indicates lower consistency (Cover & Thomas, 2006). According to previous studies, we speculated that in addition to reduced fixation duration, spacing may disturb these young beginning readers' eye movement planning as reflected in decreased eye movement consistency/increased entropy, and this may affect their comprehension accuracy. To examine whether the effect of word boundary information on reading performance, if any, was related to children's language proficiency and cognitive abilities relevant to reading, we also measured children's word reading and dictation ability, non-verbal IQ, and the ability to efficiently name highly familiar symbols (i.e., rapid automatized naming, or RAN; Ding et al., 2010; Shum & Au, 2017). We speculated spacing effect in reading performance may be particularly related to eye movement consistency change instead of children's Chinese proficiency or cognitive abilities.

Methods

Participants

Thirty-four grade 2-3 primary school students in Hong Kong were recruited (27 males; 10 grade-two students). According to a power analysis (G*Power, Faul et al., 2007), a sample size of 34 was needed to acquire a medium effect size (d = .5), with .05 alpha and 80% power in a paired sample t-test for examining highlighting or spacing effect.

Materials

Participants performed a Chinese sentence reading task, followed by a list of Chinese proficiency and cognitive ability tests that were found to be related to reading performance (e.g., Catts et al., 2008; Hage & Stroud, 1959; Logan et al., 2011; Arnell et al., 2009).

Chinese sentence reading A total of 60 age-appropriate sentences for primary three students were designed, based on the *Lexical Items with English Explanations for Fundamental Chinese Learning in Hong Kong Schools* (Education Bureau, 2008) and Territory-wide System Assessment (TSA) question papers. The length of each sentence was between 4 to 19 characters and between 3 to 11 words. Each stimulus was followed by a yes-no comprehension question. Their sentence reading time, and accuracy and reaction time (RT) of the comprehension questions were recorded. Each sentence was presented in one of three presentation conditions: normal, spacing, and highlighting (Figure 1), with 20 sentences in each condition. In the normal condition, normal unspaced sentences were presented. In the spacing condition, sentences were presented with space between words. In the highlighting condition, words in a sentence were presented in alternating black and grey so that word boundaries were marked by shading contrast. Word segmentation was performed according to the *CKIP Chinese Word Segmentation System of Taiwan Academia Sinica* (Lin & Lin, 2017). Sentences presented in the three conditions were matched in sentence length and structure and were counterbalanced across participants. Participants performed three blocks of reading task with one for each presentation condition. The block order was counterbalanced across participants. Stimuli in each block were presented in a random order.

(a) Normal condition.

鴨子在湖裏游來游去。

(b) Spacing condition.

鴨子 在 湖 裏 游來游去。

(c) Highlighting condition.

鴨子在湖裏游來游去。

Figure 1: An example sentence presented in three conditions.

Chinese proficiency A Chinese word reading task and a Chinese dictation task were administered. In Chinese word reading, 80 two-character words were chosen from Grade 1 to 4 Chinese textbooks used in the local curriculum (Chen et al., 2011), with 20 words from per grade. Participants were required to read them out accurately as fast as they could. Their accuracy and RT were recorded. In Chinese dictation, 32 two-character words were presented verbally from a recording. After hearing each word, participants wrote down the word on the answer sheet. If the participant could not write the characters correctly for consecutively 16 times (8 words), the experimenter ended the task. Participants' accuracy was measured. Stimuli in both tasks were validated by three qualified primary Chinese teachers as appropriate to primary 2 and 3 students.

Nonverbal IQ The Raven's Standard Progressive Matrices (RSPM; Raven, 1958) Set A to C were used to measure participants' nonverbal IQ (Education Bureau, 1986).

Rapid Automatized Naming (RAN) Following the Digit Rapid Naming subtest from the *Hong Kong Test of Specific Learning Difficulties in Reading and Writing for Primary School Students* (HKT-P(II); Ho et al., 2007), a total of 40 digits (randomly drawn from five digits 2, 4, 6, 7, and 9) were printed on a white A4 paper in a 5 x 8 matrix. Participants were asked to name the digits as fast as they could, and a stopwatch was used to record the total naming time. They repeated this procedure once. The average time (the nearest 1/100 second) was calculated.

Design

All Chinese stimuli were displayed in Microsoft Standard Kai font, which was a commonly used font at local primary schools. The presented size of a character was determined according to the size adopted in TSA question papers, 5 mm x 5 mm. Under a normal reading distance of 30 cm, each character subtended 1° of visual angle. During the experiment, the viewing distance was 55 cm. Thus the presented size of each character was 1 cm x 1 cm so that each character spanned about 1° of visual angle. In the spacing condition, the space between words was the half width of a character (i.e., 5 mm). Stimuli were presented in black with a white background on a 17' CRT monitor with a resolution of 1280 x 960. Participants' eye movements were recorded using an EyeLink 1000 Plus eye tracker. A chinrest was used to reduce participants' head movement.

The design consisted of an independent variable, presentation condition (normal vs. spacing vs. highlighting). Repeated-measures ANOVA was used. In addition, we conducted planned comparisons using paired t-test to examine spacing (spacing vs. normal) and highlighting effect (highlighting vs. normal). The dependent variables were reading performance including reading time, comprehension accuracy and RT, and eye movement measures including number of fixations, average fixation duration, average saccade length, regression rate, skipping rate, and eye movement consistency as measured in entropy using EMHMM (please see the EMHMM section below). Correlation was used to examine whether any observed spacing/highlighting effect in reading performance was associated with Chinese proficiency, cognitive ability, or eye movement measures.

Procedure

In the sentence reading task, participants started with a practice block with 6 trials, followed by three experimental blocks. The experimenter ensured that participants understood the task and answered all practice trials correctly before they proceeded. Each experimental block had 22 trials, with the first two trials being practice trials. At the beginning of each block, a nine-point calibration procedure was performed. Each trial started with a solid dot at the screen center for drift correction, followed by a cross on the left side of the screen. Participants were instructed to look at the cross when it appeared. After a fixation was detected at the cross, the cross disappeared, and the target sentence was presented 1° of visual angle to the right of the cross. Participants pressed the space bar to indicate finishing reading the sentence. The corresponding yes-no question then appeared, and participants pressed the button "F" and "J" for correct and incorrect answers respectively (Figure 2).

After the sentence reading task, participants completed the Chinese word reading and dictation, non-verbal IQ, and RAN tasks.

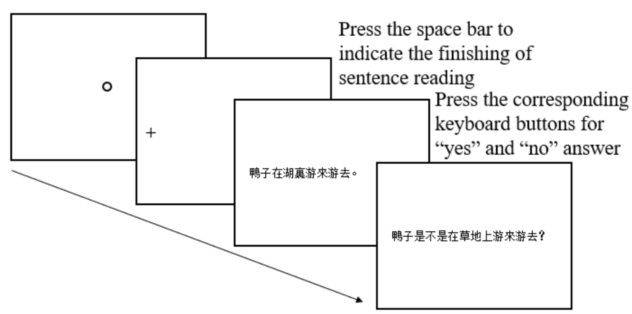

Figure 2: Procedure of sentence reading task.

EMHMM

EMHMM (Chuk et al., 2014) was used to summarize a participant's eye movement behavior during reading using a hidden Markov model (HMM, a type of time-series statistical model in machine learning). The hidden states of the HMM corresponded to the participant's regions of interest (ROIs). Eye gaze transitions among the ROIs were summarized into a transition matrix with the prior indicating the probability of the first fixation landing in each of the ROIs. We then quantified the participant's eye movement consistency using entropy of the HMM (e.g., Hsiao, Chan et al., 2021; Hsiao, An et al., 2020). To examine the contributions from participants' initial fixation preference (i.e., the prior) and the gaze transition patterns among the ROIs separately, in addition to overall entropy of the HMM, we measured marginal entropy of the first fixation and steady-state conditional entropy (where the transitions were not affected by the prior).

Here we used two different EMHMM modeling approaches to quantify participants' eye movement consistency. In the first approach, we used the original EMHMM where ROIs were discovered in a data-driven fashion (e.g., Chuk, Crookes et al., 2017; Chuk, Chan et al., 2017; Chan et al., 2018; Zhang et al., 2019; Chan, Barry et al., 2020; Chan, Suen et al., 2020; An & Hsiao, 2021; Hsiao, An, et al., 2021; Lee et al., 2021). More specifically, we summarized a participant's eye movement pattern in a presentation condition using an HMM including person-specific ROIs and transition probabilities among the ROIs estimated from the participant's data. The Variational Bayesian Expectation Maximization algorithm (Bishop, 2006) was used to determine the optimal number of ROIs for each HMM from a preset range 1 to 11 (since the maximum number of words in a sentence was 11). This measure of entropy reflected both individual differences in fixation location/ROI choice and gaze transition among the ROIs.

In the second approach, following previous eye movement studies on reading where ROIs are typically pre-defined to be on individual words with the assumption that words are the basic functional units of sentence processing (e.g., Perfetti, 1985), we predefined an ROI on each word in a sentence and summarized the participant's gaze transition probabilities among words using an HMM for each sentence (cf. Chuk et al., 2020; Cho et al., 2022a; 2022b; 2022c). We then summed over the entropies of the HMMs in each condition. This measure of entropy reflected only gaze transitions among words but not fixation location/ROI choices.

During training, each model was trained for 300 times, and the model with the highest data log-likelihood was used.

Results

Behavioral results

Participants' Chinese sentence reading performance was shown in Figure 3. The repeated-measure ANOVA revealed no presentation condition effect in sentence reading time, $F(2, 66) = .392$, $p = .677$, or in comprehension RT, $F(2, 66) = .210$, $p = .811$. In comprehension accuracy, a significant condition effect was observed, $F(2, 66) = 3.93$, $p = .024$, $\eta_p^2 = .106$: participants had higher accuracy in normal than spacing condition, $t(33) = 2.69$, $p = .029$, $d = .461$. The planned comparison for spacing effect showed that participants had higher comprehension accuracy in normal than spacing condition, $t(33) = 2.693$, $p = .611$, $d = .462$; this effect was not observed in sentence reading time, $t(33) = -.470$, $p = .641$, or comprehension RT, $t(33) = -.421$, $p = .676$. The planned comparison for highlighting effect showed no effect in sentence reading time, $t(33) = -.842$, $p = .406$, comprehension accuracy, $t(33) = 1.462$, $p = .153$, or comprehension RT, $t(33) = -.546$, $p = .589$.

Eye Movement Measures

In fixation duration, a significant condition effect was observed, $F(2, 66) = 7.48$, $p = .001$, $\eta_p^2 = .185$ (Figure 4a); in planned comparisons, participants had shorter fixation duration in spacing than normal condition, $t(33) = -3.683$, $p = .002$, $d = -.632$, whereas no highlighting effect was observed. In average saccade length, a significant condition effect was observed, $F(2, 66) = 28.9$, $p < .001$, $\eta_p^2 = .467$ (Figure 4b); in planned comparisons, participants had longer average saccade length in spacing than normal condition, $t(33) = 6.514$, $p < .001$, $d = 1.117$, whereas no highlighting effect was observed. In regression rate, a significant condition effect was observed, $F(2, 66) = 3.46$, $p = .037$, $\eta_p^2 = .095$ (Figure 4c); in planned comparisons, no spacing effect was observed; however, a highlighting effect was observed, where participants had higher regression rate in normal than highlighting condition, $t(33) = 2.392$, $p = .023$, $d = .410$. No condition effect was observed in fixation number or skipping rate.

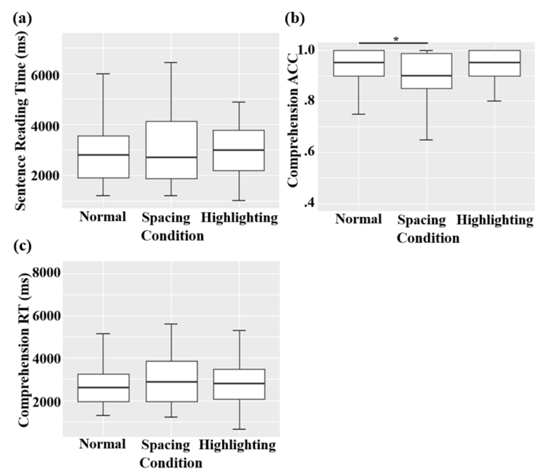

Figure 3: Behavioral results: (a) Sentence reading time. (b) Comprehension accuracy. (c) Comprehension RT.

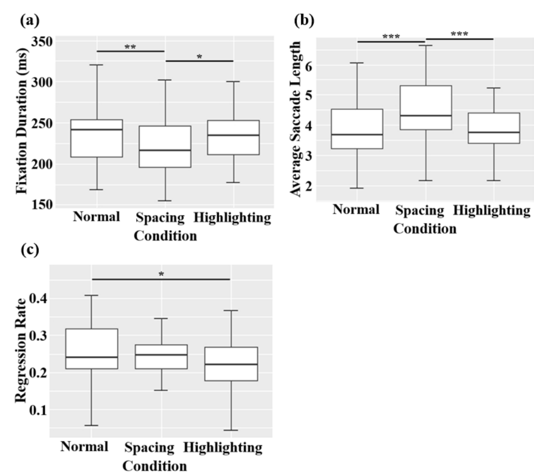

Figure 4: Traditional eye movement behaviors: (a) Fixation duration. (b) Average saccade length. (c) Regression rate.

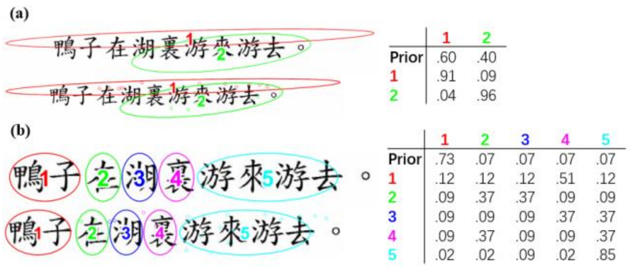

Figure 5: (a) Example model using the original EMHMM approach. (b) Example model of one sentence using the approach with predefined ROIs on individual words.

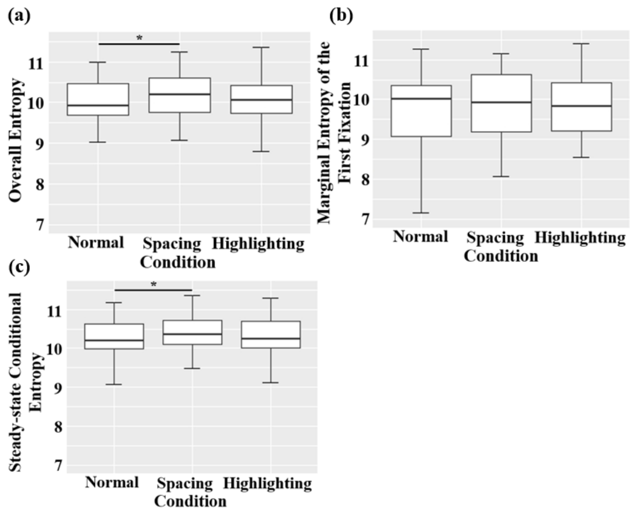

Figure 6: Entropies results: (a) Overall entropy, (b) Marginal entropy of the first fixation, and (c) steady-state conditional entropy using the original EMHMM modeling approach.

Entropies

Figure 5 shows example models resulting from the two modeling approaches. When using the original EMHMM approach, in overall entropy, no significant condition effect was observed, $F(2, 66) = 2.39$, $p = .099$. However, planned comparisons showed a significant spacing effect: participants had lower overall entropy in the normal than spacing condition, $t(33) = -2.560$, $p = .015$, $d = -.439$ (Figure 6a). In marginal entropy of the first fixation, no significant condition effect was observed, $F(2, 66) = .418$, $p = .660$, and no spacing or highlight effect was observed in the planned comparisons (Figure 6b). In steady-state conditional entropy, a significant condition effect was observed, $F(2, 66) = 3.23$, $p = .046$, $\eta_p^2 = .089$ (Figure 6c). Planned comparisons showed that participants had lower steady-state conditional entropy in the normal than spacing condition, $t(33) = -2.42$, $p = .021$, $d = -.416$. No highlighting effect was observed in any of the entropy measures. Together these results suggested that spacing decreased children's gaze transition consistency in sentence reading.

When using the pre-defined ROI EMHMM, no condition effect was observed in either marginal entropy of the first fixation, $F(2, 66) = .578$, $p = .564$, overall entropy, $F(2, 66) = .834$, $p = .439$, or steady-state conditional entropy, $F(2, 66) = .811$, $p = .449$. The planned comparisons also did not show any significant spacing or highlighting effect.

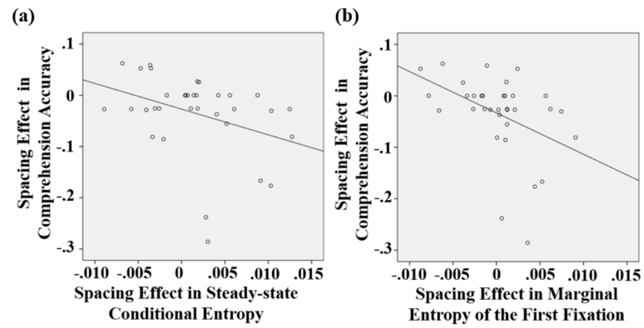

Figure 7: (a) Correlation between spacing effect in comprehension accuracy and spacing effect in steady-state conditional entropy, and (b) correlation between spacing effect in comprehension accuracy and spacing effect in marginal entropy of the first fixation calculated using the pre-defined ROI approach.

Our analysis above suggested that spacing impaired children's comprehension accuracy, shortened fixation duration, and decreased eye movement consistency during reading. To examine whether their performance impairment was associated with decrease in fixation duration or eye movement consistency, we defined spacing effect as the normalized difference in accuracy/duration/entropy between spacing and normal condition as (S – N)/(S + N), where S referred to spacing condition accuracy/duration/entropy and N referred to normal condition accuracy/duration/entropy. First, we found that none of the Chinese proficiency and cognitive ability (IQ and RAN) measures, or spacing effect in fixation duration, was associated with spacing effect in accuracy. Using the entropy measures from the original EMHMM method, after we partialed out the cognitive ability and Chinese proficiency factors, spacing effect in accuracy was marginally correlated with spacing effect in overall entropy, $r(27) = -.353$, $p = .061$, but not with marginal entropy of the first fixation, $r(27) = -.308$, $p = .104$, or change in steady-state conditional entropy, $r(27) = -.219$, $p = .253$. When we used entropy measures from the pre-defined ROI approach, spacing effect in accuracy was correlated with spacing effect in steady-state conditional entropy, $r(27) = -.389$, $p = .037$ (Figure 7a), and spacing effect in marginal entropy of the first fixation (Figure 7b), $r(27) = -.411$, $p = .027$: larger performance impairment due to word spacing was correlated with larger increase in both steady-state conditional entropy and marginal entropy of the first fixation. This effect was not observed in overall entropy, $r(27) = .016$, $p = .934$. Together these results suggested that children's impaired comprehension performance in reading sentences with space between words was particularly related to decrease in eye movement consistency due to the added space between words.

Discussion

Here we examined how word boundary information affected Chinese sentence reading performance in children as beginning readers. We tested the hypotheses that using spacing to mark word boundaries could interfere with eye movement planning for visual routines, and this may impair reading performance. Consistent with our hypotheses, we found that children had shorter fixation duration, lower comprehension accuracy, and lower eye movement consistency in the spacing than normal condition, and the spacing effect in eye movement consistency was correlated with spacing effect in comprehension accuracy. In particular, this comprehension accuracy impairment was associated with consistency in eye gaze transitions among words, as measured in entropy based on the fixed ROI approach where each ROI corresponded to a word. It is possible that young children have not developed a mature visual routine to extract meanings according to word boundaries when attempting to understand a sentence. The spacing forced them to follow clearly defined word boundaries, which may be inconsistent with their existing visual routines or knowledge of sentence structure and vocabulary. Indeed, recent studies on perceptual expertise have suggested that experts of a visual task typically demonstrated a more consistent eye movement pattern than beginners, and beginners will gradually develop a more consistent visual strategy during learning. For example, adult English readers are found to have more consistent refixation behavior when reading long words than children (Joseph et al., 2009). In problem solving, experts show higher eye movement consistency than novices (Chanijani et al., 2016). In face recognition, children's eye movement consistency increased with age and predicted recognition performance (Hsiao et al., 2020). Thus, these young beginning readers were unlikely to have developed a consistent visual routine that followed well with word boundary information. Disturbances in sentence parsing or syntactical analysis may have confused them, resulting in poorer comprehension.

In contrast, we found that using shading contrast to mark word boundaries did not influence children's comprehension accuracy, reading time, or eye movement consistency, although it reduced their regression rate. Using shading contrast to mark word boundaries did not change the sentence configuration, or relative distances between words in a sentence. Thus, it may have led to less disturbances in eye movement planning and syntactic analysis. However, although it reduced regression rate, it did not enhance children's reading performance.

The finding that children had shorter fixation duration in the spacing than normal condition was consistent with previous studies (e.g., Zang et al., 2013). Nevertheless, no difference in sentence reading time was observed between the two conditions; this result was consistent with previous studies with adults (e.g., Bai et al., 2008). Oralova and Kuperman (2021) examined the effect of amount of spacing in Chinese texts on adult readers' reading performance. They showed that when spaces were inserted between every two words, participants' sentence reading time did not differ from the normal condition without spacing. In contrast, when spaces were placed only at locations that at least 90% of the raters agreed to place a word boundary, they had shorter sentence reading time than the normal condition. In Chinese, word boundaries in a sentence are not as clearly defined those in alphabetic languages due its logographic nature. These results suggest that placing space only at locations that create meaningful character clusters to the reader may better facilitate Chinese sentence reading speed than placing space between every two words. Thus, it is possible that children's reading speed can be facilitated by placing space only at locations that are consistent with their existing knowledge of sentence structure and vocabulary. Future work will examine this possibility.

Note that here we did not manipulate sentence difficulty, as all sentences were appropriate for our participants' age according to standardized teaching materials. Thus, it remains possible that spacing may facilitate children's comprehension for easier or more difficult sentences, and the modulation effects may also depend on children's age and reading level. For instance, Wang (2015) found that 4^{th} grade children (intermediate readers) had higher comprehension scores in the spacing condition than normal condition when reading difficult texts but not easy texts. Thus, children with a higher reading level may have better syntactic knowledge and visual routines that better match word boundaries, and thus spacing may help them analyze sentences with more complicated structures, leading to better comprehension for more difficult sentences.

In conclusion, here we showed that using spacing to mark word boundaries in Chinese sentences impaired young beginning readers' reading comprehension accuracy but did not affect their reading time. The impairment in comprehension accuracy was associated with decrease in consistency of eye gaze transition behavior among words during reading. This result suggested that the performance impairment may be related to their immature visual routines for reading that may be inconsistent with the word boundary information, which may consequently interfere with their syntactic analysis. In contrast, using shading contrast between words to mark word boundaries did not influence either reading time or comprehension accuracy, although it decreased regression rate. Thus, using spacing to mark word boundaries may not facilitate young beginning readers' reading performance. Rather, it may impair their performance due to disturbances to their immature visual routines for reading. This finding has important educational implications for developing learning instructions to facilitate children's reading development.

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