# Visual span and cognitive factors affect Chinese reading speed

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**Visual span, which is the number of recognizable letters seen without moving the eyes, has been proven to impose a sensory limitation for alphabetic reading speed (Chung, 2011; Chung, Legge, & Cheung, 2004; Lee, Kwon, Legge, & Gefroh, 2010; Legge, Ahn, Klitz, & Luebker, 1997; Legge, Hooven, Klitz, Stephen Mansfield, & Tjan, 2002; D. Yu, Cheung, Legge, & Chung, 2010). However, little is known about the effects of visual span on Chinese reading performance. Of note, Chinese text differs greatly from that of the alphabetic writing system. There are no spaces between words, and readers are forced to utilize their lexical knowledge to segment Chinese characters into meaningful words, thus increasing the relative importance of cognitive/linguistic factors in reading performance. Therefore, the aim of the present study is to explore whether visual span and cognitive/linguistic factors have independent effects on Chinese reading speed. Visual span profiles, cognitive/linguistic factors indicated by word frequency, and Chinese sentence-reading performance were collected from 28 native Chinese-speaking subjects. We found that the visual-span size and cognitive/linguistic factors independently contributed to Chinese sentence-reading speed (all *p*s $<$ 0.05). We concluded that both the visual-span size and cognitive/linguistic factors represented bottlenecks for Chinese sentence-reading speed.**

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## Introduction

Visual span refers to the limited number of letters that can be recognized reliably without moving the eyes (Legge, Ahn, Klitz, & Luebker, 1997). It has been documented that larger visual span size is significantly correlated with faster alphabetic reading speed, implying the visual span may be a sensory limitation on alphabetic reading speed (Chung, 2011; Chung, Legge, & Cheung, 2004; Lee, Kwon, Legge, & Gefroh, 2010; Legge et al., 1997; Legge, Hooven, Klitz, Stephen Mansfield, & Tjan, 2002; D. Yu, Cheung, Legge, & Chung, 2010). Previous studies were mainly focused on the effects of visual span size for alphabetic writing systems (Chung, 2011; Chung et al., 2004; Lee et al., 2010; Legge et al., 1997; Legge et al., 2002; D. Yu et al., 2010). However, little is known about its effects on Chinese reading performance. Of note, Chinese text differs greatly from that of alphabetic writing systems, particularly as there are no spaces between words, and readers are forced to utilize their lexical knowledge to segment Chinese characters into meaningful words. This increases the relative importance of cognitive/linguistic factors in Chinese reading performance. Therefore, the purpose of our study is to investigate whether visual span and cognitive/linguistic factors have independent effects on Chinese reading performance.

It has been proposed that sensory, oculomotor, and cognitive/linguistic factors affect reading speed (Legge et al., 2007). According to Legge et al.'s (1997) visual-span hypothesis, only a limited number of letters can be recognized accurately in a glimpse. The visual-span size can be considered as the width of a window for reliably recognizing the limited number of letters in the visual field, and reading can be considered as a process to gain text information through moving this window. In addition, Legge, Mansfield, and Chung (2001) adopted the trigram letter-recognition task to evaluate the visual-span size and found a strong correlation between reading speed and the visual-span size. It has been indicated that the mechanism underlying the correlation between the visual-span size and reading speed may be the sensory limitation on each fixation (Legge et al., 2001). Recent studies suggest that expanding the visual-span size through perceptual learning leads to the attendant improvement in reading speed (Chung et al., 2004; Lee et al., 2010; D. Yu et al., 2010; Zhu et al., 2019). This is consistent with the notion that the visual-span size sets a limitation on the sensory load for each fixation and, therefore, mediates reading speed.

There are many differences between Chinese and alphabetic writing systems such as English (Rayner, Li, Juhasz, & Yan, 2005; Wei, Li, & Pollatsek, 2013). Chinese script is made up of more than 2,500 frequently used characters compared to 26 letters in English. Furthermore, characters in Chinese script have more visual and lexical information than letters in English. Various numbers of strokes are arranged into radicals, which are further arranged into two-dimensional, hierarchically arranged, and boxlike characters (Figure 1). These features make processing more difficult (L. Yu, Zhang, Priest, Reichle, & Sheridan, 2017). In addition to the marked visual differences between English and Chinese, Chinese script is formed by an array of equally spaced, boxlike characters (Figure 1), and English text is written with spaces between words. The lack of clear word boundaries in Chinese script makes identifying words and lexical processing more difficult. Thus, Chinese readers rely more on cognitive/linguistic factors to demarcate the boundaries of meaningful words. Even though Wang, He, and Legge (2014) documented that the visual-span size decreased as Chinese characters' complexity increased, they did not explore the effects of the visual-span size on Chinese reading speed. Given the evidence that the visual span hypothesis extends from letters to facial recognition (He et al., 2015) and from English to Korean writing systems (He, Kwon, & Legge, 2018), it may be a common sensory constraint in recognizing different types of patterns. Therefore, it is predictable that the visual span limit also applies to the recognition of Chinese characters during Chinese reading.

As indicated, cognitive/linguistic factors also affect reading speed (Legge et al., 2007). Word frequency is

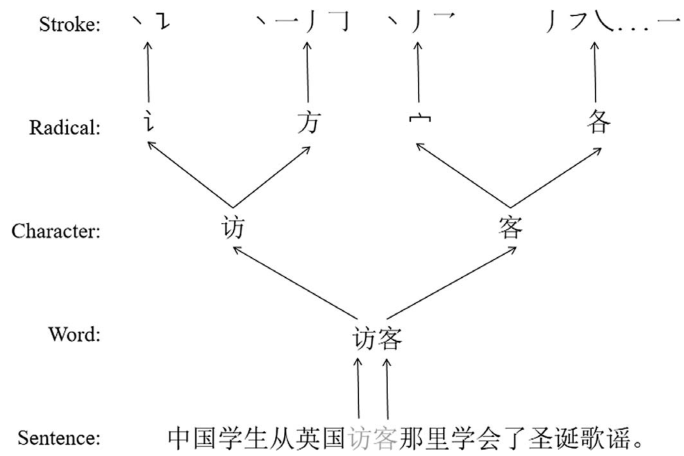


Figure 1. An example Chinese sentence showing characteristics of the writing system. Various number of strokes (two to six strokes) are arranged into radicals ("讠", "方", "宀", "各"), which can be further arranged into two-dimensional, hierarchically arranged, and boxlike characters ("访", "客"). A Chinese sentence is formed by an array of equally spaced, boxlike characters (中国学生从英国访客那里学会了圣诞歌谣, meaning: "Chinese students have learned a Christmas song from the British visitor").

known as the high-level linguistic information that affects the processing speed of a word (Inhoff & Rayner, 1986; Rayner, 1998; Rayner & Clifton, 2009; Rayner & Duffy, 1986). Both the processing and preceding speeds substantially affect the fixation duration and count on a target word (Rayner, 1998), thus mediating the reading speed. Consistent evidence has shown that high-frequency words receive shorter fixation duration and are more likely to be skipped than low-frequency words in alphabetic and Chinese writing systems (Balota, Pollatsek, & Rayner, 1985; Kliegl, Grabner, Rolfs, & Engbert, 2004; Kliegl, Nuthmann, & Engbert, 2006; Rayner & Raney, 1996; Schotter, Bicknell, Howard, Levy, & Rayner, 2014). In the present study, we investigate the effects of cognitive/linguistic factors indexed by word frequency on Chinese reading speed.

Previous studies typically explored the effects of visual span on reading speed through the rapid serial visual presentation (RSVP) paradigm (Chung, 2011; Chung et al., 2004; Lee et al., 2010; D. Yu et al., 2010). However, only a few studies have examined the relationship between the visual-span size and reading speed in a more natural mode of reading: sentence reading mode (Kwon, Liu, Patel, & Girkin, 2017; R. Liu, Patel, & Kwon, 2017). The RSVP paradigm differs significantly from the sentence reading mode. In the RSVP paradigm, a string of single words is presented in succession (Hutzler et al., 2007), and the presentation of every single word is strictly manipulated. Thus, the RSVP paradigm prevents subjects from moving their eyes and preliminarily processing upcoming words (Hutzler et al., 2013). Of note, word skipping and refixation and forthcoming word preliminary processing are essential aspects during natural reading modes (Rayner, 2009). In the present study, we explore the relationship between visual-span size, cognitive/linguistic factors, and sentence-reading performance.

## Methods

### Subjects

Twenty-eight native Mandarin speakers from Sun Yat-sen University participated in the experiment. All subjects were right-handed with normal or corrected-to-normal visual acuity in both eyes (20/20 or better) and no history of visual (except for refractive error), neurological, or psychiatric disorders. All subjects were naive to the purpose of this experiment and gave informed consent before the experiment. The study protocol was approved by the institutional review board at Sun Yat-sen University.

### Apparatus and stimuli

The experiment was programmed through Matlab (The MathWorks, Natick, MA) via Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) and presented on an ASUS monitor (model: VG278HE, refresh rate: 144 Hz, resolution: 1,960*1,080). The size of the stimuli (defined as the height of the Chinese character) subtended 1° retinal angle, which is significantly above the visual acuity threshold in central vision (Zhang, Zhang, Xue, Liu, & Yu, 2009). The stimuli used in the present study were white-colored characters on a black background (24 cd/m$^2$) presented in Song font. The Spyder calibrator was used to calibrate the correspondence between luminance and gray level. Eye movements were recorded at a sampling rate of 500 HZ with the SR Research Desk-Mount Eyelink 1000 system (monocular, right eye; spatial resolution: 0.018; Osgoode, ON, Canada). Subjects were seated 60 cm in front of the monitor. A chin rest was used to reduce head movements and maintain constant viewing distance and stable fixation. The eye tracker was calibrated and validated during the experiment when necessary.

### Experiment design

Prior to the formal experiment, all subjects were tested with the Hanyu Shuiping Kaoshi (HSK, level 4), which is a standardized test of Chinese language proficiency. After this Chinese language comprehension ability test (all scored over 95), subjects completed the trigram character-recognition task for evaluating the Chinese character's visual-span profiles (VSPs). They also completed the sentence reading task incorporating word frequency for evaluating Chinese sentence reading speed and cognitive/linguistic factors.

### Trigram character-recognition task

Figure 2 illustrates the procedure of the trigram character-recognition task. In each trial, a trigram, the sequence of three characters randomly chosen from the C3 group in Wang et al. (2014), was presented on the horizontal midline. Pelli, Burns, Farell, and Moore-Page (2006) chose 700 of the most frequently used Chinese characters from the State Language Work Committee, Bureau of Standard, 1992, and divided them into five mutually exclusive groups based on their perimetric complexity. In each group, 26 characters with a median perimetric complexity value were selected to constitute C1 to C5. The subgroup C3 was selected for the trigram character-recognition task in

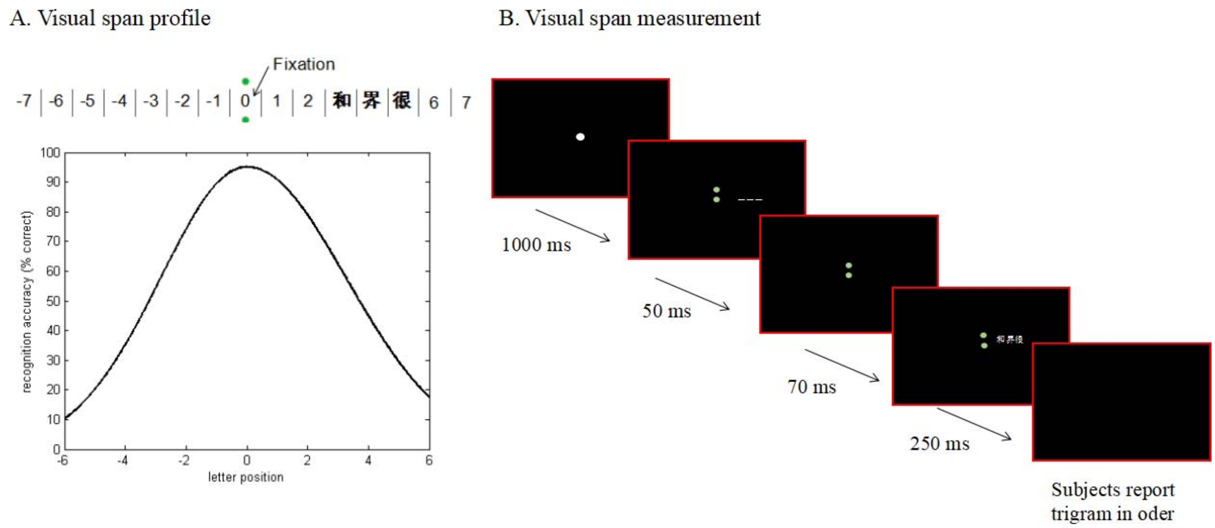


Figure 2. The visual span measurement for Chinese characters using the trigram recognition task. (A) Schematic illustration of the VSP. (B) Schematic illustration of visual span measurement. (A) Top: A string of three characters (和, 界, 很) was presented at position 4 in the horizontal midline. The gray numbers indicated the position of each position, which was not presented during the formal test. Bottom: The VSP was a plot of recognition accuracy versus character position and then converted to information transmitted in bits. The recognition accuracy approached 100% at the fixation point and gradually decreased with increasing distance from fixation. (B) After the white dot fixation stimulus display centered on the black screen midpoint for 1,000 ms, two vertically aligned green dots were presented at the center of the screen for stable fixation until the end of each trial. Three underlines were displayed indicating the following trigram positions for 50 ms. After a 70-ms interval, the trigram was presented for 250 ms on the screen. After that, the screen became blank, and the subject was asked to report the three characters of the trigram in left-to-right order.

the present study (see details in Figure 3; Zhu et al., 2019).

There were 15 positions in the horizontal midline. The center-to-center spacing between adjacent positions was 1.1 times the width of the Chinese characters (1° retinal angle). The center point was labeled as zero, the left positions as negative numbers from −7 to −1 and the right positions as positive numbers from 1 to 7 (Figure 2A). Prior to the trigram character-recognition task, the subject was shown a card with 26 characters in the C3 subgroup. A practice session was conducted first to ensure stable fixation at the white dot stimulus or between the two vertically aligned green dots at the center of the screen throughout each trial. In the formal test, after the white dot stimulus was presented at the center of the screen for 1,000 ms (Figure 2B), two vertically aligned green dots were displayed at the center of the screen for stable fixation until the end of each trial. Three underlines were displayed to indicate the upcoming trigram positions for the next 50 ms. After a 70-ms interval of two vertical green dots presentation, the trigram stimulus was presented for the following 250 ms. Then, the screen became blank, and the subject was asked to report the three characters of the trigram in order from left to right. A character was correctly recognized when the subject reported the exact character and its order in the trigram. The subject pressed the space key to release the start of the next trial when the subject was ready. The stimulus set of 26 characters in the C3 subgroup was available when needed. Each block consisted of 150 trials with a trigram being presented on each of 15 positions 10 times. All subjects were encouraged to take a short break after completing 50 trials in random order.

| C3 | | | | | | |
|---|---|---|---|---|---|---|
| 战 | 拉 | 统 | 身 | 说 | 经 | 民 |
| 的 | 有 | 他 | 和 | 总 | 点 | 使 |
| 进 | 者 | 种 | 定 | 所 | 利 | 电 |
| 把 | 很 | 金 | 话 | 界 | | |

Figure 3. The stimulus set for the visual span test selected from the C3 group in Wang et al. (2014). Based on the perimetric complexity (Pelli et al., 2006), 700 of the most frequently used Chinese characters (from State Language Work Committee, Bureau of Standard, 1992) were split into five mutually exclusive groups. Twenty-six characters with medium complexity values were selected from each complexity group to constitute C1 to C5 subgroups. Subgroup C3 was selected for the present study.

High Frequency: 中国学生从英国老师那里学会了圣诞歌谣。
（The Chinese students have learned a Christmas song from the British teacher）

Low Frequency: 中国学生从英国访客那里学会了圣诞歌谣。
（The Chinese students have learned a Christmas song from the British visitor）

Figure 4. Examples of a pair of sentences used in the experiment (target words are indicated by solid lines for illustrative purposes). The sentences were adopted from the reading material of Y. Liu et al. (2016). Each sentence frame was embedded with a high- or low-frequency word in the same location properly. The length of all target words were two characters.

### Sentence reading task

The sentence reading task, in which all characters were presented simultaneously, was used to evaluate reading speed. Word frequency was manipulated to explore the effects of cognitive/linguistic factors. Sentence materials were adopted from the materials of Y. Liu, Reichle, and Li (2016). Each sentence frame was embedded with a high- or low-frequency target word consisting of two characters in the same location (Figure 4, an example of paired high- and low-frequency words in English: metal vs. alloy). The predictability of all target words was less than 0.1, and there were no significant differences in the sentence naturalness score between high- and low-frequency conditions (Y. Liu et al., 2016). The visual complexity, indexed by the average number of strokes, was similar between low- and high-frequency words (9.40 ± 2.16 vs. 8.03 ± 1.62 strokes per character). Subjects were required to read the sentence silently as fast as they could. After a fixation calibration, the fixation white dot was presented at the center of the screen. Subjects pressed the space bar to release the presentation of the sentence on the horizontal midline and signaled the completion of reading by pressing the space bar again. Subjects were then required to answer a comprehensive question after each sentence. Each subject read 80 sentences with 40 sentences in each frequency condition over five blocks according to the counterbalanced design.

## Data analysis

### VSP and visual-span size

The recognition accuracy was calculated after combining recognition performance in each position filled by the inner (nearest to the midline), outer (farthest to the midline), and middle characters in the trigram. A trial was excluded if there was more than 1° retinal angle movement away from the fixation point detected in the eye tracking system; however, the frequency of unstable fixation was very low (less than 15 or 10% of trials per subject). After excluding invalid trials, the recognition accuracy was fitted with the split-Gaussian function, indicated by the following equation (Chung et al., 2004, Legge et al., 2001):

$$P(x) = \begin{cases} A\exp\left(-x^2/2\sigma_L^2\right) & \text{if } x < 0 \\ A\exp\left(-x^2/2\sigma_R^2\right) & \text{if } x \geq 0 \end{cases} \quad (1)$$

with $P(x)$, $x$, $A$, $\sigma_L$, and $\sigma_R$ representing recognition probabilities, different positions, split-Gaussian curves' amplitude, and the standard deviation for the left and the right half of the split-Gaussian curve, respectively. Only data from 13 letter positions (–6 to +6) were extracted for the present analysis because there was no inner character of the trigram presented at positions ±7.

The visual-span size was defined as the width of the fitted split-Gaussian curve at 80% recognition accuracy (number of Chinese characters). Consistent with previous studies (Chung et al., 2004, Legge et al., 2001), we also quantified the visual-span size as the area under the split-Gaussian curve in bits of information transmitted. The following equation was used to transform recognition accuracy to information transmitted (Beckmann, 1998):

$$\begin{aligned}&\text{bits of information}\\&\quad = -0.037 + 4.676\\&\qquad \times \text{proportion correct of character recognition.}\end{aligned} \quad (2)$$

We integrated bits of information transmitted across all positions of VSPs.

As the standard deviations for the left and the right half of the split-Gaussian curve ($\sigma_L$ and $\sigma_R$) do not fully represent character-recognition performance in parafoveal vision, we divided the area under the VSP into three subareas, representing foveal vision (–1°, +1°) and parafoveal left (–6°, –1°) and right (+1°, +6°) vision.

### Sentence reading speed and cognitive/linguistic factors

For each sentence, reading speed (character per minute, CPM) was computed as the ratio of sentence presentation time and the number of characters in the sentence. The contribution of cognitive/linguistic factors was indexed by frequency conditions. Furthermore, measures from eye tracking were used to divide the target word recognition into two cognitive processing stages: encoding and decision making (Calvo & Nummenmaa, 2009). Encoding of the target word was evaluated by the dwell time—that is, all fixation duration on the target word and the duration of the

| | $M \pm SD$ (95% CI)/No. (percentage) |
|---|---|
| Average reading speed (CPM, natural log-transformed) | 5.73 ± 0.30 (5.62–5.85) |
| Visual span profile | |
| Total information transmitted, bits | 33.7 ± 4.41 (32.0–35.4) |
| Peak | 4.52 ± 0.18 (4.45–4.60) |
| Standard deviation $\sigma_L$ | 3.94 ± 0.80 (3.63–4.25) |
| Standard deviation $\sigma_R$ | 4.51 ± 0.68 (4.24–4.77) |
| Foveal area, bits | 13.6 ± 0.43 (13.4–13.7) |
| Parafoveal left area, bits | 9.08 ± 2.34 (8.17–9.99) |
| Parafoveal right area, bits | 10.9 ± 1.96 (10.2–11.7) |
| Target word dwell time, ms | |
| Low-frequency words | 703.7 ± 177.4 (634.9–772.5) |
| High-frequency words | 568.9 ± 143.8 (513.2–624.7) |
| First fixation duration, ms | |
| Low-frequency words | 224.6 ± 36.8 (210.4–238.9) |
| High-frequency words | 204.0 ± 27.9 (193.1–214.8) |
| Target word skipping rate, % | |
| Low-frequency words | 44/1120 (3.93%) |
| High-frequency words | 64/1120 (5.71%) |
| Target word refixation rate, % | |
| Low-frequency words | 864/1120 (77.1%) |
| High-frequency words | 781/1120 (69.7%) |

Table 1. VSP, cognitive/linguistic factors, and sentence reading speed among subjects. *Note*: $\sigma_L$, $\sigma_R$ = standard deviation for the left and the right Gaussian curves, respectively.

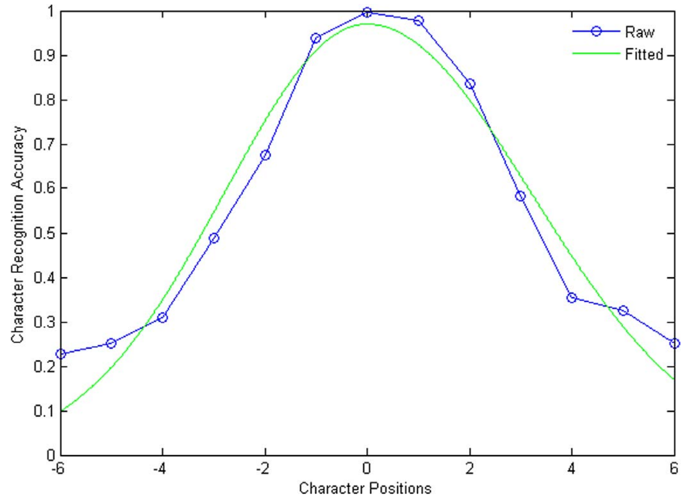


Figure 5. The average raw and fitted split-Gaussian curves across all subjects. Recognition accuracy for the middle character in character trigrams presented at different positions relative to fixation position at 0°. The average raw and fitted split-Gaussian curves across all subjects. The VSPs had slightly asymmetric shapes broader to the right of fixation. Mean recognition accuracy across subjects approached 100% (4.7 information bits) at the fixation point and gradually dropped with increasing distance from fixation.

first fixation on the target word in the first pass. Decision making on the target word was examined by the skipping and refixation rate of the target word. The skipping or refixation rate was defined as the number of target words skipped or refixated divided by the total number of target words.

## Statistical analysis

Statistical analyses were performed using Stata (version 14.0; StataCorp., College Station, TX). Recognition accuracy in different positions was fitted using MATLAB 5.2.2 with an asymmetric or split-Gaussian function. Dwell time and first fixation duration in the target word of the same sentence frame were compared using the paired *t* test. The generalized estimating equations (GEE) model was used to compare the probabilities of skipping and refixation on the target word in the same sentence frame. Linear mixed-effects models (LMMs) were used to determine associations between each of VSP parameters, cognitive/linguistic factors indexed by word frequency, and sentence reading speed. The VSP parameters and cognitive/linguistic factors were included as fixed effects, and the deviations of each subject and each sentence were included as random effects. Reading speed (CPM) was natural log-transformed.

# Results

## VSPs

The subjects' VSP parameters as indexes of different characteristics of the visual span are shown in Table 1. The raw and fitted average VSP curves across all subjects are illustrated in Figure 5. The average VSP curves showed slightly asymmetric shapes that were relatively broader to the right of fixation. In details, the recognition accuracy across all subjects approached 100% (4.7 information bits) at the fixation point and gradually decreased with increasing distance from the fixation point. The visual-span size for C3 group was 7.10 characters. The subjects' 95% confidence interval (CI) of total information transmitted in bits ranged from 32.0 to 35.4 ($M = 33.7$, $SD = 4.41$) and peak amplitudes ranged from 4.45 to 4.60 ($M = 4.52$, $SD = 0.18$), indicating comprehensive performance across 13 positions and performance at the fixation point. The 95% CI of standard deviations for the left and right sides of the VSPs curves ranged from 3.63 to 4.25 ($M = 3.94$, $SD = 0.80$) and from 4.24 to 4.77 ($M = 4.51$, $SD =$

| | Univariable LMM | | | |
|---|---|---|---|---|
| | Coefficient | Standard error | $z$ | $p$ |
| Visual span profile | | | | |
| Total information transmitted (bits) | 0.03 | 0.01 | 2.58 | 0.010 |
| Peak | 0.28 | 0.30 | 0.90 | 0.366 |
| Standard deviation $\sigma_L$ | 0.15 | 0.06 | 2.30 | 0.022 |
| Standard deviation $\sigma_R$ | 0.16 | 0.08 | 2.09 | 0.036 |
| Foveal area, bits | 0.23 | 0.13 | 1.86 | 0.062 |
| Parafoveal left area, bits | 0.06 | 0.02 | 2.60 | 0.009 |
| Parafoveal right area, bits | 0.06 | 0.03 | 2.21 | 0.027 |
| Target word profile | | | | |
| Dwell time, ms | $-2.22*10^{-7}$ | $1.24*10^{-8}$ | −17.9 | <0.001 |
| First fixation duration, ms | $-2.18*10^{-7}$ | $5.56*10^{-8}$ | −3.86 | <0.001 |
| Skipping rate, % | 0.15 | 0.03 | 5.48 | <0.001 |
| Refixation rate, % | −0.12 | 0.01 | −9.38 | <0.001 |
| Frequency condition | | | | |
| Low-frequency words | | Reference | | |
| High-frequency words | 0.03 | 0.01 | 2.35 | 0.019 |

Table 2. Univariate LMM for VSP and cognitive/linguistic factors with sentence reading speed. *Note*: $\sigma_L$, $\sigma_R$ = standard deviation for the left and the right Gaussian curves, respectively.

0.68), respectively. The area under the VSPs for the foveal, parafoveal left, and parafoveal right subareas were 13.6 ± 0.43, 9.08 ± 2.34, and 10.9 ± 1.96 bits, respectively.

## Chinese sentence reading speed

The 95% CI of sentence reading speed for all subjects ranged from 5.62 to 5.85 ($M = 5.73$, $SD = 0.30$) CPM. Using a paired $t$ test, dwell time on high-frequency target words ($M = 568.9$ ms, $SD = 143.8$ ms) were significantly lower than that on low-frequency target words ($M = 703.7$ ms, $SD = 177.4$ ms, $t = 7.09$, $p < 0.001$). Similar results were observed in the first fixation duration for high- and low-frequency target words (high: $M = 224.6$ ms, $SD = 36.8$ ms; low: $M = 204.0$ ms, $SD = 27.9$ ms, $t = 3.60$, $p < 0.001$; Table 1). GEE models suggested that the high-frequency target words were much more likely to be skipped and less likely to be refixated compared to the low-frequency target words (skipping rate: high: 5.71% vs. low: 3.93%, coefficient = 0.393, $p < 0.05$; refixation rate: high: 69.7% vs. low: 77.1%, coefficient = −0.382, $p < 0.001$).

Table 2 displays the univariate LMMs for VPSs, cognitive/linguistic factors with sentence reading speed. The total information transmitted in bits was positively associated with reading speed (coefficient = 0.03, $p = 0.01$). Similarly, reading speed significantly increased with larger standard deviations of left (coefficient = 0.15, $p = 0.022$) and right (coefficient = 0.16, $p = 0.036$) sides of VSPs curves and larger parafoveal left (coefficient = 0.06, $p = 0.009$) and right subareas (coefficient = 0.06, $p = 0.027$). The foveal subarea under the VSP curve was marginally associated with reading speed (coefficient = 0.23, $p = 0.062$). However, the peak amplitude was not a predictor for reading speed (coefficient = 0.28, $p = 0.366$).

Reading speed in sentences with high-frequency target words was faster than those with low-frequency target words (coefficient = 0.03, $p = 0.019$). In the target words encoding process, both the dwell time and the first fixation duration were negatively related to reading speed (dwell time: coefficient = $-2.22 \times 10^{-7}$, $p < 0.001$; first fixation duration: coefficient = $-2.18 \times 10^{-7}$, $p < 0.001$). With respect to the decision making on the target words, we observed a positive relationship between the skipping rate and reading speed (coefficient = 0.15, $p < 0.001$) and a negative relationship between the refixation rate and reading speed (coefficient = −0.12, $p < 0.001$).

Because of strong correlations among VSP parameters and cognitive/linguistic factors (all $p$s $< 0.001$), each significant VSP parameter combined with each significant cognitive/linguistic factor and were included in separate multivariate LMMs. Multivariate LMMs incorporating each significant VSP parameter with word frequency conditions are presented in Table 3. Fast readers had larger total information transmitted in bits (coefficient = 0.03, $p < 0.05$) than slow readers, and sentences with high-frequency target words were significantly associated with faster reading speed (coefficient = 0.03, $p < 0.05$). Similar results were observed for other significant VSP parameters. Multivariate LMMs combining other significant cognitive/linguistic factors, including dwell time, first fixation

| | Model A | Model B | Model C | Model D | Model E |
|---|---|---|---|---|---|
| Intercept | 4.66*** | 5.08*** | 4.93*** | 5.15*** | 5.02*** |
| Fixed effects | | | | | |
| Visual span profile | | | | | |
| Total information transmitted, bits | 0.03* | - | - | - | - |
| Standard deviation $\sigma_L$ | - | 0.15* | - | - | - |
| Standard deviation $\sigma_R$ | - | - | 0.16* | - | - |
| Parafoveal left area, bits | - | - | - | 0.06** | - |
| Parafoveal right area, bits | - | - | - | - | 0.06* |
| Word frequency (high vs. low) | 0.03* | 0.03* | 0.03* | 0.03* | 0.03* |

Table 3. Multivariate LMMs for VSP and cognitive/linguistic factors with sentence reading speed. *Note*: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

duration, skipping rate, and refixation rate in the target word with statistically significant VSP parameters also led to comparable results.

## Discussion

In the present study, we found that VSP parameters that include total information transmitted in bits; standard deviation of the left and right sides of the fitted curves; parafoveal right and left areas under curves; and cognitive/linguistic factors that include frequency condition, dwell time, first fixation duration, skipping, and refixation rate in the target words independently contributed to Chinese sentence reading speed. We concluded that the visual-span size and cognitive/linguistic factors independently represented bottlenecks for Chinese sentence reading speed.

In the present study, we observed variations in fitted split-Gaussian curves for all subjects. However, they followed a similar pattern: being slightly asymmetric and broader to the right of fixation. The recognition accuracy was nearly 100% at the fixation point and gradually decreased with farther positions away from the fixation point. The mechanism underlying the similar recognition pattern could be explained by the crowding effects. Crowding is defined as the inability to recognize target objects due to the contiguity of neighbors (Bouma, 1970; Pelli, Palomares, & Majaj, 2004; D. Yu, Legge, Wagoner, & Chung, 2014). Pelli et al. (2004), Pelli et al. (2007), and Whitney and Levi (2011) reported that the effects of crowding were minimal at the fovea and increased with eccentricity. The asymmetry of fitted split-Gaussian curves in our study was consistent with previous results (Chung et al., 2004; Legge et al., 2007; Legge et al., 2002; Legge et al., 2001), which might be due to the left-to-right reading habit. The visual-span size was 7.10 Chinese characters. The visual-span size for the C3 group in our study was relatively larger than that in study by Wang et al. (2014), who reported the visual-span size for the C3 group was 6.00 characters. Differences in education background (medical education vs. general background) and/or study sample sizes (28 vs. 12 participants) between these two studies might explain these inconsistencies.

Our results from univariate LMMs suggested VSP parameters, including total information transmitted in bits, standard deviation of the left and right side of the fitted curves, and parafoveal right and left area under curves, were significantly related to Chinese reading performance. The relationship between the total information transmitted in bits and reading speed observed in our study was in line with findings from alphabetic writing systems (Legge et al., 2007; Pelli et al., 2007; Risse, 2014; D. Yu, Cheung, Legge, & Chung, 2007). The relationship between the rightward extension of visual span (estimated standard deviation right side and parafoveal right area of the split-Gaussian curves) and sentence reading speed does not seem surprising because of the left-to-right reading habit. A fair amount of work gives evidence that the reading direction may influence the spatial perception and attention (Afsari, Ossandon, & Konig, 2016). Risse (2014) reported a significant relationship between foveal recognition performance and reading speed although we found a marginal relationship between foveal recognition performance and sentence reading speed ($p = 0.062$). Given the fovea had the highest vision and the lowest crowding effect, readers might benefit from freely choosing fixation for fast inspection. However, no significant association between peak amplitude and sentence-reading speed was observed. This might be explained by the ceiling effect of recognition performance in the fixation point.

Reading is a complex process and involves multiple cognitive components (Pugh et al., 2000). Chinese readers intensively rely on cognitive/linguistic factors due to dense visual and lexical details in Chinese characters and the lack of clear word boundaries in Chinese script. In the univariate LMMs, results suggest the importance of cognitive/linguistic factors indexed by frequency condition in Chinese sentence reading performance. Previous studies suggested that reading speed was influenced by cognitive/linguistic factors relating to the utilization of context information and phonological processing (Balota et al., 1985; Hoeft et al., 2011; Kliegl et al., 2004; Kliegl et al., 2006; Pugh et al., 2000; Rayner & Raney, 1996; Richlan, Kronbichler, & Wimmer, 2013). We divided the recognition of the target word into two cognitive processing stages: encoding and decision making. Given the evidence that dwell time and the first-fixation duration represent the amount of visual and cognitive resources required for recognition (Rayner, 2009) and similar visual complexity between low- and high-frequency words, the significant association between dwell time or the first-fixation duration and Chinese sentence-reading performance further indicated effects of encoding processes on Chinese reading performance. In addition, the decision making assessed by the skipping and refixation rate on the target word was also a significant predictor for Chinese sentence reading performance. These results were qualitatively in favor of our findings that the cognitive/linguistic factors were also important limitations in Chinese reading performance.

In the multivariate LMMs, we found that VSP parameters and cognitive/linguistic factors independently contributed to the Chinese reading performance. A large number of studies reported the critical contributions of factors ranging from low perceptual (e.g., word order) to high cognitive levels (e.g., memory; He et al., 2018; Legge et al., 2007; Legge et al., 2001; Primativo, Spinelli, Zoccolotti, De Luca, & Martelli, 2016; Risse, 2014) on the reading speed. However, little is known about the independent effect of the visual span and cognitive/linguistic factors on the reading performance. Contrary to findings in the present study, Bochsler, Wagoner, and Legge (2009) reported that both the vocabulary score of the Wechsler Intelligence Scale for Children and the visual-span size were significant predictors of RSVP reading speed in children although these two predictors were highly correlated and did not independently contribute to reading speed. The close relationship between cognitive and sensory predictors of reading speed might be due to the fact that both vocabulary size and the visual-span size increased with the amount of reading experience during childhood (Kwon, Legge, & Dubbels, 2007). Differences in the assessment of cognitive factors (the Wechsler Intelligence Scale vs. target word frequency), reading speed paradigm (RSVP vs. sentence reading mode), and age range of included subjects (children vs. young adults) may explain discrepant results in our study and in the study by Bochsler et al.

In summary, we reported that both the visual-span size and cognitive/linguistic factors independently contributed to Chinese sentence reading speed. Our results extend the current knowledge on visual span to the Chinese writing system and imply that a common sensory constraint might exist in the pattern of recognition. Further studies investigating whether the expansion of visual-span size through perceptual learning could improve Chinese reading performance accordingly would further confirm these findings.

*Keywords: visual span*, *cognitive factors*, *Chinese reading speed*

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