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Perceptual Span in Oral Reading: The Case of Chinese

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ABSTRACT

The present study explores the perceptual span, that is, the physical extent of the area from which useful visual information is obtained during a single fixation, during oral reading of Chinese sentences. Characters outside a window of legible text were replaced by visually similar characters. Results show that the influence of window size on the perceptual span was consistent across different fixation and oculomotor measures. To maintain normal reading behavior when reading aloud, it was necessary to have information provided from three characters to the right of the fixation. Together with findings from previous research, our findings suggest that the physical size of the perceptual span is smaller when reading aloud than in silent reading. This is in agreement with previous studies in English, suggesting that the mechanisms causing the reduced span in oral reading have a common base that generalizes across languages and writing systems.

During sentence reading, lexical processing starts before a word is fixated. Information beyond the currently fixated word is critical for maintaining a normal reading speed (McConkie & Rayner, 1975). The physical extent of an area from which useful visual information is obtained during a single fixation, termed the *perceptual span* (McConkie & Rayner, 1975), has been examined in various writing systems. Most of these studies tested only silent reading. One important aspect in which oral reading differs from silent reading is that the former involves muscle movement during speech production. Little is known about how such additional articulatory and associated coordinative demands in oral reading influence the effective field of vision. More critically for Chinese, certain properties of the writing system, such as high information density and emphasis on semantics over phonology, on which we elaborate next, offer a unique opportunity to understand language-specific and general processes. For these reasons, it is of theoretical importance to determine the spatial extent of visual processing during oral reading. In the present study, we adopt the moving-window paradigm (McConkie & Rayner, 1975) and establish the size of the perceptual span during oral reading of Chinese sentences.

Using the gaze-contingent moving-window paradigm, the visibility of text is manipulated depending on fixation position, so that the window of visible text moves with the eyes while people are reading. Visual information is available only within an area around the current fixation, and letters outside this window are masked. In this paradigm, window sizes are increased across conditions until the window is large enough to provide sufficient information so that there is no difference in reading performance between a window condition and a no-window control condition. Using this paradigm, the perceptual span in silent reading has been widely studied. For example, the perceptual span of English adults covers up to four letters leftward and 15 letters rightward (McConkie & Rayner, 1975). Veldre and Andrews (2014) found that among adult readers, perceptual span is modulated by reading/spelling ability. The span for beginning English readers is considerably

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smaller, extending about 11 letters rightward (Rayner, 1986). By comparing readers from different grades, Rayner concluded that the size of the span increases with age/reading ability. Similar results were documented for Finnish (Häikiö, Bertram, Hyönä, & Niemi, 2009) and German (Sperlich, Schad, & Laubrock, 2015). In the first longitudinal study on the development of the perceptual span, Sperlich, Meixner, and Laubrock (2016) demonstrated that the transition from synthetic letter-based to whole word reading coincides with a critical increase in the perceptual span in German elementary school students. Arguably, beginning readers have to devote more attention to foveal processing, leading to decreased efficiency in the processing of upcoming parafoveal words (Henderson & Ferreira, 1990; Schad & Engbert, 2012; Yan, 2015). Indeed, Meixner, Nixon, and Laubrock (2017) showed that the perceptual span is modulated by momentary processing demand (operationalized by foveal word frequency), and this process is already effective in beginning readers.

The existing literature just reviewed suggests that the perceptual span varies as a function of processing difficulty. Although silent and oral reading processes may share many characteristics (Huey, 1908/1968; Pan, Yan, Laubrock, Shu, & Kliegl, 2014), the additional articulatory demands in oral reading and the associated scheduling and coordination demands obviously make it a more complex task (Laubrock & Kliegl, 2015). In agreement with this view, it has been widely documented that, compared to silent reading, oral reading leads to prolongation of fixation duration, reduction of saccade amplitude, more regressions, and more refixations (Inhoff & Radach, 2014; Laubrock & Bohn, 2008; Laubrock & Kliegl, 2015; Pan, Laubrock, & Yan, 2016). Therefore, parafoveal processing in oral reading is expected to be less efficient than in silent reading. By using a variant of the moving-window paradigm, Ashby, Yang, Evans, and Rayner (2012) manipulated parafoveal information availability by presenting English sentences in a one-word window condition and a three-word window condition. They found that parafoveal masking impaired both oral and silent reading modes and the effect was larger in silent than in oral reading. They reported important findings which indicate that parafoveal processing efficiency decreased in oral reading. The present study reports the physical size of the perceptual span in Chinese at character-level resolution, as most previous studies on alphabetic scripts have done. Although alphabetic and Chinese characters differ in the information conveyed, on which we elaborate next, they are both treated as the basic writing units.

We are interested in whether the result from Ashby et al. (2012) that the perceptual span is smaller in oral than in silent reading can be generalized to Chinese. If results generalize across writing systems, this would suggest that general mechanisms such as the depletion of attentional resources by coordinative demands (e.g., phonological working memory needed to maintain words to be pronounced, articulation processes, and competition between phonological representations stored in working memory and the currently activated phonological representation) are responsible for the reduction of the span in oral reading.

An additional language-specific difference may cause the reading mode-related reduction in span to be even larger in Chinese than in alphabetic scripts. The Chinese writing system is different from alphabetic scripts in many aspects, including higher information density and lack of explicitly marked word boundaries (see Hoosain, 1992; Liversedge, Hyönä, & Rayner, 2013, for reviews). One critical difference is that the Chinese and alphabetic scripts seem to be optimized for different kinds of information intake. Whereas phonological information is extracted quickly, early, and before semantics in alphabetic languages, semantic information is extracted earlier than phonology in Chinese (Chen & Shu, 2001; Yan, Richter, Shu, & Kliegl, 2009). On the other hand, the Chinese writing system is known to be less optimized for phonology as compared to English. The late phonological access in Chinese may imply more processing load and thus less efficient parafoveal processing efficiency. Thus the oral-reading-related reduction in span is expected to be even larger in Chinese than in English.

However, this might partly be counteracted by the opportunity for longer preprocessing during the “idle time” when the eye waits for the voice, as reflected in the generally longer fixation durations for oral reading. Indeed, Yan (2015) demonstrated that contrary to the foveal load hypothesis

(Henderson & Ferreira, 1990), prolonged fixations due to high visual complexity of Chinese foveal words provided more time for parafoveal processing of the upcoming words, leading to decreased processing time when they were subsequently fixated. Similarly in oral reading of Chinese, prolongation in fixation due to articulatory demands may also lead to enhanced parafoveal processing.

Despite these interesting language-specific properties, there are only a few experiments on the perceptual span in the Chinese writing system. Inhoff and Liu (1998) first reported that the perceptual span in Chinese is also asymmetric to the right, but with a much smaller physical size due to its high information density, extending one character leftward and up to three characters rightward. As a replication and extension of the original work, Yan, Zhou, Shu, and Kliegl (2015) demonstrated that the perceptual span depends on font size and the rightward span can subtend at least four characters, offering a new understanding of the perceptual span in Chinese. These two studies tested silent reading; the present study extends our knowledge about the perceptual span in Chinese to oral reading. We use the Yan et al. (2015) data for a comparison between reading modes.

Method

Participants

Forty students from Beijing Normal University with normal or corrected-to-normal vision, who were native speakers of Chinese, participated in the experiment. The large sample size given the simple experimental design allows for solid conclusions.

Material and design

We used the Beijing Sentence Corpus (BSC; Yan, Kliegl, Richter, Nuthmann, & Shu, 2010) as reading materials, which has 150 sentences. The BSC sentences are 15–25 characters ($M = 21.0$, $SD = 2.5$) or seven to 15 words ($M = 11.2$, $SD = 1.6$) in length and comprise 1,686 tokens of 936 words (types). Most word types in the BSC are two characters long, which is representative of the Chinese language. The number of strokes, an index of visual complexity, varies from two to 42 per word ($M = 15.6$, $SD = 5.5$). Word frequencies according to a database of 1.2 million words (Beijing Language Institute Publisher, 1986) vary from 1 to 64,100 ($M = 403$, $SD = 2,454$).

Like Yan et al. (2015, Experiment 1), the present study had four viewing conditions, including a *full line* control condition, in which the whole sentence was visible independent of fixation location. In addition, three *window* conditions were created, revealing one character to the left of the fixated character, and two to four characters to the right of it, which is henceforth referred to as L1R2, L1R3, and L1R4 conditions.

Masking characters were also adopted from Yan et al. (2015, Experiment 1), that is, shapes, structures, and complexities were matched between original and masking characters. As shown in Figure 1, the original and masking characters were closely matched for layout, visual complexity, and character frequency. Further details can be found in Yan et al. (2015). The masking characters never provided meaningful continuations of the sentences beyond the experimentally defined window. Sentences were randomly assigned to four blocks of viewing conditions using a Latin-square design.

Apparatus

Eye movements were recorded with an EyeLink 1000 system running at 1000 Hz. Sentences that occupied only one line on the screen were presented at the vertical position one third from the top of the screen of a 21-in. ViewSonic G220f CRT monitor (resolution = 1280×1024 pixels; frame-rate = 85 Hz). Given these parameters, display change should complete within a maximum of 15 ms (including eye-tracker trigger delay and monitor refresh cycle). Participants were seated comfortably with a forehead rest at a distance of 65 cm from the monitor. No chin-rest was used so that the

专家指出近期发生地震的可能性不大。	Full Line
*	
手象惜击建期发生地箱和司彩的禾不。	L1R2
*	
手象惜击建期发生地震和司彩的禾不。	L1R3
*	
手象惜击建期发生地震的司彩的禾不。	L1R4
*	

Figure 1. An example sentence displayed with different viewing conditions. *Note.* Modern Chinese is written horizontally from left to right. Visible (i.e., nonmasked) characters in all conditions, given the fixation location (as indicated by the asterisks) on the seventh character in the sentence, are highlighted with a gray background—only for the purpose of illustration, not during the experiment. Characters outside the moving window were used for masking and were not related to the sentence. The sentence is translated as *Experts point out that earthquakes are currently unlikely*. L1R2 = one character to the left of the fixated character; L1R3 = two characters to the right of the fixated character; L1R4 = four characters to the right of the fixated character.

participants could freely perform oral reading. Each character occupied a 36×36 pixel grid, with one character subtending approximately 1° of visual angle. All recordings and calibrations were done monocularly based on the right eye, and viewing was binocular.

Procedure

After calibration and validation (maximum error = 0.5°) of participants' gaze positions and prior to the presentation of each sentence, a fixation point appeared on the left side of the monitor for fixation check. On failure of detecting participants' eyes around the initial fixation point, an extra calibration was performed. Fixation on the fixation point initiated presentation of the next sentence with its first character occupying the position of the fixation point.

Participants were instructed to read the sentences aloud for comprehension, then fixate a dot in the lower right corner of the monitor, and finally press a joystick button to signal the completion of a trial. The sentence was followed by an easy yes–no question pertaining to the current sentence on 38 trials, which the participant answered with two joystick buttons. These questions served primarily to encourage reading for comprehension. Participants correctly answered 96% of all questions ($SD = 3\%$).

Data analysis

Fixations were determined with an algorithm for saccade detection introduced by Engbert and Kliegl (2003). For eye movement measure analyses, trials were removed due to participants' blinks, coughs, or body movements (according to the observation of the experimenter) during reading, or tracker errors ($N = 523, 9\%$). For the analyses of all eye movement measures, the first and last words and the first and last fixated words in a trial (i.e., a total of 11,902 words) were removed. First-fixation durations (duration of the first fixation on a word, irrespective of the number of fixations) shorter than 60 ms or longer than 800 ms and gaze durations (the sum of fixation durations during the first-pass reading of a word) longer than 1,200 ms were excluded from the analyses of first-fixation duration, first-fixation location, single fixation duration, gaze duration, refixation, and regression probabilities. Fixations shorter than 60 ms or longer than 800 ms were excluded from the analyses of mean fixation duration and mean saccade amplitude. We increased the upper cutoff for fixation

durations as compared to Yan et al. (2015) because fixations are naturally longer in oral than in silent Chinese reading (e.g., Pan et al., 2016). In addition, we also removed all data from sentences with an extremely low number of effective observations (i.e., fewer than five fixations or fewer than three fixated words). In total, we kept 41,470 fixated words (i.e., 97% of all valid words) and 63,617 fixations (i.e., 98% of all valid fixations) for the following analyses.

Rayner (1998) pointed out that the basic assumption of the gaze-contingent moving-window paradigm “is that when the window is as large as the region from which the reader can obtain information, there is no difference between reading in that situation and when there is no window” (p. 379). Increasing window size increases the amount of information available per fixation. We therefore tested the minimum amount of information required for a normal reading behavior by using a priori *treatment contrasts*, with the full line condition as a reference category. Estimates were obtained using linear mixed models (LMMs) for reading speed (in number of characters per minute), saccade amplitude, fixation location, and duration analyses and using generalized LMMs for skipping, regression and refixation probability analyses. Models included variance components for intercepts for items and for subjects, and variance components for fixed effects and correlation parameters. Analyses were conducted using the lmer program of the lme4 package (Version 1.1–18; Bates, Maechler, Bolker, & Walker, 2015) in the R environment for statistical computing and graphics (Version 3.3.0; R Core Team, 2016). For the LMMs, we report regression coefficients, standard errors, and *t* values ($t = b/SE$). There is no clear definition of “degrees of freedom” for LMMs, and therefore precise *p* values cannot be estimated. Effects 1.96 times larger than their standard errors are interpreted as significant at the 5% level. This is because, given the large number of observations and the small number of fixed- and random-effects estimated, the *t* statistic (M/SE) effectively corresponds to the *z* statistic (i.e., the contribution of the degrees of freedom to the test statistic is negligible). Duration measures were log-transformed in the LMMs (Kliegl, Masson, & Richter, 2010).

Results

Effects of window size on eye-movement measures during oral reading are shown in Table 1. As expected, there was a global trend that increasing window size facilitated sentence reading.

The L1R2 condition led to a significant slowdown in reading speed ($b = -16.70$, $SE = 4.33$, $t = -3.9$) whereas the other two window conditions did not ($|t \text{ values}| < 1.7$), suggesting that reading was relatively unimpaired when as few as three characters were fully visible to the right of the current fixation. The size of the rightward perceptual span in Chinese oral reading was confirmed by a number of different eye movement measures. When viewing was limited to two rightward characters, Chinese readers tended to skip words less often ($b = -0.198$, $SE = 0.054$, $z = -3.646$, $p < .001$), have longer gaze duration ($b = 0.041$, $SE = 0.012$, $t = 3.5$), refixate words more often ($b = 0.188$, $SE = 0.056$, $z = 3.338$, $p < .001$), and execute shorter rightward saccades

Table 1. Effects of viewing constraint on eye-movement measures.

Measures	L1R2	L1R3	L1R4	Full Line
Reading speed (characters/min)	199 (35)	210 (32)	212 (34)	215 (28)
Mean fixation duration (ms)	319 (45)	318 (41)	318 (40)	315 (40)
Rightward saccade amplitude (characters)	1.46 (.29)	1.54 (.26)	1.56 (.28)	1.55 (.28)
First-fixation duration (ms)	325 (48)	321 (43)	323 (41)	321 (41)
First-fixation location relative to word length (%)	40 (5)	41 (4)	41 (4)	41 (4)
Single fixation duration (ms)	329 (50)	324 (45)	325 (42)	324 (43)
Gaze duration (ms)	440 (54)	423 (46)	425 (50)	422 (42)
Refixation probability (%)	34 (13)	31 (11)	30 (11)	31 (11)
Skipping probability (%)	13 (4)	14 (4)	15 (5)	15 (5)

Note. Values were computed across participants' means. L1R2 = one character to the left of the fixated character; L1R3 = two characters to the right of the fixated character; L1R4 = four characters to the right of the fixated character.

($b = -0.090$, $SE = 0.024$, $t = -3.77$) than in the full line condition. For the same eye movement measures, the comparisons between L1R3/L1R4 and full line conditions failed to reach significance (all $|t \text{ values}| < 1.3$). The other eye movement measures, including first-fixation duration and location, regression probability and mean fixation duration showed the same nonsignificant numerical trends.

In an additional analysis to further demonstrate the difference in the perceptual span between oral and silent reading in Chinese, we combined the oral reading data in the present study with the silent reading data based on 28 participants reported by Yan et al. (2015, Experiment 1) and submitted the whole data set of fixation duration into two-way factorial analyses with LMMs. In contrast to reading speed in oral reading just reported, data from Yan et al. (2015) showed that in silent reading, reading speed in the full line condition was significantly faster than in the L1R2 ($b = -61.13$, $SE = 11.70$, $t = -5.2$) and L1R3 ($b = -33.07$, $SE = 16.24$, $t = -2.0$) but not L1R4 ($b = -12.31$, $SE = 14.12$, $t = -0.9$) conditions. Note that both experiments used identical experimental materials, manipulation, and apparatus. In addition, both of the studies recruited random samples of healthy (under)graduate students who were not diagnosed with any psychological or reading disorders, therefore the comparison is valid and based on a representative sample of skilled Chinese readers. Replicating Pan et al. (2016), Chinese readers had longer processing times (first-fixation duration: $b = -0.180$, $SE = 0.028$, $t = -6.5$; SFD: $b = -0.187$, $SE = 0.029$, $t = 6.4$; gaze duration: $b = -0.328$, $SE = 0.026$, $t = -12.6$) and more leftward first-fixation locations ($b = 0.053$, $SE = 0.008$, $t = 6.6$) in oral than in silent reading. More important, significant interactions were found between reading mode and L1R2/L1R3 versus full line contrasts in first-fixation duration ($b = 0.068$, $SE = 0.018$, $t = 3.7$ and $b = 0.040$, $SE = 0.015$, $t = 2.6$), single fixation duration ($b = 0.070$, $SE = 0.019$, $t = 3.6$ and $b = 0.040$, $SE = 0.016$, $t = 2.5$), gaze duration ($b = 0.067$, $SE = 0.023$, $t = 2.9$ and $b = 0.036$, $SE = 0.022$, $t = 1.6$), and reading speed ($b = -44.712$, $SE = 11.014$, $t = -4.1$ and $b = -27.160$, $SE = 14.582$, $t = -1.9$). As shown in Figure 2, these interactions provide clear evidence that restricting sentence viewing with L1R2 and L1R3 windows results in more interference in silent than in oral reading, indicating a larger perceptual span in silent reading.

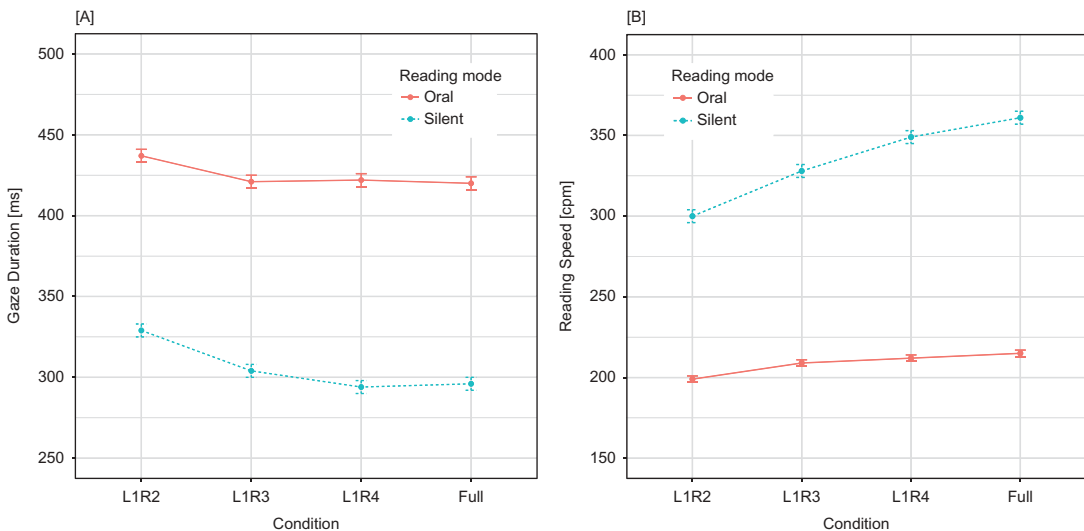


Figure 2. Partial effects (i.e., linear mixed models estimates after removal of between-participant and between-sentence random effects) on gaze duration (A) and on reading speed (B), as a function of viewing constraint, generated using the remef (version 0.6.10; Hohenstein & Kliegl, 2015) and the ggplot2 packages (version 2.1.0; Wickham, 2009). Note. Error bars indicate twice standard errors of the mean. L1R2 = one character to the left of the fixated character; L1R3 = two characters to the right of the fixated character; L1R4 = four characters to the right of the fixated character.

Discussion

In the present study, using the gaze-contingent boundary paradigm, we tested the perceptual span during oral reading of Chinese sentences. Previous studies had mainly focused on silent reading: In Chinese, it has been reported by Inhoff and Liu (1998) that the span covers three characters to the right of the current fixation when visually dissimilar characters were used as masks (see also Chen & Tang, 1998, for results from self-spaced moving-window technique). When using visually similar characters as masks, Yan et al. (2015) found a larger span, extending four characters rightward. Yan et al. (2015) attributed the difference to the use of different masking characters: Chinese readers utilize useful orthographic information from masks to facilitate lexical processing. Using the same experimental materials and manipulation as Yan et al. (2015), we demonstrated in the present study that the perceptual span in Chinese oral reading is also asymmetrically rightward, extending to only three characters to the right of the current fixation, providing the first estimation of the size of the perceptual span during oral reading.

Parafoveal processing efficiency, which is generally considered to be closely related to the size of the perceptual span, has been established with the gaze-contingent boundary paradigm (Rayner, 1975). In this paradigm, the visibility of a parafoveal word during fixations on and prior to pretarget words is under experimental control; during a saccade crossing an invisible boundary located between the pretarget and target words, different types of preview words (identical or masking) are replaced by the correct target words. The size of preview benefit (i.e., the reduction in fixation duration on the target word when parafoveal preview is provided, compared to when it is masked) is considered a measure of the amount of parafoveal information acquired during the previous fixations (Henderson & Ferreira, 1990). Using this paradigm, Inhoff and Radach (2014) compared parafoveal processing in silent and oral reading and found a smaller preview benefit for oral than silent reading. Results from the present study in principle agree with those reported by Inhoff and Radach (2014), showing a cross-language effect of reduction in parafoveal processing efficiency.

Our findings show that results suggesting a reduced span in oral as compared to silent reading (Ashby et al., 2012) generalize across languages and writing systems. Although silent reading activates certain articulation-related word properties in both alphabetic and Chinese writing systems (e.g., Abramson & Goldinger, 1997; Ashby & Clifton, 2005; Eiter & Inhoff, 2010; Inhoff, Connine, & Radach, 2002; Yan, Luo, & Inhoff, 2014), word articulation in oral reading involves muscle movements in the speech tract and operates more slowly than cognitive processes. This characteristic of oral reading serves as a language-universal factor influencing eye movements in reading, given the limited capacity of the working memory buffer.

Oral reading in Chinese is much slower than silent reading. Yan (2015) suggested that prolongation of fixations may provide more time for parafoveal processing of the upcoming words. However, results from the present study indicate that in Chinese oral reading, the increase in parafoveal processing time of the upcoming words due to prolonged fixations does not seem to compensate for the decrease in parafoveal processing efficiency due to increased processing demands.

It remains an open question whether the *percentage* of reduction of the perceptual span in oral reading is language-universal. On one hand, coordinative demands in maintaining a working memory buffer while managing a stream of incoming visual and outgoing articulatory information (see Laubrock & Kliegl, 2015) might be similar across languages. On the other hand, languages differ in the relative importance of certain features. Whereas alphabetic languages are often optimized for fast access to phonology, which is essential for oral reading, Hoosain (1992) pointed out that the Chinese writing system has been well optimized for early and fast semantic processing but less so for phonological processing. Indeed, experimental evidence so far suggests that semantic activation can be faster than phonological activation in Chinese (e.g., Chen & Shu,

2001; Zhou & Marslen-Wilson, 2000; Zhou, Marslen-Wilson, Taft, & Shu, 1999), especially for parafoveal processing (Pan et al., 2016; Yan et al., 2009).

Due to the difference in their optimization for phonology between alphabetic and logographic writing systems, we expect the oral reading-related reduction in span is even larger in Chinese than in English or German. Based on these facts, it is of great theoretical interest and importance for future studies to directly compare the perceptual span in oral and silent reading across different writing systems.

Conclusion

To summarize, the present study illustrates for the first time the physical size of perceptual span in oral reading of Chinese sentences. More critically, we demonstrate that the rightward span is substantially reduced (by 25%) in oral as compared to silent reading. Due to the additional demands of articulation and the associated scheduling and coordination, oral reading may use more attentional resources and lead to higher foveal load than silent reading, resulting in a reduction in the perceptual span (Henderson & Ferreira, 1990; Yan, 2015).

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