Vision Research 150 (2018) 8–14

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Korean reading speed: Effects of print size and retinal eccentricity

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ARTICLE INFO

Number of Reviews = 2

Keywords:
Reading
Peripheral vision
Age-related macular degeneration
Low vision
Crowding

ABSTRACT

Evaluating the effects of print size and retinal eccentricity on reading speed is important for identifying the constraints faced by people with central-field loss. Previous work on English reading showed that 1) reading speed increases with print size until a critical print size (CPS) is reached, and then remains constant at a maximum reading speed (MRS), and 2) as eccentricity increases, MRS decreases and CPS increases. Here we extend this work to Korean, a language with more complex orthography. We recruited 6 Korean native speakers (mean age = 22) and measured their reading speed in central vision (0°) and peripheral vision (10° in the lower field). 900 Korean sentences (average 8.25 words) were created with frequently-occurring beginner-level words, presented using a rapid serial visual presentation (RSVP) paradigm. Data for English reading were obtained from Chung, Mansfield & Legge, *Vision Research*, 1998, for comparison. MRS was similar for Korean and English at 0° (713 vs. 787 wpm), but decreased faster with eccentricity for Korean. CPS was larger for Korean than for English regardless of eccentricity, but increased with eccentricity similarly for both languages. From 0 to 10°, MRS decreased by a factor of 6.5 for Korean and 2.8 for English, and CPS increased by a factor of 11.7 for Korean and 10.2 for English. Korean reading speed is more affected by retinal eccentricity than English, likely due to additional within-character crowding from more complex orthography. Korean readers with central-field loss may experience more difficulty than English readers.

1. Introduction

Age-related macular degeneration (AMD) is a degenerative eye disease that causes damage to the central visual field. It is the third leading cause of moderate or severe visual impairment worldwide (Flaxman et al., 2017). One of the most valued activities impaired for people with AMD is reading (Mitchell & Bradley, 2006), because reading is typically slow and effortful in peripheral vision (Legge, Rubin, Pelli, & Schleske, 1985). The current study measured Korean reading speed in central and peripheral vision and compared it with English reading speed. In Korea, AMD affects approximately 1.54 million (7.4%) of the population who are 40 years or older (Cho, Heo, Kim, Ahn, & Chung, 2014). In the United States, the number of people aged 50 years or older with AMD has increased from 1.75 million in 2000 to 2.07 million in 2010, and is projected to reach 5.44 million by 2050 (National Eye Institute, n.d.). It is important to understand Korean and English reading in both central and peripheral vision.

One of the crucial factors influencing reading speed is the print size. Within a certain range, reading speed will first increase with print size until a *critical print size (CPS)* is reached, and then remain at a *maximum reading speed (MRS)* (Chung, Mansfield, & Legge, 1998; Mansfield, Legge, & Bane, 1996). The CPS increases with retinal eccentricity (Chung et al., 1998). The range of print sizes seen in daily reading materials generally exceeds the critical print size for normally-sighted young adults, but may be below the critical print size for people with central-field loss (Legge & Bigelow, 2011). One of the most common prescriptions for AMD patients is magnification using optical or digital devices.

But size is not the only factor limiting peripheral reading speed. Magnifying text size can equate the threshold duration for a 10-alternative forced-choice word-recognition task in peripheral vision to that in central vision (Latham & Whitaker, 1996). However, the speed of reading meaningful text in peripheral vision is still slower than in central vision (Chung et al., 1998; Latham & Whitaker, 1996). For normally-sighted readers, Chung et al. found a 6-fold decrease in maximum reading speed from 0° (central vision) to 20° in peripheral vision (Chung et al., 1998). In the current study, we were interested in how reading speed for Korean text is influenced by print size and eccentricity, and whether the relationship differs from the findings for English reading (Chung et al., 1998).

Korean (Hangul) and English writing systems are both alphabetic. There are 24 basic Korean letters (14 consonant letters and 10 vowel

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https://doi.org/10.1016/j.visres.2018.06.013
Received 30 January 2018; Received in revised form 25 June 2018; Accepted 25 June 2018

letters), 5 double consonants formed by two same consonant letters, and 11 compound vowels formed by two different vowel letters. But unlike English reading where letters are arranged in a linear fashion, Korean letters are arranged left-to-right, top-to-bottom in a block to form a character (Yoon, Bolger, Kwon, & Perfetti, 2002). Each character is one syllable. One or more characters are arranged left-to-right to form a word. For example, letters ㄱ(“g”), ㅏ(“ah”), and ㅁ (“m”) are arranged into the character/syllable 감 (“gahm”), and this character could appear in words such as 감 (persimmon), 촉감 (touch), or 공포감 (fear).

This special letter configuration introduces within-character crowding for Korean reading (He, Kwon, & Legge, 2018). Identifying a Korean character involves identifying different crowded symbols with an inter-symbol spacing that is even smaller than the character spacing. Since crowding poses a major sensory limitation on reading (He & Legge, 2017; He, Legge, & Yu, 2013; Pelli et al., 2007), Korean reading, which is limited by both within-and between-character crowding, may exhibit different characteristics compared to English reading, which is limited mainly by between-character crowding. In our study, we compared Korean and English reading performance in central and peripheral vision.

2. Methods

2.1. Subjects

We recruited 6 normally-sighted (4 female and 2 male), Korean-English bilingual students from the University of Minnesota. These subjects were native Korean-speakers with English fluency sufficient to support college studies in the United States. Subjects were between 18 and 26 years old (mean = 22) and their average binocular letter acuity was −0.017 logMAR (Lighthouse Near Acuity Chart, Lighthouse Low Vision Products, Long Island City, NY). All subjects signed an IRB-approved consent form prior to the experiment, and received monetary compensation. Our experimental procedure was in compliance with the Declaration of Helsinki.

2.2. Stimuli and apparatus

900 Korean sentences were generated for measuring reading performance. The sentences were first extracted from elementary school-level reading materials and shortened to about 8 words. They were then altered to include words that appear on the lists of frequent words in the Korean language (“부록:자주 쓰이는 한국어 낱말 5800 [Appendix: 5800 Frequently used Korean words],” n.d.; National Institute of the Korean Language, 2005) and vocabulary words recommended for learning Korean (National Institute of the Korean Language, 2003). Some sentences were further changed according to the standardized Korean spell-checker tool (“네이버 맞춤법 검사기 [Naver Spell-Checker],” n.d.). The final set of sentences was 8.25 ± 1.02 words long, and 95.7% of the words were within the frequent or educational word lists. An example sentence is “우리는 호랑이가 보고 싶어서 동물원에 왔습니다” (25 characters including spaces, 6 words, read left-to-right; translation: “We came to the zoo because we wanted to see tigers”).

For comparison, the English sentences used in Chung et al. (1998) had an average length of 11 ± 1.7 words, and all words came from the 5000 most frequent words in written English according to the British National Corpus. The English sentences are longer, but in general more words are needed for English compared to Korean to convey similar information. We compared the word count of the English and Korean versions of the Universal Declaration of Human Rights (http://www.ohchr.org/EN/UDHR/Pages/SearchByLang.aspx), excluding headings and numeration. The English version contained 1680 words, which is 1.55 times larger than the Korean version (1087 words). The average word count for the English sentences used in Chung et al. (1998) was 1.33 times larger than our Korean sentences.

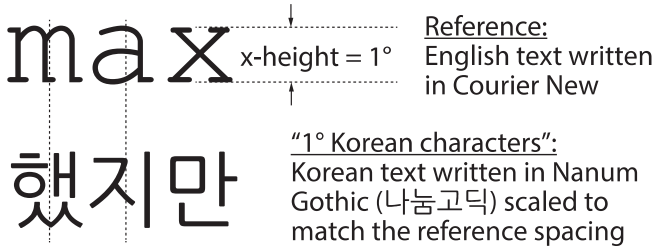

Fig. 1. Definition of Korean print size (details see text).

The Korean characters were rendered in *Nanum Gothic (*나눔고딕*)*, which is a fixed-width font for Korean. There are many potential ways to equate Korean and English text size, but we specified the print size for Korean text by equating the character spacing to the reference English text written in *Courier New* (also fixed-width; Fig. 1). For example, to create 1° Korean characters, we scaled Korean text (written in *Nanum Gothic* with its default spacing) so that the center-to-center spacing between characters matched that for the reference English text with an x-height of 1°. These “1° Korean characters” have an ink height of about 1.33°. Courier New was selected as the reference font because it is fixed-width and it has a stroke width similar to Korean text when scaled. We could not use the font used in Chung et al. (1998), Times-Roman, as the reference because it was a proportional-width font. While the stroke width may differ between Courier New and Times-Roman, English reading performance with normal vision remains unchanged for a range of stroke widths, in both central and peripheral vision (Bernard, Kumar, Junge, & Chung, 2013). We defined Korean print size by matching character spacing because x-height is a well-defined measurement for the size of English letters, and letter spacing is an important factor influencing letter-recognition and reading performance via influencing crowding (Chung, 2002, 2014; Levi & Carney, 2009; Pelli et al., 2007; Yu, Cheung, Legge, & Chung, 2007).

Our stimuli were black Korean characters on a white background (background luminance 102 cd/m^2; Weber contrast = 98%). The stimuli were generated and presented using MATLAB R2014b with Psychophysics Toolbox 3 (Brainard, 1997; Pelli, 1997). We used a NEC MultiSync CRT monitor (model FP2141SB-BK, NEC, Tokyo, Japan; refresh rate = 100 Hz) controlled by a Mac Pro Quad-Core computer (model A1186, Apple Inc., Cupertino, CA). The stimuli were either presented foveally or at 10° in the lower visual field. For measurements in central and peripheral vision, the viewing distance was 200 and 40 cm respectively, and the corresponding spatial resolution of the screen was 0.009°/pixel and 0.04°/pixel.

2.3. Procedure

The experiment required two 2-h sessions, scheduled on two different days at least one week apart. In each session reading speed was measured using Rapid Serial Visual Presentation (RSVP) (Forster, 1970; Rubin & Turano, 1992), similar to Chung et al. (1998). RSVP reading speed was measured in both central and peripheral visual fields (0° and 10° in the lower visual field), using 6 different print sizes each. The print sizes (in x-height) were 0.1, 0.14, 0.19, 0.26, 0.36, and 0.5° in central vision, and 1.2, 1.46, 1.78, 2.63, 3.55, and 5.01° in peripheral vision. The sets of print sizes were chosen based on pilot testing to cover both the rising and the flat part of the two-line reading curve. Each print size was tested in one block of 18 trials. The order of two visual fields and 6 print sizes was counterbalanced across subjects for the first daily session, and reversed in the second daily session.

2.4. RSVP reading speed measurement

In each RSVP trial, a sentence was randomly selected without

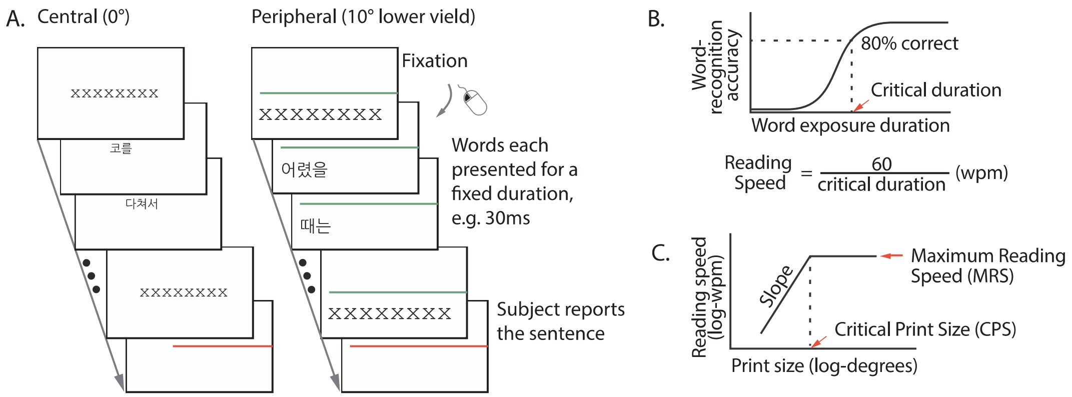

Fig. 2. RSVP reading task and curve fitting. A. Diagrams of the RSVP reading task in central (0°) and peripheral (10° in the lower visual field) vision. The subject fixated on the x's (central vision) or on the green line (peripheral vision). After the subject clicked the mouse, a sentence was presented word-by-word, each word for a fixed duration (e.g. 30 ms), followed by a post mask. The subject could report the sentence during or after the sentence was presented. The number of correctly-read words was recorded. B. Psychometric function fitting. Word-recognition accuracy from the RSVP reading task was plotted against word exposure duration and fitted with a cumulative Gaussian function. The word exposure duration yielding 80% correct word-recognition was then used to calculate the reading speed (in words per minute, wpm). C. Two-line reading curve fitting. Reading speed (wpm) was plotted against print size (degrees) on a log–log scale and then fitted with a two-line reading curve. Three parameters were extracted from the curve for further analyses: the maximum reading speed (MRS), the critical print size (CPS), and the slope of the small-print segment.

replacement from our pool of 900 sentences. As illustrated in Fig. 2A, the sentence was presented word-by-word, with the first word preceded and last word followed by masks of "xxxxxxxx". Masks were rendered in *Courier New*. Subjects were required to read the sentence out loud, and an experimenter who is a Native Korean speaker scored the correctly-read words regardless of word order. For measurements in central vision, the words were presented in the center of the screen, and the subjects directly fixated on the words. For peripheral measurements, a fixation line was presented in the center of the screen and the words were presented 10° below the line. A subject's central fixation was monitored using *Gsou T21v* webcam at 30 frames per second with a dynamic resolution of 640 × 480. This method can reliably detect saccades of 2° or more (Cheong, Legge, Lawrence, Cheung, & Ruff, 2007). Horizontal eye-movements along the line were permitted, but if vertical eye-movements were detected, the trial was replaced by a new trial. On average, 0.7% trials tested in peripheral vision were rejected due to saccades.

Within a trial, the word exposure duration was the same for all the words (e.g. 30 ms). In a block of 18 trials, 6 different exposure durations were each tested in 3 trials in a random order. The set of exposure durations for each individual in each block spanned 1–1.5 log units (e.g. 0.03, 0.06, 0.12, 0.25, 0.50, and 1 s), and the set was chosen according to the performance of that subject in practice trials. Every subject read 6 sentences (average 49.5 words) for each print size × duration × eccentricity combination.

2.5. Data analysis

Individual data were pooled from the two daily sessions for each eccentricity × print size combination and reading speed was computed (Fig. 2B). Two-line reading curves were fitted for each eccentricity (Fig. 2C) where the slope of the small-print segment could vary and the slope of the large-print segment was fixed to zero. Three parameters were extracted and analyzed: MRS, CPS, and the slope of the small-print segment. Our results were compared with corresponding English data (Chung et al., 1998) provided by Dr. Susana T.L. Chung. The original English data set contained reading speeds for 6 subjects, 6 eccentricities/subject, and 8 print sizes/eccentricity, except for 1 subject at 1 eccentricity where there was only 7 print sizes, totaling 287 data points. Here, we only analyzed data from 2 eccentricities (0° and 10°) corresponding to our measurement of Korean reading. We fitted individual two-line reading curves using these data and extracted the MRS, CPS, and slope.

We performed 2 × 2 mixed-design analysis of variance (ANOVA) to examine the effect of language (between-subject) and eccentricity (within-subject) on the MRS, CPS, and slope, respectively. Significant interaction between language and eccentricity was further analyzed using *R* with the package *phia* (Post-hoc Interaction Analysis) (Martínez, 2015). Outliers were detected using Bonferroni Outlier Test (*R* package *car*) and removed before the analyses.

Many visual functions in central and peripheral can be equated using the equation

$$y = y_0 \times \left(1 + \frac{E_{cc}}{E_2}\right) \tag{1}$$

where y_0 is the value (e.g. CPS) when eccentricity is 0 (i.e. using central vision), y is the value at a given eccentricity Ecc, and E_2 is a factor describing how y changes with eccentricity (Levi, Klein, & Aitsebaomo, 1984; Wilson, Levi, Maffei, Rovamo, & DeValois, 1990). The ecological meaning of E_2 is the eccentricity at which y reaches twice the value of central vision, y_0. A larger E_2 value indicates a smaller effect of eccentricity on the variable of interest. To quantify the influence of eccentricity on MRS, CPS, and the slope, we computed the E2 values for these three parameters and compared between Korean and English.

3. Results

Fig. 3 compares two-line reading curves for Korean (this study; top) and English (from Chung et al., 1998; bottom). Reading speed is plotted against print size on a log–log scale, with separate curves for 0° (open circles; central vision) and 10° in the lower visual field (solid circles). Lines represent the fitted two-line reading curves.

For both languages, and in both central and peripheral vision, the two-line function fit the reading speed data very well: Reading speed first increased with print size until the critical print size, and then remained constant at the maximum reading speed. Table 1 summarizes the key parameters of reading excluding outliers: the maximum reading speed, the critical print size, and the slope for the small-print segment. In the next sections we will examine the interaction between language and eccentricity for these parameters.

3.1. Maximum reading speed

The first two rows in Table 1 compare maximum reading speed for Korean and English in central and peripheral vision. One outlier,

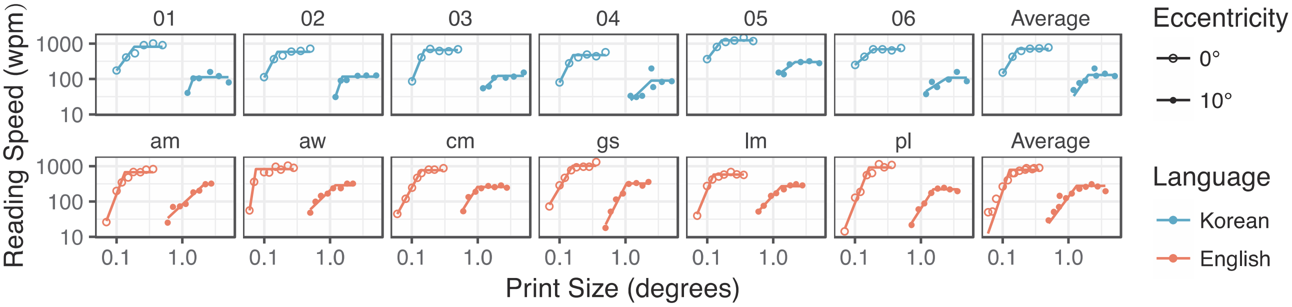

Fig. 3. Two-line reading curves for Korean and English. Each panel shows data for one subject (first six columns) or the group average (last column). Top, Korean data (this study); bottom, English data (Chung et al., 1998). Subject designators for the English data correspond to those used by Chung et al. (1998). Open circles, central vision (0°); filled circles, peripheral vision (10° in the lower visual field). Lines, fitted curves. The fitted curves for the average data were produced using the averaged slope, CPS, and MRS of individual fittings, rather than by fitting the averaged data.

Table 1
Summary of key parameters of reading (mean ± SEM).

Parameter	Eccentricity	Korean	English
Maximum reading speed (wpm)	0°	713 */ 1.14	787 */ 1.09
	10°	110 */ 1.05	277 */ 1.06
Critical print size (°)	0°	0.17 */ 1.04	0.13 */ 1.12
	10°	1.99 */ 1.10	1.33 */ 1.13
Slope for the small-print segment (log-wpm/log-degree)	0°	3.07 ± 0.45	4.12 ± 0.36
	10°	2.72 ± 0.78	2.50 ± 0.31

The values for maximum reading speed and critical print size were initially averaged in the log space because the two-line curve was fitted on a log–log scale. Here we convert the Mean ± SEM in the log space back to the original unit as 10^{Mean} */ 10^{SEM} (the symbol */ means "multiply or divide by", similar to the sign ±, "plus or minus"). Outliers were detected and removed before summarizing.

Korean subject "05" at 10°, was detected and removed, marked by a blue arrow in Fig. 4A. In general, MRS decreased with eccentricity for both languages, but the decrease was faster for Korean than for English. From 0 to 10°, MRS decreased by a factor of 6.5 for Korean and 2.8 for English. Mixed-design ANOVA on log-MRS revealed a significant interaction between language and eccentricity ($F_{(1,\ 10)} = 29.52$, $p < 0.001$), indicating that eccentricity had a larger impact on Korean reading than on English reading. Further analysis of the interaction showed that log-MRS did not differ between Korean and English in central vision (2.85 vs. 2.90 log-wpm, or 713 vs. 787 wpm, adjusted $p = 0.56$), but differed significantly at 10° in the lower field (2.04 vs. 2.44 log-wpm, or 110 vs. 277 wpm, adjusted $p < 0.001$).

To quantify the influence of eccentricity, we fitted the data using Eq. (1) to extract E_2 values (Fig. 4A). But instead of using maximum reading speed, we used the critical word exposure time corresponding to the maximum reading speed, because the latter changed linearly with eccentricity while the former did not (Chung et al., 1998). Larger critical exposure time means slower maximum reading speed. For example, if the maximum reading speed is 800 wpm, the corresponding exposure time for each word is 60/800 = 0.075 s.

For Korean, E_2 for critical exposure time was 2.11 ± 0.17° (mean ± SEM). For English, E_2 for critical exposure time was 5.92 ± 0.93° and was larger than Korean, indicating a slower change with eccentricity. The English E_2 value was slightly larger than the original fitted value of 4.13 ± 0.78° reported by Chung et al. (1998). Note that here we only used English data for 0° and 10° instead of all 6 eccentricities from the original study (Chung et al., 1998), but the E_2 value was similar if we included all the data (5.07 ± 1.35°). It is worth mentioning that there were differences in the curve fitting methods between the original study and the current study. In the original study, data were weighted by the inverse of their SEM values and fitted using *Igor Pro*, which uses the Levenberg-Marquardt algorithm to solve the non-linear least squares problem. In our study, data were not weighted, and were fitted with R, which uses the Gauss-Neuton algorithm.

3.2. *Critical print size*

Both Korean and English critical print sizes (Table 1) increased with eccentricity similarly: from 0 to 10°, there was an 11.7-fold increase for

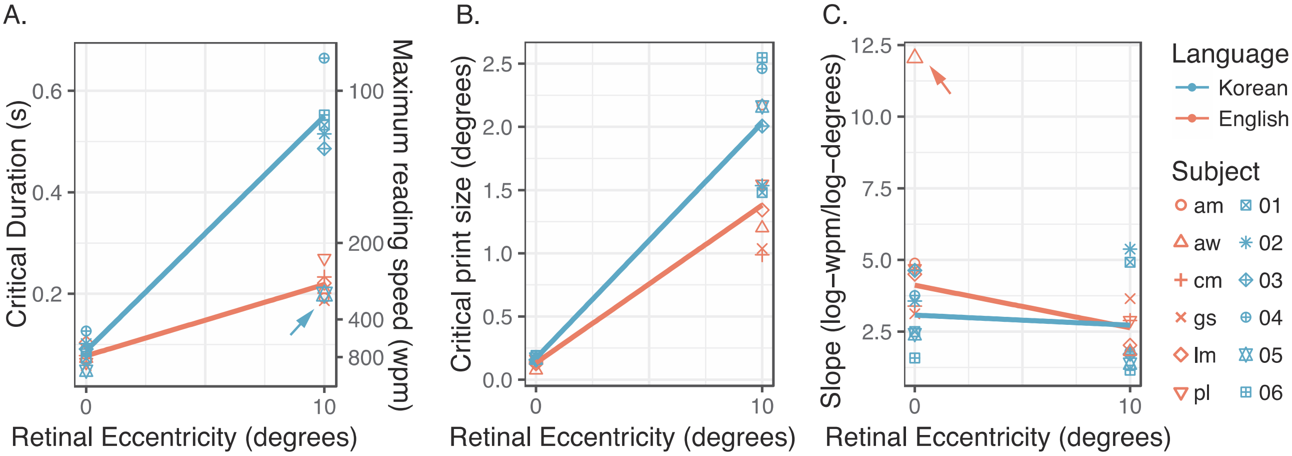

Fig. 4. The change of three parameters as a function of retinal eccentricity (in degrees). A. The critical exposure time (seconds) reciprocally related to maximum reading speed (left y-axis) and the corresponding maximum reading speed in wpm (right y-axis). B. Critical print size (degrees). C. The slope for the first segment of the reading curve (log-wpm/log-degree). Points, individual data. Two outliers, Korean subject "05" in panel A at 10°, and English subject "aw" in panel C at 0°, are marked by arrows in the matched color. Lines, linear regression using Eq. (1), excluding outliers. Blue, Korean; red, English.

Korean and a 10.2-fold increase for English. ANOVA on log-CPS revealed no significant interaction between language and eccentricity, so we removed the interaction term from the model. In the updated model, there was a main effect of eccentricity ($F_{(1,\ 11)} = 694.41$, $p < 0.001$), indicating that critical print size increased with eccentricity. There was also a main effect of language ($F(1, 10) = 11.29$, $p = 0.007$), indicating that Korean critical print size was larger than English critical print size.

Fig. 4B shows how critical print sizes changed with eccentricity. Using Eq. (1), we found an E_2 value of 1.16 ± 0.20° for English CPS. Including English data from all six eccentricities barely changed the E_2 value, 1.12 ± 0.35°. These values are similar to the original finding of 1.39 ± 0.75° in Chung et al. (1998). For Korean CPS, the E_2 value was 0.96 ± 0.11°. The similar E_2 values for Korean and English indicate that eccentricity has a similar impact on the CPS for both languages.

3.3. *The slope*

The slopes for the small-print segment were mostly the same regardless of language and eccentricity except for one outlier: subject "aw" in central vision (Fig. 4C, outlier marked by a red arrow). After excluding the outlier, no significant main effect or interaction was found by ANOVA. This was consistent with the previous finding that the slope did not change with eccentricity (Chung et al., 1998). The average slope, excluding the outlier, was 2.90 ± 0.43 log-wpm/log-degree for Korean and 3.23 ± 0.34 for English. Including all 6 eccentricities for English from Chung et al. (1998), and excluding the outlier, barely influenced the average slope (3.00 ± 0.17). Our computed value was larger than the one originally reported (2.32 ± 0.18) (Chung et al., 1998), likely due to the differences in curve fitting methods mentioned in 3.1.

3.4. *Reading acuity*

One meaningful and important parameter that can be extracted from the reading curves is the reading acuity, that is, the smallest print size that can be read. We computed reading acuity by extrapolating the reading curve to the print size where reading speed is 10 wpm, i.e. log-wpm = 1. The slope for subject "aw" in central vision was an outlier and thus was not included in this analysis. From central to peripheral vision, the logMAR reading acuity value increased, faster for Korean reading (from −0.38 ± 0.11 to 0.79 ± 0.12 logMAR) compared to English reading (from −0.24 ± 0.05 to 0.62 ± 0.05 logMAR). The letter acuity had an average of −0.017 logMAR for our Korean subjects, and ranged from −0.19 to 0.00 logMAR for English subjects (Chung et al., 1998). The reading acuity in central vision is smaller than letter acuity for both Korean and English subjects, consistent with previous findings (Xu & Bradley, 2015).

Note that there are other scoring methods for reading acuity that are similar to the logic behind logMAR acuity charts (Calabrèse et al., 2016; Xu & Bradley, 2015), but those do not apply to our RSVP paradigm. Calabrèse et al. (2016) used such a method to estimate reading acuity for English subjects from childhood to old age. For 21-year-old subjects, the estimated reading acuity was −0.17 logMAR. Our calculated reading acuity in central vision (−0.24 ± 0.05 logMAR) was close to the previous estimation (Calabrèse et al., 2016).

4. Discussion

4.1. *Korean MRS decreases faster with eccentricity*

Maximum reading speed decreased faster with eccentricity for Korean than for English. That is, eccentricity has a stronger impact on Korean MRS than English MRS. What accounts for this difference? Since all subjects were native speakers of the tested language, this difference cannot be explained by the lack of proficiency in the tested language. One possible factor that contributes to the difference is the visual span for reading. The visual span describes the amount of information captured within a glimpse, i.e. how many letters can be recognized without eye movements (Legge, Mansfield, & Chung, 2001). The size of the visual span decreases with eccentricity (Legge et al., 2001), correlated with the decrease of reading speed (Legge et al., 2007). A major sensory factor limiting the size of the visual span is visual crowding (He et al., 2013; Pelli et al., 2007; Wang, He, & Legge, 2014; Yu, Legge, Wagoner, & Chung, 2014). More complex stimuli such as Korean or Chinese characters and faces had smaller visual spans due to increased between-stimulus crowding as well as additional within-stimulus crowding (He et al., 2015, 2018; Wang et al., 2014).

Another possible factor is temporal in nature. Longer exposure time of stimuli yields better letter acuity (McAnany, 2014), higher contrast sensitivity (Legge, 1978; Rovamo, Leinonen, Laurinen, & Virsu, 1984), larger visual span (Legge et al., 2001), and better lexical judgment (H.-W. Lee, Legge, & Ortiz, 2003), suggesting that the temporal integration of visual information is a limiting factor on letter recognition and reading. It has been shown that for contrast sensitivity at a given eccentricity, the effect of exposure time is more striking for higher spatial frequencies compared to lower frequencies (Legge, 1978; Rovamo, et al., 1984). More complex characters have a broader spectrum of spatial frequencies and require higher cut-off frequencies to recognize (Wang & Legge, 2018). Therefore, Korean characters, being more complex than English letters and thus having more higher-frequency components, may be more susceptible to temporal processing limits.

A third possible influencing factor is lexical inference. For English reading, when there are errors in letter identification or localization, human readers need to use knowledge of the lexicon of possible words to infer the correct word. Letter identification and localization errors increase with eccentricity (e.g. Chung & Legge, 2009; He et al., 2013; Wang et al., 2014), and therefore peripheral vision may rely more on lexical inference. But lexical inference of human readers is suboptimal (Legge, Klitz, & Tjan, 1997). Do English and Korean reading makes similar use of lexical inference? One way to assess the role of lexical inference is to evaluate the transposed-letter effect. In English or Korean reading, a nonword created by transposing letters within a base word (e.g. nakpin from napkin, or 밤눅 (bamnuk) from 남북 (nambuk)) can activate the lexical representation of the base word to facilitate reading. It has been shown that this effect is much reduced for Korean compared to English (C. H. Lee & Taft, 2009). In other words, Korean reading may make less use of lexical inference and therefore be more vulnerable to position uncertainty of characters. This difference between English and Korean reading might help to explain the more rapid decline in Korean reading speed in peripheral vision.

4.2. *CPS has similar dependency on eccentricity for Korean and English*

Unlike maximum reading speed, the critical print size for reading had similar dependency on eccentricity for both languages. Critical print size can be derived from the critical spacing of crowding (Pelli et al., 2007), and the critical spacing for crowding is proportional to retinal eccentricity regardless of the object (for reviews, see Levi, 2008; Pelli & Tillman, 2008). Pelli and colleagues measured the spatial extent of crowding using letters in different fonts, and found that letter complexity does not change the extent of crowding (Pelli, Palomares, & Majaj, 2004). Therefore, although Korean characters are more complex, it is not surprising that the critical print size for Korean and English had similar dependency on eccentricity. Note that identifying a Korean character involves identifying different crowded symbols with an inter-symbol spacing that is even smaller than the character spacing. Our findings suggest that in terms of determining the critical print size, English letter spacing is more equivalent to Korean inter-character spacing rather than the inter-symbol spacing. The influence of inter-character and inter-symbol spacing on Korean reading can be further teased apart and evaluated in future studies.

As a side note, we measured the font sizes of body text used in mainstream Korean and English newspaper websites. If the websites are well designed, their print sizes should exceed the critical print sizes under a typical viewing condition to ensure fluent reading. At a typical viewing distance of normally-sighted computer users for English text (about 50 cm, Granquist et al., in press), and with the browser's default magnification (no zooming, 100% size), the font sizes of body text for the top 5 Korean newspapers ("2017년도 일간신문 발행 유료부수 [2017 daily newspapers paid circulation]," 2017) ranged from 0.34° to 0.46° in ink height, which was larger than the ink height corresponding to our measured Korean critical print size in central vision (0.23°). For the top 5 US newspapers (Top 15 U.S. Newspapers by Circulation, 2017), the x-height was about 0.23°, also exceeding the previously measured English foveal critical print sizes (0.2° across studies, summarized in Legge, 2007; Legge & Bigelow, 2011). Along with previous findings (Legge & Bigelow, 2011), these results demonstrate that basic visual properties put constraints on the choice of print sizes.

4.3. Clinical implications

For people with central-field-loss, appropriate magnifying tools have to be supplied in order to achieve maximum reading speed. There are various types of reading aids, ranging from simple optical magnifiers to powerful video magnifiers (Virgili, Acosta, Grover, Bentley, & Giacomelli, 2013). Suppose an eye-care clinician wants to provide recommendations for a patient. What power of magnification should be prescribed? Our finding suggests that the scaling factor depends on the position of the preferred retinal locus, i.e. the retinal eccentricity for reading, but not the language of the text. However, as shown in the current study and elsewhere (Chung et al., 1998; Legge, Ross, Isenberg, & LaMay, 1992), magnification per se cannot restore peripheral reading speed to the level in central vision. For some languages, in our case Korean compared to English, the disadvantage in reading speed brought about by central-field-loss is more severe.

Acknowledgements

The authors would like to thank Susana T.L. Chung for providing the data from Chung et al. (1998) and explaining the curve fitting method, MiYoung Kwon for her help in preparing the testing material and providing constructive suggestions for the manuscript, and Charles Bigelow for valuable information regarding font metrics. The study was supported by NIH Grant EY002934 and a Doctoral Dissertation Fellowship from the University of Minnesota.

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