Comparing reading speed for horizontal and vertical English text

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There are three formats for arranging English text for vertical reading—upright letters arranged vertically (marquee), and horizontal text rotated 90° clockwise or counterclockwise. Previous research has shown that reading is slower for all three vertical formats than for horizontal text, with marquee being slowest (M. D. Byrne, 2002). It has been proposed that the size of the visual span—the number of letters recognized with high accuracy without moving the eyes—is a visual factor limiting reading speed. We predicted that reduced visual-span size would be correlated with the slower reading for the three vertical formats. We tested this prediction with uppercase and lowercase letters. Reading performance was measured using two presentation methods: RSVP (Rapid Serial Visual Presentation) and flashcard (a block of text on four lines). On average, reading speed for horizontal text was 139% faster than marquee text and 81% faster than the rotated texts. Size of the visual span was highly correlated with changes in reading speed for both lowercase and uppercase letters and for both RSVP and flashcard reading. Our results are consistent with the view that slower reading of vertical text is due to a decrease in the size of the visual span for vertical reading.

Keywords: visual span, letter recognition, reading speed, vertical reading

Citation: Yu, D., Park, H., Gerold, D., & Legge, G. E. (2010). Comparing reading speed for horizontal and vertical English text. *Journal of Vision, 10*(2):21, 1–17, http://journalofvision.org/10/2/21/, doi:10.1167/10.2.21.

Introduction

Although native English speakers normally read horizontal text, there are some situations in which text is presented vertically. The three main vertical text formats are text rotated 90° clockwise or 90° counterclockwise, and marquee in which upright letters are arranged vertically (see Figure 1). One familiar example of vertical text is when the title of a book is written vertically along the spine, typically with the text rotated 90° clockwise in North America and 90° counterclockwise in Europe. The term "marquee" is derived from the traditional use of marquee text above a theater entrance, usually containing information on a current play or film. In some situations, when text needs to be written vertically because of limited horizontal space, the marquee format may be used. For example, on buses, "watch your step" signs are often painted in marquee text on the poles next to the doors. In some cities, such as Key West, Florida, and Carmel-by-the-Sea, California, street names are painted on pillars in marquee style (see the example in Figure 2).

Perceptual hypothesis

Which of the three vertical formats is easiest to read? Byrne (2002) found that reading a page of text composed of 30 three-syllable words was slower for all three vertical formats compared to the horizontal format, with marquee being slower than either of the rotated formats. Reading time for the marquee format was 1.8 times longer than for the horizontal format, and an average of 1.3[1] times longer than for the two rotated formats (Byrne, 2002). However, subjects in Byrne's study read from pages which required eye movements as in everyday reading, so it is unclear whether the horizontal–vertical differences are perceptual in origin, or due to differences in oculomotor control.

To address the role of oculomotor factors, we measured reading speed using two types of text displays—RSVP (Rapid Serial Visual Presentation) and flashcard (a four-line block of text; see Figure 1C). The flashcard task is similar to everyday page reading in requiring saccadic eye movements (such as forward saccades and return sweeps at the ends of lines). It differs from most page reading in having very short lines and hence a greater reliance on

doi: 10.1167/10.2.21 Received April 7, 2009; published February 23, 2010 ISSN 1534-7362 © ARVO

Figure 1. Examples of lowercase and uppercase (A) trigrams, (B) RSVP words, and (C) flashcard stimuli in the four different text formats: horizontal, rotated clockwise, rotated counterclockwise, and marquee.

return sweeps. We have used this type of display to study eye-movement based reading in previous research because it permits the use of a wide range of print sizes for testing both normal and low vision. Unlike the flashcard task, RSVP presents words sequentially in one retinal location, thereby minimizing the need for eye movements during reading, and removing the ceiling on reading speed imposed by oculomotor limitations. Given this advantage, RSVP reading speed is usually about 50% to 100% faster than regular page reading (Juola, Ward, & McNamara, 1982; Legge, 2007; Yu, Cheung, Legge, & Chung, 2007).

It has been proposed that the size of the visual span, the number of adjacent letters that can be recognized reliably without moving the eyes, imposes a bottom-up sensory limitation on reading speed (Legge et al., 2007; Legge, Mansfield, & Chung, 2001). RSVP reading speed is thought to be closely linked with sensory limitations (i.e., the size of the visual span), and indeed, this has been validated by many studies (Legge et al., 2007; Legge et al., 2001; Pelli et al., 2007; Yu, Cheung et al., 2007). The current study investigated whether there is a perceptual explanation for the slower vertical reading speeds—the slower speed is due to a smaller visual-span size.

An ideal-observer model, Mr. Chips, has been used to simulate saccade planning in reading (Legge, Hooven, Klitz, Mansfield, & Tjan, 2002; Legge, Klitz, & Tjan, 1997). Mr. Chips exhibits a strong relationship between the size of the visual span and saccade length, and indicates that the correlation between RSVP reading speed and visual-span size can generalize to reading with eye movements. Such a correlation was found by Yu, Cheung et al. (2007). These authors found that the size of the visual span and reading speed measured by the flashcard presentation method showed a qualitatively similar dependence on letter spacing, and were also highly correlated. The present study shows that text orientation, like letter spacing, has corresponding effects on visual-span size and flashcard reading speed, providing further evidence for an association.

Figure 2. A picture taken in Key West, Florida shows that street names are painted on pillars in marquee style.

Possible factors limiting vertical reading speed

In horizontal text, the orientation of individual letters (vertical) is orthogonal to the spatial arrangement (horizontal) of letters within the word. Vertical text can affect either the orientation of individual letters or the orthogonal relationship between letter orientation and word orientation. It has been shown that both reaction time and accuracy for single letter recognition are largely independent of letter orientation, but word or connected text recognition can be affected by letter orientation (Koriat & Norman, 1984, 1985, 1989). These authors found that the performance of subjects on a lexical-decision task deteriorated (increased reaction time and decreased accuracy) when a word or non-word was presented in rotated formats, keeping the orthogonal relationship between letters and words. The effect was strongest when text was presented at an angle between 60° and 120° from the horizontal. This suggests an adverse effect of rotation on word recognition although the relative positions of letters within a word-centered coordinate system are unchanged. In contrast, for marquee text, the normal orthogonal relationship between letter orientation and word orientation is disrupted and both the letters and words have a vertical orientation. Babkoff, Faust, and Lavidor (1997) found reduced performance (increased reaction time and decreased lexical-decision accuracy) on a lexical-decision task when the letter strings were moved from the horizontal to the vertical orientation while maintaining the upright position of the letters (marquee format). It is possible that disrupting the normal orthogonal relationship between letter and word orientation has an impact on the parallel processing of letters within words. In the present study, we measured both letter-recognition accuracy and reading speeds in the typical horizontal format and the three vertical formats and examined how performance is affected by letter orientation and the relative positions of letters within a word-centered coordinate system.

While horizontal flashcard reading proceeds from left to right across the page, vertical flashcard reading changes the direction of eye movements (reading direction) to either top to bottom for rotated clockwise and marquee or bottom to top for rotated counterclockwise. Since readers of English text have less experience with planning and making reading saccades up or down compared with reading in the regular left-to-right direction, flashcard reading speed with vertical words may be further reduced by lack of practice with vertical reading. If so, we would expect to see a larger difference between the RSVP and flashcard reading speeds for the three vertical formats than for the horizontal format. Previous findings (Oda, Fujita, Mansfield, & Legge, 1999) on Japanese readers who have extensive experience with both horizontal and vertical reading showed that reading speeds were the same for horizontal and vertical text. This finding may mean that with extensive experience, reading speed in the two directions can be equivalent.

We also investigated how letter case affects horizontal and vertical reading and which text format favors lowercase and which favors uppercase. Several studies have addressed the influence of letter case on letter or word legibility and reading speed for horizontal text. Lowercase letters and words have more shape variations than uppercase letters because of the ascenders and descenders. These extra features may make letter and word recognition easier in lowercase text than in uppercase text (Lete & Pynte, 2003; Perea & Rosa, 2002; Tinker, 1963, p. 34). On the other hand, uppercase letters are generally larger than lowercase letters, given the same font size (for example, lowercase x-height and uppercase x-height have different angular sizes in the same font size), which may make uppercase letters more legible (Arditi & Cho, 2007). These authors found that for the Arial font, the size threshold for uppercase words and random letter strings was about 0.1 log unit lower than for lowercase words and random strings. Even so, the majority of readers still prefer lowercase text to uppercase text (Tinker, 1932; Tinker & Patterson, 1929). Arditi and Cho (2007) also found that uppercase text is read more quickly than mixed-case text when print sizes are close to the acuity size, but the advantage disappeared when print sizes are large and presumably above the critical print sizes (CPS, beyond which reading speed is not limited by print size). The present study investigates the effect of letter case on letter recognition and reading for both horizontal and vertical text formats by directly comparing uppercase with lowercase text in the Courier font.

Relevance to low vision

In addition to real-world applications for normal vision, vertical text may have practical applications for some people with low vision, especially those who have a central scotoma. Age-related macular degeneration (AMD), which frequently causes scotomas in central vision, is the leading cause of visual impairment in developed countries. Afflicted patients must rely on their peripheral vision, making reading slow and difficult (Faye, 1984; Fine & Peli, 1995; Fletcher, Schuchard, & Watson, 1999; Legge, Ross, Isenberg, & LaMay, 1992; Legge, Rubin, Pelli, & Schleske, 1985). Evaluating the potential utility of vertically aligned letters in reading rehabilitation for people with AMD may yield beneficial results. Due to individual differences in retinal damage, the region of central-vision loss (scotoma) shows substantial variation across AMD patients. Patients often select a region in the peripheral visual field near the boundary of the scotoma for fixation and reading, called the preferred retinal locus (PRL). Previous studies have found that the majority of patients with central scotoma have either a left-field PRL or a lower-field PRL (Fletcher & Schuchard, 1997; Fletcher, Schuchard, Livingstone, Crane, & Hu, 1994; Sunness, Applegate, Haselwood, & Rubin, 1996; Timberlake et al., 2005). If PRL locations were adopted purely by chance, only 25% of PRLs would fall into the left field, but the preference for a left-field PRL reached 63% in the study by Sunness et al. (1996). For PRLs on the left or right of a scotoma, the scotoma will block a significant amount of the horizontal text and reading will be compromised. What kind of text format would be best for these AMD patients? Peli (1986) suggested that the optimal direction of saccadic eye movements (reading direction) for AMD patients is the tangential direction (orthogonal to the line connecting the fovea with the PRL), while saccadic eye movements along the radial line are more difficult.

The potential value of vertical text may be linked to properties of crowding. Many studies have suggested that crowding explains the slow reading speeds exhibited in peripheral vision (see Pelli et al., 2007 for detailed discussion). Toet and Levi (1992) found a stronger crowding effect in the radial direction than in the tangential direction, implying that text presented tangentially may be easier to read than radial text. Furthermore, Feng, Jiang, and He (2007) reported that the crowding effect is stronger when the target and flankers were horizontally arranged than vertically arranged. Together, the findings on eye movement control and crowding indicate that people with a lateral PRL may read vertical text more easily than regular horizontal text.

Additionally, rearranging text in the vertical direction may expand the usable visual field. It has been shown that AMD patients can be trained to develop a new retinal location (trained retinal locus, TRL) for reading when the current PRL is not optimal (Nilsson, Frennesson, & Nilsson, 1998, 2003; Watson, Schuchard, De l'Aune, & Watkins, 2006). When the usable visual field is larger on the left or right of the scotoma compared to above and below the scotoma, training patients to read vertical text in the left or right visual field may result in better performance than reading horizontal text in the upper or lower visual field.

Although we tested only the foveal area in normally sighted subjects in the present study, this work is a significant preliminary step toward implementing vertical text presentation as a form of rehabilitation for people with central-field loss.

In this study, we investigated how fast native English speakers can read three vertical text formats, whether letter case affects reading speed, and most importantly why reading is slower with vertical text than horizontal text. According to an experiential hypothesis, the difference between reading horizontal and vertical text occurs because most English speakers regularly read horizontal text and seldom read vertical text. In this study, we tested an alternative perceptual hypothesis—the slower vertical reading speed is due to the reduced visual-span size for the three vertical formats.

Experiment 1: Critical print size (CPS)

A preliminary experiment was devoted to measuring the Critical Print Size (CPS). CPS is defined as a threshold value beyond which print size does not limit maximum reading speed. Previous studies have measured CPS for horizontal text, and found that CPS in normal central vision is approximately 0.1°–0.2° (Chung, 2002; Yu, Cheung et al., 2007). CPS has not been measured for vertically oriented text. It is important to characterize this property of reading for the three vertical text formats. A print size larger than the CPS is usually selected for testing to minimize character-size effects on reading. In Experiment 1, we determined a print size for use in Experiment 2 by measuring the CPS for both lowercase and uppercase text and for horizontal, marquee, rotated clockwise, and rotated counterclockwise text formats.

Subjects

Ten normally sighted, native English-speaking, young adults recruited from the University of Minnesota were randomly assigned to either the lowercase text group or the uppercase text group (5 subjects per group). Table 1 shows a summary of age, gender ratio, binocular distance visual acuity measured by the Lighthouse distance visual acuity chart, log contrast sensitivity measured by the Pelli–Robson contrast sensitivity chart, and three measures from the MNREAD reading acuity chart. The MNREAD data were analyzed with the method described in Cheung,

	Experiment 1		Experiment 2	
	Lowercase	Uppercase	Lowercase	Uppercase
Age (year)	21 ± 0.7	20.6 ± 0.9	21.3 ± 1.1	21.6 ± 0.7
Gender ratio (M:F)	2:3	3:2	6:6	6:6
Visual acuity (logMAR)	−0.23 ± 0.02	−0.18 ± 0.02	−0.17 ± 0.02	−0.15 ± 0.02
Log contrast sensitivity	2.00 ± 0.02	1.98 ± 0.02	1.98 ± 0.01	1.96 ± 0.01
MNREAD reading acuity (logMAR)	−0.21 ± 0.01	−0.22 ± 0.03	−0.17 ± 0.03	−0.16 ± 0.02
MNREAD critical print size (logMAR)	0.06 ± 0.04	0.03 ± 0.03	0.02 ± 0.03	0.04 ± 0.02
MNREAD maximum reading speed (wpm)	190 ± 9	200 ± 4	201 ± 9	186 ± 3.3

Table 1. Summary table of age, gender ratio, and clinical test results (mean ± standard error).

Kallie, Legge, and Cheong (2008). All subjects signed an IRB-approved consent form before beginning testing. None of the subjects had prior experience with the vertical text stimuli used in this study.

Apparatus, stimuli, and experimental design

MATLAB 5.2.1 and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) were used to generate the experimental stimuli and control our experiments. The stimuli were presented on a SONY Trinitron color graphic display (model: GDM-FW900; refresh rate: 76 Hz; resolution: 1600 × 1024), controlled by a Power Mac G4 computer (model: M8570).

Courier, a serif font with fixed width, was used in the study. All the stimuli were rendered as black characters on a white background (87.7 cd/m^2) with Michelson contrast of nearly 100%. For all 10 subjects, RSVP and flashcard reading speeds were measured at five print sizes. For the lowercase group, the print sizes (defined as x-height in lowercase) were 0.06°, 0.085°, 0.16°, 0.30°, and 0.55° of visual angle. For the uppercase group, the print sizes (defined as x-height in uppercase) were 0.08°, 0.11°, 0.20°, 0.38°, and 0.68° of visual angle. A viewing distance of 40 cm was used for the two largest print sizes (0.30° and 0.55° for lowercase and 0.38° and 0.68° for uppercase) and a viewing distance of 200 cm was used for the other three print sizes to ensure good pixel resolution of the letters.

Subjects read text in four different formats: horizontal, rotated clockwise (90°), rotated counterclockwise (90°), and marquee. Marquee text is composed of upright letters arranged vertically. The standard center-to-center letter spacing (in normal Courier text), defined as 1.16 times the width of the letter x, was used in the horizontal, rotated clockwise, and rotated counterclockwise conditions. Since there is no existing standard for letter spacing of marquee formatted text, we equated spacing for horizontal and marquee letters by matching the edge-to-edge separation. For example, two letter x's displayed in the horizontal condition have a standard edge-to-edge separation of 0.16 × x-width. In marquee text, the same separation distance was created between letter x's. This method works well for uppercase letters because uppercase letters all have the same height (except the letter Q) and do not overlap when this standard edge-to-edge separation is used. However, many lowercase letters have ascenders or descenders and consequently require much more space in the vertical direction than the letter x. Therefore, we adjusted the lowercase letter spacing so that no two letters overlapped and used this minimal non-overlapping letter spacing (1.67 × x-width) as the standard for lowercase marquee text. Since the center-to-center letter spacing is fixed for both uppercase and lowercase, the edge-to-edge separation is normally larger in the lowercase than the uppercase marquee text except when a descender letter is followed by an ascender letter.

Measuring RSVP reading speed

For RSVP reading, words were presented sequentially at a single location (left justified) on the display screen. Subjects were instructed to read the sentences aloud as accurately as possible immediately after the stimuli were presented. They were permitted to complete their report after the sentence disappeared from the display and to move their eyes during the testing. Sentences were randomly selected from a pool of sentences developed by Chung, Mansfield, and Legge (1998). The average sentence length was 11 words and the average word length was four letters. A pre-mask (for example, "xxxxxxxxxxxxxx" for the horizontal text format) was presented before the first word in each sentence to indicate the location of upcoming words. A column of x's was used as a pre-mask for the three vertical text formats. A row (or column, as appropriate) of x's was also shown after the last word of each sentence as a post-mask.

Measuring flashcard reading speed

The computerized MNREAD procedure (Legge, Ross, Luebker, & LaMay, 1989) was used in the flashcard paradigm to measure reading speed. As shown in Figure 1C, in flashcard text presentation, the sentence was arranged into four lines. Each line had 14 characters (including spaces) and an implied space at the end of each line. Since the letter spacing for the marquee text is larger than the letter spacing for the other three text formats, the inserted space between words is correspondingly larger for the marquee text format.

Reading these text blocks required reading eye movements (forward saccades and return sweeps) like everyday reading. The flashcard sentence pool consisted of 411 sentences with an average length of 11.5 words per sentence and an average word length of four letters. Before the beginning of each trial, a block of x's (four lines and 13 x's per line) was presented as a pre-cue to indicate the sentence location, and a short green bar (perpendicular to the reading direction) was placed directly in front of the first x of the first line to indicate the reading direction. As in RSVP reading, subjects were instructed to read the sentences aloud as accurately as possible immediately after the stimuli were presented on the display screen. They were permitted to complete their report after the sentence disappeared from the display and to move their eyes during the testing. In both the RSVP and flashcard reading tests, none of the sentences were tested more than once for each subject.

Both lowercase and uppercase groups read text in 8 testing conditions, derived from all possible combinations of the two presentation methods and four text formats. To obtain the reading speed in a given testing condition and print size, we measured the proportion of words read correctly at each of five exposure times using the method of constant stimuli. For each subject, five exposure times were selected from a range of 26 ms (2 frames, the frame rate of the display is 76 frames/s) to 2.95 s (224 frames) per word for RSVP reading and 316 ms (24 frames) to 29.5 s (2240 frames) per sentence for flashcard reading. The five exposure times increased in steps of approximately 0.26 log units (a factor of 1.82), within the constraints of the integer number of video frames. The range was adjusted so that each subject read at least 80% of words correctly at the longest duration and no more than 30% of words correctly at the shortest duration (e.g., 2, 4, 7, 12, and 22 frames). Four sentences were tested at each of the five exposure times, with 20 trials for each print size and testing condition. Each set of data was fitted with a Weibull function and a criterion reading speed was derived from the exposure time yielding 80% of words read correctly.

Only RSVP and flashcard reading were measured in Experiment 1. Both measures were computer-based and completed binocularly in a dark room. A total of 400 RSVP trials and 400 flashcard trials were divided into two sessions, where subjects completed 40 blocks of RSVP trials and 40 blocks of flashcard trials per session. A block consisted of five trials presented in five different exposure times. The block sequence was pseudo-randomized and counterbalanced across sessions to minimize any sequencing effects. At the beginning of each session, subjects were given a few minutes to practice.

Data analysis

To obtain the CPS, a nonlinear mixed-effects (NLME) model using an exponential decay function was fitted to the grouped data set to estimate the group means and variances (Cheung et al., 2008; Lindstrom & Bates, 1990; Pinheiro & Bates, 1995, 2000). Reading speed function parameters (CPS and maximum reading speed) for each subject were estimated with the "best linear unbiased predictor" (BLUP; Henderson, 1975; Robinson, 1991). A criterion of 80% of maximum reading speed was chosen to obtain the CPS.

The exponential-decay function used in the model is

$$\begin{aligned} g(x) &= \phi_1(1 - e^k), \\ k &= -e^{\phi_2}(x - \phi_3), \end{aligned} \tag{1}$$

where x is the print size in degrees, $g(x)$ is the corresponding reading speed in log words per minute, ϕ_1 is the maximum reading speed in log words per minute, $\exp(\phi_2)$ is the rate of change in reading speed as a function of print size, and ϕ_3 is the print size at which reading speed is one word per minute (Cheung et al., 2008).

A repeated measures ANOVA was used to analyze CPS. The two within-subject factors were presentation method (RSVP, flashcard) and text format (horizontal, rotated clockwise, rotated counterclockwise, and marquee), and the single between-subject factor was letter case (lowercase, uppercase). For any significant main effect of text format, or any significant interaction effect between text format and another factor, post-hoc pairwise comparisons were conducted.

Results

The mean CPS values are listed in Table 2 for uppercase and lowercase letters, two presentation methods (RSVP and flashcard), and four text formats (horizontal, marquee, rotated clockwise, and rotated counterclockwise). Across all subjects and conditions, CPS ranged from 0.06° to 0.23° of visual angle. Consistent with a previous study (Yu, Cheung et al., 2007), the CPS measured by the RSVP and flashcard methods showed no significant difference.

We found significant main effects on CPS of text format and group (upper vs. lowercase) and a significant two-way interaction of text format × upper/lowercase group. The three vertical text formats had larger CPS (range 0.09° to 0.23° of visual angle) than the horizontal text format (range 0.06° to 0.14° of visual angle), $F(3,24) = 15.55$, $p < 0.0005$. On average, the vertical CPS is 0.03° larger than the horizontal CPS. As shown in Table 2, there is a significant interaction between letter case and text format, $F(3,66) = 8.32$, $p = 0.001$. In the lowercase group, CPS was larger for the marquee format than for the rotated clockwise format. In the uppercase group, CPS was largest for the rotated clockwise format, and rotated counterclockwise format had a larger CPS than marquee format. Table 2 shows that the CPS for the uppercase group was

		Horizontal	Rotated CW	Rotated CCW	Marquee
Lowercase	RSVP	0.09° ± 0.009°	0.11° ± 0.004°	0.12° ± 0.003°	0.13° ± 0.003°
	Flashcard	0.09° ± 0.005°	0.12° ± 0.004°	0.13° ± 0.005°	0.16° ± 0.025°
Uppercase	RSVP	0.12° ± 0.004°	0.15° ± 0.008°	0.14° ± 0.009°	0.13° ± 0.006°
	Flashcard	0.12° ± 0.006°	0.15° ± 0.010°	0.14° ± 0.008°	0.13° ± 0.004°

Table 2. Summary table of mean CPS values (x-height or X-height in degrees) for each letter case, presentation method, and text format (mean ± standard error).

larger than the CPS for the lowercase group, $F(1,8) = 6.49$, $p = 0.034$. As mentioned in the Apparatus, stimuli, and experimental design section, print size was defined as x-height in degrees of visual angle. When we converted degrees of visual angle into pt (for lowercase, pt = degree of visual angle × viewing distance (cm) × 1.28; for uppercase, pt = degree of visual angle × viewing distance (cm) × 1.03), the upper/lowercase group effect disappeared, while the effect of text format and the interaction between text format and upper/lowercase group remained significant.

For lowercase horizontal text, the mean CPS (0.09°) obtained in the present study is slightly smaller than that obtained in other studies (Chung, 2002; Yu, Cheung et al., 2007). This difference may result from our use of an exponential decay function to find the CPS, rather than the two-line curve fitting method used by previous researchers.

A print size of 0.55° (28 pt) in lowercase and a print size of 0.68° (28 pt) in uppercase were selected for Experiment 2 because both print sizes exceeded the CPS in all conditions, and thus allowed subjects to read at their maximum speed.

Experiment 2

According to the visual-span hypothesis, we expect to find that size of the visual span and reading speed have a qualitatively similar dependence on text format, both being greater for the horizontal format than for the three vertical formats. In Experiment 2, we examined this prediction by measuring reading speeds (both RSVP and flashcard) and visual-span sizes for the four text formats and two letter cases.

Subjects

Twenty-four native English-speaking, normally sighted young adults recruited from the University of Minnesota were randomly assigned to groups of 12 for either the lowercase or the uppercase text conditions. Table 1 shows the summary of age, gender ratio, binocular distance visual acuity, log contrast, and three measures from the MNREAD reading acuity chart. Subjects signed an IRB-approved consent form before the testing.

Apparatus, stimuli, and experimental design

The details are the same as described in Experiment 1 (see Apparatus, stimuli, and experimental design section), with the following exceptions. The viewing distance was maintained at 40 cm for the whole experiment. The print size was 28 pt, in which lowercase x-height is 0.55° (physical size of 13 pixels or 0.39 cm; the ratio of x-height to x-width is 0.9) and uppercase x-height is 0.68° (physical size of 16 pixels or 0.48 cm; the ratio of x-height to x-width is 1.1).

Measuring RSVP and flashcard reading speeds

The same procedure described in Experiment 1 (see Apparatus, stimuli, and experimental design section) was used to measure RSVP reading speed and flashcard reading speed, except that we measured the proportion of words read correctly at 7 exposure times with 6 sentences presented per exposure time. The seven exposure times in frames per word were 2, 3, 5, 8, 12, 19, and 30 frames per word for the RSVP test (13.2 ms/frame) and 24, 36, 60, 96, 144, 228, and 360 frames per sentence for the flashcard test. An extra exposure time of 552 frames per sentence was added at the conclusion of the flashcard test if the subject's performance did not reach 80% correct.

Measuring visual-span profiles

Visual-span profiles were obtained with a letter-recognition task (Chung, Legge, & Cheung, 2004; Legge et al., 2007; Legge et al., 2001; Yu, Cheung et al., 2007; Yu, Legge, Park, Gage, & Chung, 2010). The stimuli were trigrams, random strings of three letters selected from the 26 lowercase English letters with replacement. The exposure duration for each trigram was 105 ms (8 frames). Subjects were asked to fixate at the center of the display (between two green dots) and identify all three letters of each trigram. Trigrams were presented at 13 different letter distances left and right of the fixation point for horizontal text and above and below the fixation point for vertical text.

Figure 3 shows trigrams in four different text formats and an example of a visual-span profile. For the horizontal text format, letter slots along a horizontal line are labeled by negative or positive numbers to indicate positions to the left or right of the fixation point. For the three vertical

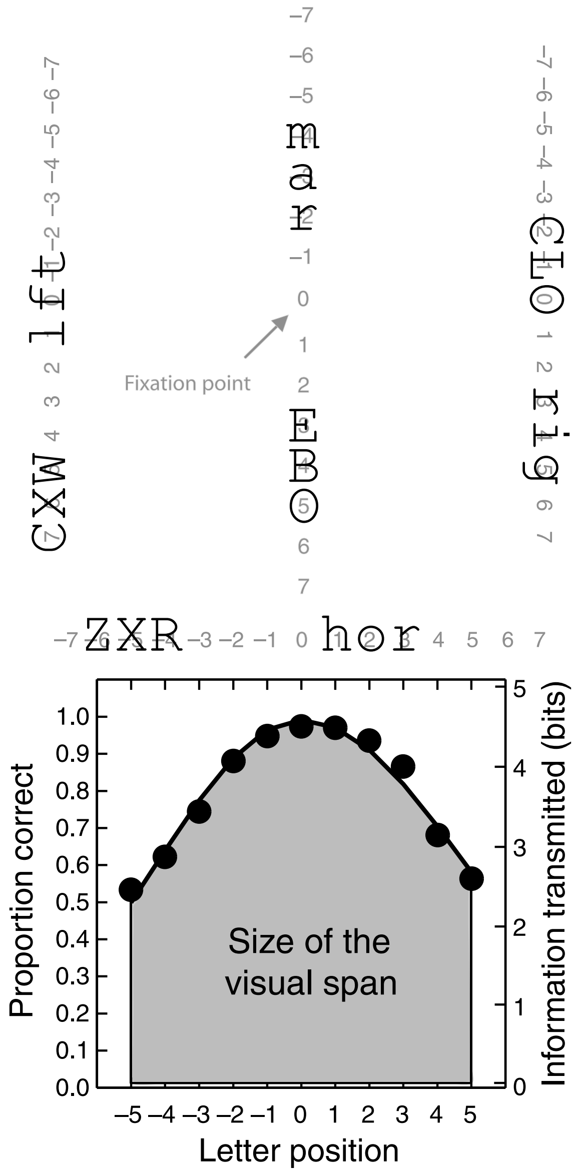

Figure 3. Examples of trigrams presented in different text formats and a sample visual-span profile. Each trigram is presented at a letter position left or right of the fixation point for the horizontal text format, or above or below the fixation point for the three vertical text formats. A visual-span profile is a plot of letter-recognition accuracy (proportion correct) as a function of letter position. The right vertical scale shows a conversion from proportion correct to information transmitted in bits. The area under the curve indicates the visual-span size.

formats, letter positions were distributed along a vertical line. Negative numbers in the plots indicate positions in the upper visual field and positive numbers indicate positions in the lower visual field. Our selection of positive and negative positions is arbitrary, but we prefer to assign positive numbers to the right visual field and the lower visual field because the right visual field usually shows better performance in letter recognition and reading than left visual field, and the lower visual field has a similar advantage over the upper visual field (see Discussion and conclusions section).

The position of the middle letter within a trigram ranged from −6 to 6. For example, in Figure 3, under the horizontal condition, the trigram "hor" is located in letter position 2 because the three letters are presented at positions 1 ("h"), 2 ("o"), and 3 ("r") to the right of the fixation point, respectively. In the marquee condition, the position of trigram "mar" is −3 in the upper visual field, indicating that letters "m" and "r" are at positions −4 and −2, respectively. Like the marquee example, rotated clockwise trigram "CLO" is presented at position −1 and the letter string covers letter positions from −2 to 0 along the vertical midline of the display. For the counterclockwise condition, "CXW" is presented at position 6 in the lower visual field, with the letter "C" at position 7 and the letter "W" at position 5. Subjects were asked to report the three letters in each trigram in the "normal" reading direction—from left to right for the horizontal format, from top to bottom for the marquee and rotated clockwise formats, and from bottom to top for the rotated counterclockwise format.

Data at each letter position were accumulated from the inner, middle, and outer letters of the trigrams. The proportion of letters recognized correctly was calculated as shown on the left vertical scale of Figure 3. Each visual-span profile was based on six blocks of 39 trigram trials per block. In each block, three trials were completed for each of the 13 letter positions, ranging from −6 to 6. Since only the outer letters of the trigrams were presented for positions −7 and 7, and no inner letters were shown at positions −6 and 6, there were fewer data points collected for these four letter slots. Therefore, visual-span data were only analyzed for letter positions −5 to 5, where data for outer, middle, and inner letters were all available. An asymmetric Gaussian function was used to fit the visual-span profile with three parameters: the peak amplitude, the left-side standard deviation, and the right-side standard deviation (Legge et al., 2001). Proportion correct for letter recognition was converted to bits of information transmitted (the right vertical scale in Figure 3) using letter-confusion matrices (Beckmann & Legge, 2002). For each letter position, 100% accuracy in letter recognition corresponds to 4.7 bits of information transmitted and 3.8% accuracy (chance accuracy) to 0 bits of information transmitted. Visual-span size was calculated by summing up the amount of information transmitted by the 11 slots in the profile from −5 to +5 (see Figure 3).

Subjects were tested with RSVP, flashcard, and trigram tasks in Experiment 2. A total of 168 RSVP trials, 168 flashcard trials, and 936 trigram trials were divided into two sessions, with 36 blocks (12 blocks of RSVP, 12 blocks of flashcard, and 12 blocks of trigram) per session. The block sequence was pseudo-randomized and counterbalanced across sessions to minimize any sequencing effects. Practice trials were administered at the beginning

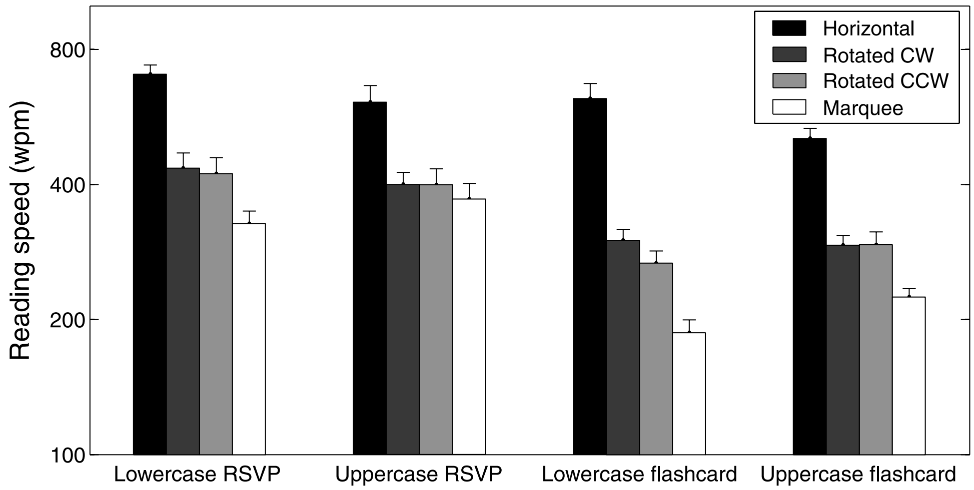

Figure 4. The reading speeds for the 16 testing conditions (all possible combinations of two presentation methods, two letter cases, and four text formats). Each bar represents the average reading speed for 12 subjects. CW—clockwise; CCW—counterclockwise. The error bars indicate standard errors.

of each session for all the four text formats and were not included in the data analysis. Subjects were informed which text format to expect at the beginning of each block.

Data analysis

A repeated measures ANOVA was used to analyze log reading speeds and visual-span sizes. For the reading speed data, the two within-subject factors were presentation method (RSVP, flashcard) and text format (horizontal, rotated clockwise, rotated counterclockwise, and marquee), and the single between-subject factor was letter case (lowercase, uppercase). For visual-span data, text format was the only within-subject factor. Post-hoc tests were performed as needed.

Results

RSVP and flashcard reading speeds

Figure 4 and Table 3 show reading speeds for the 16 testing conditions (two letter case groups × two presentation methods × four text formats). A three-factor repeated measures ANOVA revealed two significant main effects—presentation method and text format. The upper/lowercase group difference in reading speed did not reach significance. There were two significant two-way interactions—presentation method × text format and letter case × text format. The three-way interaction was not significant.

As expected, reading speeds were faster for RSVP presentation than flashcard presentation across groups (lowercase and uppercase) and text formats, $F(1,22) = 126.11$, $p < 0.0005$. The ratio of RSVP reading speed to flashcard reading speed is 1.45 (average across all conditions and subjects), which is consistent with the mean ratio (1.44) found by Yu, Cheung et al. (2007).

Across presentation methods and groups, reading speeds differed among the four text formats (see Figure 4 and Table 3), $F(3,66) = 229.76$, $p < 0.0005$. Reading speed was fastest for the horizontal text format. Horizontal reading speed exceeded the two rotated reading speeds by an average factor of 1.81, and marquee reading speed by an average factor of 2.39. Within the three vertical formats, reading speed was faster for the rotated formats than for the marquee format by an average factor of 1.32. No significant difference was found between the rotated clockwise and rotated counterclockwise conditions. The above results are qualitatively consistent with the previous findings of Byrne (2002), although we found a larger difference between the horizontal reading speed and the three vertical reading speeds.

		Horizontal	Rotated CW	Rotated CCW	Marquee
RSVP	Lowercase	706 ± 33	436 ± 35	424 ± 36	328 ± 21
	Uppercase	611 ± 53	401 ± 25	400 ± 33	372 ± 30
Flashcard	Lowercase	623 ± 49	301 ± 17	268 ± 17	187 ± 13
	Uppercase	508 ± 26	293 ± 14	294 ± 19	225 ± 10

Table 3. Mean reading speed ± standard error (wpm). CW—clockwise; CCW—counterclockwise.

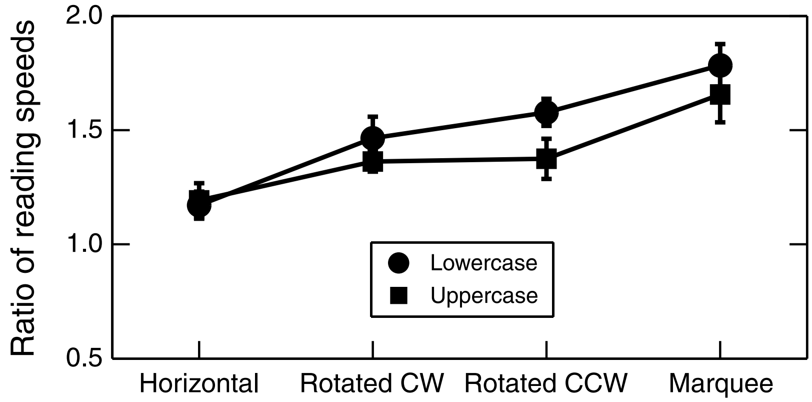

Figure 5. Ratio of RSVP reading speed to flashcard reading speed as a function of text format for the two letter cases. CW—clockwise; CCW—counterclockwise. The error bars indicate standard errors.

A significant interaction between presentation method and text format was also found, $F(3,66) = 24.56$, $p < 0.0005$. When text was presented vertically, the RSVP presentation method showed a larger reading speed advantage over the flashcard presentation method than when text was presented horizontally (see Figure 5). Text presented in the marquee format showed the largest advantage for RSVP over flashcard presentation. These results imply that vertical flashcards were the most difficult to read, possibly due to lack of practice with vertical reading eye movements.

Although there was no significant main effect on reading speed of the group (lowercase vs. uppercase), there was an interaction between text format and case group on reading speed, $F(3,66) = 9.43$, $p < 0.0005$. The lowercase group outperformed the uppercase group for horizontal text, but the uppercase group outperformed the lowercase group for marquee text (see Figure 4 and Table 3).

Visual-span profiles

In Figure 6, group visual-span profiles are plotted for the lowercase and uppercase groups and the four text formats. We predicted that visual-span size and reading speed would show a similar dependence on text format. Given the reading speed results, we expected smaller visual-span sizes for the three vertical text formats, and this is what we found, $F(3,66) = 258.65$, $p < 0.0005$. Visual-span sizes were different between the four text formats. However, the difference was most prominent between the horizontal format and the three vertical formats, as shown in Table 4.

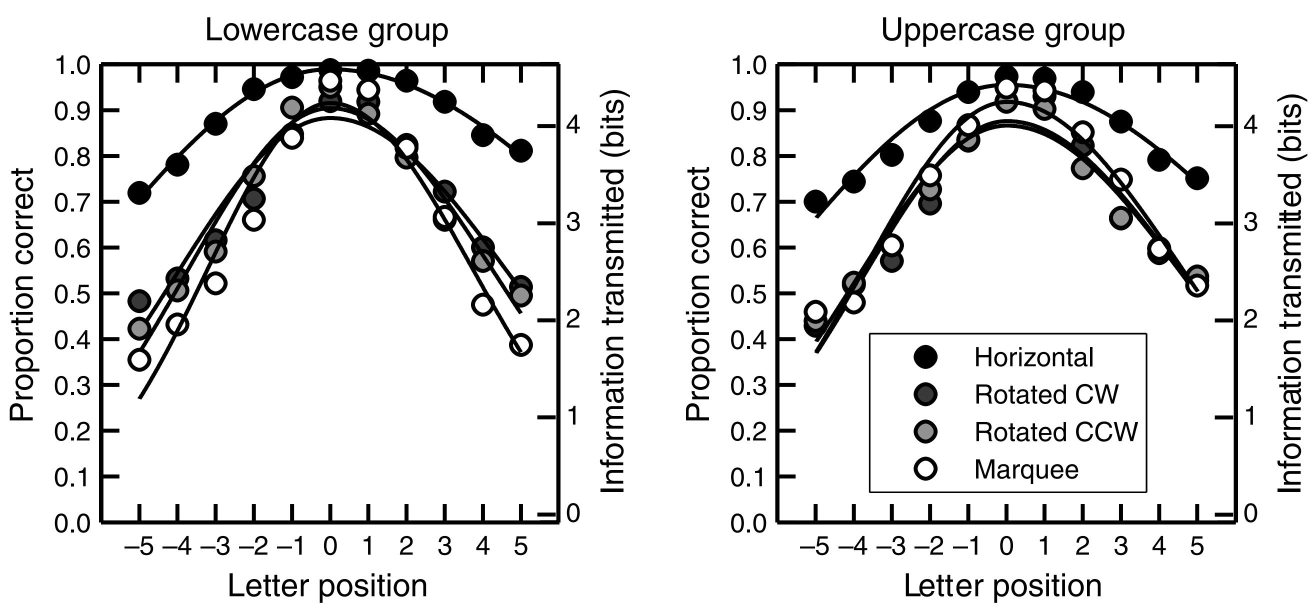

Figure 6. Visual-span profiles (group average) are shown for each of the case groups in four text formats. CW—clockwise; CCW—counterclockwise.

	Horizontal	Rotated CW	Rotated CCW	Marquee
Lowercase	45.4 ± 0.7	35.5 ± 1.2	34.9 ± 1.1	32.6 ± 1.2
Uppercase	43.4 ± 0.7	34.7 ± 1.2	34.7 ± 1.1	36.0 ± 1.0

Table 4. Mean visual-span size (information transmitted in bits from 11 letter positions) ± standard error.

Although there was no significant main effect of letter case on visual-span size, there was a significant interaction such that lowercase performance was better than uppercase performance for horizontal text and the reverse was true for marquee text, $F(3,66) = 14.62$, $p < 0.0005$, which is consistent with our reading speed data.

The visual-span profiles peak near letter position 0 (see Figure 6). The letter-recognition accuracy data at position 0 revealed that the peak amplitudes are not significantly different between horizontal (0.98) and marquee formats (0.96). However, the horizontal format has higher peaks than the two rotated conditions for both lowercase and uppercase groups (0.92 for rotated clockwise and 0.93 for rotated counterclockwise), $F(3,66) = 10$, $p < 0.0005$. The left spread of the visual-span profile is characterized by the left standard deviation of the asymmetric Gaussian fit, while the right spread is characterized by the right standard deviation (see Apparatus, stimuli, and experimental design section). The right side of the visual-span profile corresponds to the right visual field for the horizontal format and to the lower visual field for the three vertical text formats. The left side corresponds to the left visual field for the horizontal format and to the upper visual field for the three vertical text formats. The right halves of the visual-span profiles are slightly broader than the left halves regardless of text orientation, as indicated by larger values of the right standard deviations (see Table 5), $F(1,22) = 26$, $p < 0.0005$. More specifically, the spreads are broader in the lower visual field than in the upper visual field for both the rotated clockwise and rotated counterclockwise conditions. Text presented in the horizontal format yielded profiles that are broader than those from the rotated formats, and these in turn have greater breadth than profiles from the marquee format, $F(3,66) = 450.76$, $p < 0.0005$.

Relationship between the size of the visual span and reading speed

Figure 7 shows mean RSVP and flashcard reading speeds as a function of mean visual-span size associated with the four different text formats. A correlation between log reading speed and visual-span size was computed across the four text formats and two letter cases. Strong correlations between group means were found for both RSVP reading, $r = 0.97$, $p < 0.0005$, and flashcard reading, $r = 0.94$, $p < 0.0005$. The size of the visual span accounted for 93.7% of the variability in RSVP reading speed and 88.9% of the variability in flashcard reading speed. Similar results were found for the correlations computed at the individual subject level (median correlation coefficient for both RSVP and flashcard reading was 0.95).

Discussion and conclusions

Why vertical reading is slower than horizontal reading

The visual-span hypothesis proposes a causal link between the size of the visual span and reading speed. The underlying theory was presented in detail in two previous studies. Legge et al. (1997) described an ideal-observer model (Mr. Chips) in which the size of the visual span is a key parameter. Simulation results showed that the model's mean saccade length decreased as the model's visual-span size decreased. Given that a reduction in mean saccade length would normally correspond to a reduced reading speed, the model shows how a smaller visual-span size would result in a slower reading speed. In a later study, Legge et al. (2001) formulated a related model that takes empirically measured visual-span profiles as input and produces reading speeds as output. The model demonstrated a clear dependence of reading speed on the size of the visual span.

In the present paper, we generated and tested predictions from the visual-span hypothesis concerning expected correlations. Although we have not conclusively proven a causal link between visual-span size and reading speed, the present study adds support for the basic hypothesis. The correlational data strengthen the case for a theory-based

		Horizontal	Rotated CW	Rotated CCW	Marquee
Lowercase	Left Std.	6.47	4.07	3.79	3.20
	Right Std.	9.33	4.85	4.46	3.75
Uppercase	Left Std.	6.33	3.82	4.04	3.76
	Right Std.	9.00	4.96	4.91	4.78

Table 5. Mean left and right standard deviations.

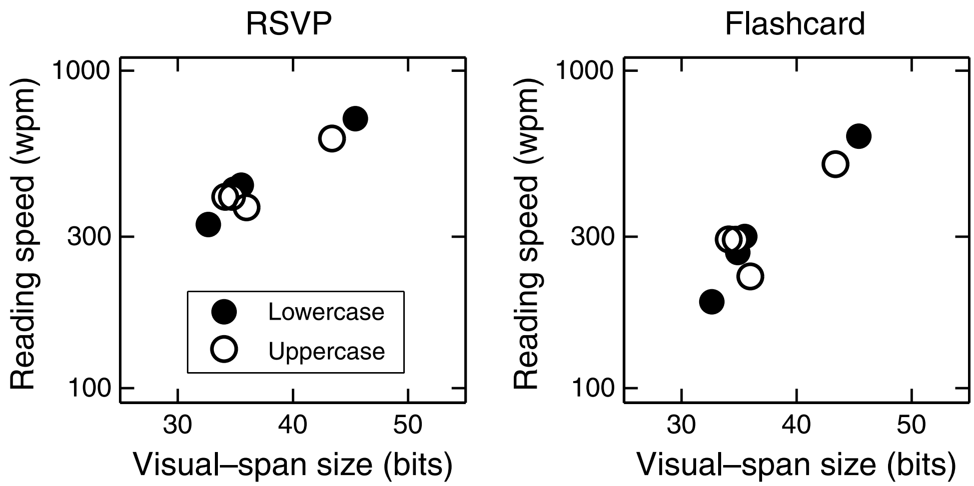

Figure 7. Relationship between reading speed and visual-span size for the two presentation methods. Each data point represents mean reading speed and mean visual-span size (bits of information transmitted across the central 11 letter slots) for a given text format. Two of the data points were offset slightly to avoid completely overlapping. Filled circles and open circles represent data for lowercase and uppercase, respectively.

causal connection between visual-span size and reading performance.

According to the visual-span hypothesis, slower reading speeds with vertically oriented text result from a smaller visual-span size for vertical reading. The size of the visual span is probably affected by lower-level sensory factors, such as crowding, positional uncertainty, and changes in peripheral acuity (for a review, see Legge, 2007, Ch. 3). These low-level sensory factors may mediate their effects on reading through reduction in the size of the visual span. It is possible that structural properties of the visual pathway (e.g., horizontal–vertical asymmetries in crowding, positional uncertainty, and spatial resolution), unrelated to reading, might account for the horizontal–vertical differences we observed.

Some form of holistic processing (in which a word is perceived as a whole unit) might contribute to the horizontal–vertical difference in reading speed. Lavidor, Babkoff, and Faust (2001) proposed a lateralized word recognition model suggesting that in the left hemisphere, a word stimulus is sent directly to the semantic lexicon if it can be processed holistically, which is true when the word is in standard word format (e.g., horizontal format). If the word has a nonstandard format (e.g., one of the three vertical formats), it can no longer be processed holistically; it must undergo an additional encoding phase (visual-orthographical processing) prior to accessing the lexicon (Lavidor et al., 2001). Could the breakdown in holistic processing be a common underlying factor accounting for both slower reading and reduction of the size of the visual span in our vertical formats? We think this is unlikely. Holistic analysis is unlikely to apply to the recognition of random trigrams, since no lexical analysis is required nor do we expect sufficient familiarity with random trigrams for holistic processing to develop. Disruption of holistic processing in the vertical formats might contribute to slower reading but would not account for the correlation between reading speed and size of the visual span.

Reversing the causal direction, it is possible that shrinkage of the visual span results in fewer letters being recognized per fixation for vertical words, and this attenuation of letter information might disrupt holistic processing. As shown in Figure 6, the maximum number of letters that can be identified at 80% accuracy without moving the eyes is about 4 for the three vertical formats and about 8 for the horizontal format. At 90% accuracy, it is 2 for the vertical text formats and 5 for the horizontal format.

Our results do not exclude the possibility that both the size of the visual span and reading speed are influenced by reading experience. A study on developmental changes in the visual span for reading showed correlated growth of visual-span size and reading speed across grade levels (Kwon, Legge, & Dubbels, 2007). Experience could play a role not only in the visual-span explanation and the holistic processing explanation for the slower reading but also in eye movement control during reading. For Japanese readers who are experienced in reading both horizontal and vertical text, reading speeds and critical print sizes do not differ significantly for the horizontal and vertical arrangements of text (Oda et al., 1999). However, for most English speakers, the unfamiliarity with vertical text may hinder the ability to plan and make saccades up or down through a vertical sentence, and thereby reduce reading speed. See RSVP and flashcard section for additional comments on oculomotor factors.

Uppercase and lowercase

A significant interaction effect between text format and case was found for both reading speed and visual-span size, although there was no significant main effect of case.

For text presented horizontally, subjects in the lowercase group generally performed better than those in the uppercase group. Although uppercase letters are more legible when print sizes are close to the acuity limit (Arditi & Cho, 2007), our results showed that the lowercase group outperformed the uppercase group in the trigram letter-recognition task for a print size larger than the CPS for the horizontal condition. The lowercase group also showed an advantage over the uppercase group in reading horizontal text. These results indicate that the extra features of lowercase letters can benefit reading and letter recognition when print size exceeds the critical print size.

For marquee text, the performance on both the trigram test and reading tests of the uppercase group was better than the performance of the lowercase group. This effect may be an artifact of the difference in center-to-center letter spacing between uppercase and lowercase stimuli for the marquee format. Unlike the other formats, the center-to-center letter spacing in lowercase marquee text is larger than for uppercase marquee. Extra-wide letter spacing is known to be associated with slower reading (Yu, Cheung et al., 2007). Furthermore, Yu, Gerold, Legge, Cheong, and Park (2007) reported that when uppercase marquee letter spacing increased from 1× to 2× normal letter spacing, RSVP reading speed decreased by 20% and visual-span size decreased by 15%. Therefore, the wide letter spacing in lowercase marquee may be the reason that reading slows down.

RSVP and flashcard

Consistent with our previous finding (Yu, Cheung et al., 2007), the present study showed that RSVP reading speed was 45% faster than flashcard reading speed, averaged across all conditions. Moreover, the advantage of RSVP presentation over flashcard presentation was larger when text was presented vertically than when it was presented horizontally. Slower flashcard reading is mainly due to oculomotor limitations. Vertical flashcard reading was probably slow because subjects have less experience planning and making saccades up or down through a sentence than reading in the regular left-to-right direction. Schmidt, Ullrich, and Rossner (1993) found that eye movements during vertical reading were less regular and involved more small saccades of varying size than eye movements during horizontal reading. Given the evidence showing that low-level visuomotor constraints are the primary limiting factors on eye movement control in horizontal reading (e.g., Radach, Inhoff, & Heller, 2004), it is possible that visuomotor limitations play an important role in the irregular eye movements during vertical reading. The findings on horizontal and vertical reading performances in Japanese readers (Oda et al., 1999) indicate that the difference between RSVP and flashcard reading speeds for English readers might diminish or disappear with extensive practice in reading vertical text. Our results on RSVP reading confirmed that the horizontal–vertical differences are not simply due to the differences in oculomotor control. If the effect was strictly oculomotor, the horizontal–vertical differences should disappear for RSVP.

Visual-field asymmetry

Previous research has shown that letter recognition for horizontal text is slightly better to the right of fixation than to the left of fixation. This is true for both words (Bouma, 1973; Mishkin & Forgays, 1952) and letter strings (Bryden, 1970; Dornbush & Winnick, 1965; Legge et al., 2001; Yu, Cheung et al., 2007). For bilingual subjects, the advantage depends on reading direction. A right-side advantage was found for reading English and a left-side advantage was found for reading Hebrew, in which the normal reading direction is from right to left (Barton, Goodglass, & Shai, 1965). Battista and Kalloniatis (2002) provided evidence that the right-side advantage in English reading is due to the reader's habit of allocating more attention to the right visual field than the left. These previous findings prompt the question of whether there is an asymmetry for the upper and lower vertical visual fields as well. Does this potential asymmetry depend on reading direction also? In the present study, we have learned that upper/lower asymmetry occurs in the three vertical text formats, with better performance in the lower visual field regardless of reading direction (see Figure 6 and Table 5). This lower-field advantage for vertically oriented letter strings is hard to account for by explanations based on experience or habits in allocating attention during reading.

Asymmetry in the vertical visual field has been reported for performance on many visual tasks. People often show a performance decrement when stimuli are presented in the upper visual field compared to the lower visual field at an equal eccentricity (Cameron, 2005; Carrasco, Talgar, & Cameron, 2001; He, Cavanagh, & Intriligator, 1996; Levine & McAnany, 2005; McAnany & Levine, 2007; Talgar & Carrasco, 2002). Some authors argue that the lower field advantage is due to greater attentional resolution in the lower field (He et al., 1996). However, Carrasco et al. (2001) came to a different conclusion. Since they found the shapes of performance fields (showing performance accuracy at particular eccentricities across the visual field) do not change when attention is manipulated, they concluded that the performance fields were controlled by visual sensory constraints rather than by attention. Our results are consistent with both the attentional and sensory accounts of the field asymmetry.

Rotated clockwise and counterclockwise text formats

Since the general reading direction is from the top of the page to the bottom, it is possible that readers prefer the top-down reading direction to the bottom-up reading direction when they read vertical text. However, consistent with the previous findings of Byrne (2002), our results showed no substantial difference in performance between the rotated clockwise condition (corresponding to top-down reading direction) and rotated counterclockwise condition (corresponding to bottom-up reading direction). The lack of difference may indicate that the reading direction defined in a word-centered coordinate system is what really matters. For both rotated text formats, the reading direction in the word-centered coordinate system is from left to right, the same as the normal reading direction in horizontal text.

In the trigram task, subjects fixated at letter position 0, which corresponds to peak performance in the visual-span profile. The data for letter position 0 (fixation point) indicate that subjects can recognize letters equally well in the horizontal and marquee formats (although this equality may be due to a ceiling effect), but less well in the two rotated formats. Our results suggest that when the letter string is rotated, flanked letter recognition is affected by letter orientation even at the fixation point, although isolated letter recognition is orientation invariant (Koriat & Norman, 1984, 1985, 1989).

Implications for low vision

According to our theory, shrinkage of the visual span causes slower vertical reading. If this theory is correct, it would be reasonable to propose that vertical reading speed might improve if the size of the vertical visual span was enlarged. Previous studies have shown that perceptual learning can increase horizontal visual-span size and improve the corresponding reading speed in peripheral vision (Chung et al., 2004; Yu, Cheung, Legge, & Chung, 2005; Yu et al., 2010). In the Introduction section, we described why vertical text might be helpful in reading for people with a central scotoma with a PRL lateral to the scotoma. Future research should investigate how perceptual learning can be used to enhance vertical reading in the left or right visual fields, with the ultimate goal of helping these individuals to read faster. The empirical findings from such research might be helpful in developing an effective training protocol for improving reading speed as part of the rehabilitation of low-vision patients. Our finding also suggests that among the three vertical text formats, the two rotated text formats are likely to yield faster reading. This is fortunate because it is easier to implement vertical reading through a simple 90° rotation of the page than reformatting into marquee text.

Acknowledgments

This research was supported by NIH Grant R01 EY002934. We would like to thank Tiana Bochsler for editorial assistance.

Commercial relationships: none.

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Footnote

[1]These factors were estimated from the high frequency word condition in Figure 2 from Byrne (2002).

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