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The effect of letter-stroke boldness on reading speed in central and peripheral vision

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ABSTRACT

People with central vision loss often prefer boldface print over normal print for reading. However, little is known about how reading speed is influenced by the letter-stroke boldness of font. In this study, we examined the reliance of reading speed on stroke boldness, and determined whether this reliance differs between the normal central and peripheral vision. Reading speed was measured using the rapid serial visual presentation paradigm, where observers with normal vision read aloud short sentences presented on a computer monitor, one word at a time. Text was rendered in Courier at six levels of boldness, defined as the stroke-width normalized to that of the standard Courier font: 0.27, 0.72, 1, 1.48, 1.89 and 3.04× the standard. Testings were conducted at the fovea and 10° in the inferior visual field. Print sizes used were 0.8× and 1.4× the critical print size (smallest print size that can be read at the maximum reading speed). At the fovea, reading speed was invariant for the middle four levels of boldness, but dropped by 23.3% for the least and the most bold text. At 10° eccentricity, reading speed was virtually the same for all boldness <1, but showed a poorer tolerance to bolder text, dropping by 21.5% for 1.89× boldness and 51% for the most bold (3.04×) text. These results could not be accounted for by the changes in print size or the RMS contrast of text associated with changes in stroke boldness. Our results suggest that contrary to the popular belief, reading speed does not benefit from bold text in the normal fovea and periphery. Excessive increase in stroke boldness may even impair reading speed, especially in the periphery.

1. Introduction

Reading is difficult and slow for many patients with visual impairment. However, because reading is crucial for society participation, it is often identified as the primary goal for patients seeking visual rehabilitation (Bullimore & Bailey, 1995; Elliott et al., 1997; Kleen & Levoy, 1981). Many low vision practitioners and agencies for visual rehabilitation often advise their patients or clients to make the most of their remaining sight by making things bigger, brighter and bolder. In relation to reading, “bigger” can be accomplished by making print larger physically, through the use of electronic magnifiers, or simply by bringing the reading materials closer to read, which often improves reading performance. In many cases, reading through magnifiers or using large print is still slower than that for people with normal vision. Indeed, reading speed is reported to improve with print size only up to the critical print size (CPS), beyond which further increase in print size does not improve reading speed (Chung, Mansfield, & Legge, 1998; Legge et al., 1985). “Brighter” is often achieved by using bright illumination, which often improves reading due to an increase in the physical contrast of the print, an increase in the depth of focus as the pupil contracts under bright illumination, as well as ensuring that the visual system operates under photopic light level. As for “bolder”, the popular advice given to patients is to use dark thick felt-tip pens for writing to increase the thickness of the letter-strokes, or use the boldface option on word processor. Despite the many anecdotal reports from people with normal or impaired vision asserting that boldface print is easier to read, to date, there is very little systematic investigation that examines the advantages, if any, of reading boldface print.

Luckiesh and Moss (1940) examined the effect of varying the boldness (referred to as the “weights” in typography) of the Memphis font in 10-point print for people with normal vision. Using the relative blink rate as an index of readability (assuming that more readable print produces fewer blinks), they examined the readability of four boldness settings: Light (standard), Medium (20% bolder than standard), Bold (35% bolder than standard) and Extra Bold (69% bolder than standard). Readability was found to be the highest for Memphis Medium, producing a 10% improvement in readability when compared with the standard. When reading speed was measured, both the Medium and Bold settings produced the highest reading speeds, although the improvement was only 2–3%. In terms of legibility, Memphis Bold and Extra Bold were found to be the most legible. In another classical study, Paterson

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1 For example, see the webpages from Vision Australia (http://www.visionaustralia.org.au/info.aspx?page=1511) and RNIB (http://www.rnib.org.uk/livingwithsightloss/copinewithsightloss/remainsingsight/).
and Tinker (1940) compared reading speed for boldface and ordinary print in two groups of 100 college students each. They failed to find any difference in reading speed measurement, although when asked for subjective preference, 70% of a different group of 244 readers preferred the ordinary font. Likewise, Perera (2001) assessed the subjective preference of boldness (“weight” of the typeface) of print for reading. The three settings of weights she investigated were light, medium and dark, although it was unclear how these three levels of weights differed from one another quantitatively. Among a group of 26 subjects with self-reported poor or fair vision (none reported good vision), Perera found that 18 of them preferred the dark setting; however, no performance measurement was reported. This result implies that among Perera’s sample of reading materials, those with the heaviest weights were thought to be the most legible. Several studies have reported a small advantage in terms of performance measurement for bolder letters. Arditi (2004) asked a group of 40 low vision observers to adjust several font parameters, including letter spacing, stroke-width, serif size, x-height and letter-width-to-height aspect ratio to maximize the subjective legibility of the font. Averaged across the 40 observers, the setting of the stroke-width that yielded the optimal subjective legibility improved reading acuity by approximately 10%. Similarly, Sheedy et al. (2005) reported a small benefit (<1%) of increasing stroke-width of letters and words on legibility. Note that however, the benefit of increased stroke-width is usually found for some intermediate values. In other words, when the stroke-widths are too small or large, legibility of the letters or words decreases (Arditi, Cagnello, & Jacobs, 1995) and reading is expected to become slower.

The evidence provided by previous investigations, combined with the overwhelming anecdotal subjective preferences by clinical patients, suggest that there may exist a stroke boldness that could improve reading speed, although the improvement may be modest. Considering that bolder letters contain more contrast energy in the low spatial frequencies than letters that are less bold, and that the spatial frequency at which our contrast sensitivity is the highest shifts toward lower spatial frequency in peripheral vision (Virsu & Rovamo, 1979), we hypothesized that the benefit of reading boldface print may be larger in peripheral vision than at the fovea. This would have significant relevance to people who have central vision loss and thus cannot use their macular region to read due to eye diseases such as age-related macular degeneration—the primary cause of blindness for people over 65 years of age (Congdon et al., 2004). Therefore, in this study, we investigated the effect of boldness of letter-strokes on reading speed, and compared the effect between central and peripheral vision. Specifically, we sought to determine the optimal boldness of a popular font, Courier, for reading, at the fovea and at 10° eccentricity in the inferior visual field. We chose a testing eccentricity of 10° to represent “peripheral vision” because despite a large variability in the disease process and the size, shape and location of the central scotoma in the eyes of people with macular degeneration, the median size of central scotomas reported by many studies ranges from 10° to 20° in diameter (see Cheung & Legge, 2005; for a review). Considering that printed text has existed since 1455 (Meggis, 1998), we expected that the various typographic characteristics of any given font are already optimized to provide the most legible letters, and are likely to yield the highest reading speed possible for the font. Consequently, we predicted that at the fovea, reading speed is highest for the standard stroke-boldness (“standard” refers to the version of the font that is currently offered by the common word-processing software). In the periphery, based on anecdotal reports from clinical patients with central vision loss who prefer bolder print to standard print when they use common word processing software, and that bolder letters contain more contrast energy in the low spatial frequencies, we predicted that reading speed is higher for print that is bolder than the standard print. Here, we sought to determine the optimal boldness that yields the optimal reading speed in the periphery. For both the fovea and the periphery, we further predicted that reading speed would fall below that for the standard print when the stroke-width of the print is either too thin or too bold.

2. Methods

Oral reading speed was measured for single sentences rendered in Courier font and for a range of letter-stroke boldness, defined as the width of the letter-stroke relative to that of the standard Courier font (for the standard Courier font, the average stroke-width is 0.165 x the height of the lowercase letter c, at the fovea and at 10° eccentricity in the lower visual field for six observers. To ensure that the effect of letter-stroke boldness on reading speed does not vary with letter size, we tested two nominal letter sizes at each eccentricity.

2.1. Observers

Six young adults with corrected-to-normal vision (20/20 acuity or better in each eye) and aged 17–24 participated in the main and the control experiments of this study. All observers were native English speakers. None of the observers had prior experience in the tasks used in this study, or had participated in other experiments involving testing of peripheral vision. Refractive errors were corrected by contact lenses, if necessary. Written informed consent was obtained from each observer after the procedures of the experiment were explained, and before the commencement of data collection. The experimental protocol was approved by the Institutional Review Board at the University of California, Berkeley.

2.2. Apparatus

All the stimuli were generated on a Macintosh G4 computer with software custom-written in MATLAB 7.7.0 (The MathWorks, MA), using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997), and were presented on a Sony color graphics display monitor (model# GDM-17E21, refresh rate = 85 Hz). The resolution of the monitor was 1280 x 1024 pixels. The temporal dynamics of the monitor were verified with a photo-detector and an oscilloscope.

2.3. Stimuli

A set of 2630 sentences from classic literature was used as stimuli for measuring reading speed. This was the same set of sentences used in our previous studies (e.g. Chung, 2002; Chung, Legge, & Cheung, 2004; Chung, Mansfield, & Legge, 1998). Each sentence contained between 8 and 14 words (mean = 10.9 ± 1.7 [SD]) and included only words that were among the 5000 most frequently used words in normal written English usage. On each trial, a sentence was randomly chosen, without replacement, from the set and presented one word at a time in a rapid succession, using the rapid serial visual presentation (RSVP) paradigm (Forster, 1970; Potter, 1984; Rubin & Turano, 1992, 1994). All words were presented left-justified on a computer display. Words were rendered in black (2.7 cd/m2) and presented against a white background (154.2 cd/m2) at a Weber contrast of ~58.2%. Throughout the course of data collection (main and control experiments), none of the sentences were presented more than once to any observer.
To create the Courier font in different letter-stroke boldness, we used the freeware FontForge. Letters with a stroke-width boldness greater than 1 (stroke-width greater than that of the standard Courier font) were created as if we added extra layers of pixels around the letter-strokes of the standard Courier font. Letters with a stroke-width smaller than 1 (smaller than that of the standard Courier font) were created as if we removed layers of pixels around the letter-strokes of the standard Courier font. The addition or removal of layers of pixels was accomplished by varying the weight parameter in FontForge. Because Courier font comprises letters with curvatures and the ends of the letter-strokes or serifs are round, after we added or removed layers of pixels from the standard font to create the fonts with different stroke-widths, we visually inspected all the letters, and adjusted the curvatures if necessary. This process was repeated until all authors agreed that each letter looked consistent when compared with other letters with the same stroke-width, and when compared with the same letter of the standard Courier font. Then we used software custom-written in MATLAB to construct the skeleton (Bernard & Chung, 2011) of each letter for each stroke. Then we used software custom-written in MATLAB to construct and when compared with the same letter of the standard Courier font. The addition or removal of layers of pixels was accomplished by varying the weight parameter in FontForge. Because Courier font comprises letters with curvatures and the ends of the letter-strokes or serifs are round, after we added or removed layers of pixels from the standard font to create the fonts with different stroke-widths, we visually inspected all the letters, and adjusted the curvatures if necessary. This process was repeated until all authors agreed that each letter looked consistent when compared with other letters with the same stroke-width, and when compared with the same letter of the standard Courier font. Then we used software custom-written in MATLAB to construct the skeleton (Bernard & Chung, 2011) of each letter for each stroke boldness, for a fixed nominal print size (i.e., with reference to the standard) of 88 pixels. For each pixel along the skeleton, we determined the number of black pixels along the direction tangential to the skeleton. The averaged value was used to represent the mean stroke-width of the given letter. The stroke-widths of all the 26 letters of the alphabet were then averaged, and normalized with respect to the same measurement of the standard Courier font. Using this method, a set of Courier fonts with the following stroke-widths was created and used for testing: 0.27x, 0.72x, 1x (the standard), 1.48x, 1.89x and 3.04x the standard stroke-width. Fig. 1 shows a sample sentence rendered in the different boldness.

2.4. Reading speed measurement

Oral reading speed was measured using the RSVP paradigm (e.g., Chung, Mansfield, & Legge, 1998; Forster, 1970; Potter, 1984; Rubin & Turano, 1992, 1994), which minimized the need to make eye movements during reading. Because words were presented one at a time, this paradigm also allowed us to present words at a more specific retinal location, which was not possible with page reading. On each trial, a sentence was chosen randomly from the set of 2630 sentences, and words of the sentence were presented one at a time, each for a fixed exposure duration specific to that trial. Observers read aloud the words of the sentence as quickly and as accurately as possible. There was no time pressure on the response and observers were free to complete verbalizing the words after the sentence was presented. An experimenter counted the number of words read correctly for each trial (sentence). For each condition (e.g., a given stroke boldness of a given print size), we used the Method of Constant Stimuli to present words at six exposure durations that spanned a range of approximately one log unit so as to obtain a range of reading accuracy. The range of durations was chosen such that only a small proportion of words could be read at the shortest exposure duration, but most of the words could be read (close to perfect performance) at the longest exposure duration. In general, the exposure durations were 16 ms, 25 ms, 50 ms, 80 ms, 140 ms and 230 ms for foveal testing; and 120 ms, 200 ms, 320 ms, 500 ms, 800 ms and 1200 ms for the peripheral testing. Occasionally we shifted the range of duration by one step (approximately 0.2 log units) toward a shorter duration if the observer’s performance accuracy was over 20% even for the shortest duration, or shifted the range by one step toward a longer duration if the observer’s performance accuracy was below 80% even for the longest duration. Three sentences were tested for each exposure duration, with a total of 18 sentences tested in each block (each condition). The various conditions (eccentricity, print size, stroke boldness) were tested in a random order that was different for all observers. Each condition was tested twice, on two different days. Data from the two blocks of the same condition were then combined, from which we calculated the proportion of words read correctly as a function of word exposure duration. Then we fit the set of data using a cumulative-Gaussian function from which we derived the word exposure duration that

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2 Each letter in FontForge is defined with points and curvature values that can be changed by the user. The software is available from http://fontforge.sourceforge.net.

3 Because the RSVP paradigm minimizes the need for eye movements, reading speed is usually much higher when measured using the RSVP paradigm than the conventional page-reading method. Rubin and Turano (1992) reported average reading speeds of 1171 wpm and 303 wpm for RSVP and page-reading, respectively. They claimed that several of their observers were even able to read at 100% accuracy at 1800 wpm using the RSVP method.
yielded 80% of words read correctly, as in previous studies (e.g., Chung, 2002; Chung, Legge, & Cheung, 2004; Chung, Mansfield, & Legge, 1998). This word exposure duration (in seconds) was then converted to reading speed (in words per minute, wpm) according to the following equation:

\[
\text{Reading speed (wpm)} = 60 / \text{RSVP word exposure duration (s)}
\]

Fig. 2 shows a sample set of RSVP data fitted with a cumulative-Gaussian function. In this example, the word exposure duration that yielded 80% of words read correctly (dashed lines and arrow) was 0.5 s, which was equivalent to a reading speed (at 80% correct) of 120 wpm.

For foveal testing, observers were allowed to look directly at the words while they were being presented. For testing at 10° eccentricity in the inferior visual field, observers were instructed to fixate along a thin, horizontal green line positioned 10° above the words (measured from the center of the lowercase letters). To ensure that words were presented at the correct eccentricity, observers’ eye movements were monitored using an Eyelink II video eyetracker (SR-Research, Ontario, Canada). This eyetracker was used in the pupil-only tracking mode at a sampling rate of 500 Hz. Gaze-position calibration was performed before and after each block of trials (18 sentences) using the software routines supplied by the manufacturer. Peripheral trials began only after a successful completion of the calibration procedure.4 Observers were instructed to fixate the green fixation line that extended across the entire midline of the monitor. No additional instructions were provided to the observers and they were allowed to adopt any horizontal eye movement strategies that were most comfortable to them. Extensive practice trials were conducted so that each observer had ample time to find the best fixation strategy. Overall, almost all observers adopted a strategy in which they fixated at one or two letter-widths inward from the left edge of the fixation line and did not move their eyes throughout each trial. Custom written software was used to monitor observers’ vertical eye positions. A tolerance of ±1° vertically from the fixation line was allowed. When observers’ gaze extended outside this tolerance window, the trial was discarded and repeated subsequently with a different sentence.

2.5. Experimental design

The primary goal of this study was to evaluate how reading speed varies with stroke boldness, at the fovea and 10° eccentricity. To ensure that any effect we obtained was not specific to print sizes, we tested two nominal print sizes at each of the two eccentricities: 0.8 and 1.4 × the critical print size (CPS, the smallest print size at which the maximum reading speed is still attainable). To determine the CPS for each observer and at each eccentricity, we first measured RSVP reading speed for five print sizes at each eccentricity, as in Chung (2002). The five print sizes ranged from 0.05× to 0.2× at the fovea (except for observer JZ who was tested with print sizes ranging from 0.035× to 0.14× because of her better reading acuity) and 0.7× to 2.8× at 10° eccentricity. These print sizes were chosen such that they straddled the reported CPS at the fovea and at 10° in the inferior visual field, based on previous studies (Chung, 2002; Chung, Legge, & Cheung, 2004; Chung, Mansfield, & Legge, 1998). The font used was the standard Courier font (standard stroke boldness). For each set of reading speed vs. print size data (for each observer and each eccentricity), we fit the data using a two-line fit (on log–log axes), where the intersection of the two lines represents the CPS. The slope of the first line was constrained to 2.32 (on log–log axes), based on the empirical finding that the slope of the first line did not vary systematically with eccentricity and averaged 2.32 across all the curve fits in a previous study (Chung, Mansfield, & Legge, 1998). The slope of the second line was constrained to zero. The CPS was then used to determine the physical print sizes (0.8 and 1.4 × CPS) used in the main experiment.

In the main experiment, we measured reading speeds for print of different stroke boldness, for the two print sizes (0.8 and 1.4 × CPS) and at the fovea and 10° eccentricity for each observer. All observers also participated in two control experiments (see below). Although the methods and the results of the main and the control experiments are described in sequence in this paper, in reality, the different conditions for the main experiment and the two control experiments were tested in the same sessions in a random order that was different for different observers. Three observers completed testing with the smaller print size first (for the two eccentricities and different stroke boldness), before being tested with the larger print size. The other three observers were tested in reverse order of print size.

2.6. Control experiments

Reading speed is known to be influenced by print size (Chung, Mansfield, & Legge, 1998; Legge et al., 1985) and contrast (Legge, Rubin, & Luebker, 1987). When we manipulated the stroke boldness of print, not only did the stroke-width of print change, but the actual x-height (defined as the topmost row to the bottommost row of black pixels of the lowercase letter x: Legge and Bigelow (2011)) and the root-mean square (RMS) contrast of the letters also changed. Table 1 lists the ratios of the x-height and the RMS contrast of letters rendered in the different stroke boldness relative to the values for the standard boldness, for the same nominal print size. To determine if the changes in reading speed for letters rendered at different stroke boldness could be explained by a change in the actual x-height or the RMS contrast of the letters, we conducted two auxiliary experiments. The basic experimental paradigm for deriving reading speed was the same as that used in the main experiment.

In the first control experiment, we sought to determine if the differences in x-height [see our definition above] for print of different boldness could account for our results. Based on Table 1, the x-height for the least bold condition (stroke boldness = 0.27 × ) was equivalent to 0.88 × the nominal print size; and the x-height for the boldest condition (stroke boldness = 3.04 × ) was equivalent to 1.33 × the nominal print size. We measured RSVP reading speeds for text rendered at the standard boldness at these equivalent print sizes (0.88 × and 1.33 × of the original nominal print sizes). We equated for the equivalent print size based on x-height because this measurement was suggested as a good predictor of reading speed (Legge & Bigelow, 2011).

To control for the RMS contrast of the letters, for a given nominal print size, we determined the number of pixels that made up the set of letters ‘a’–‘z’ for the following three stroke boldness: 0.27 × (the least bold), 1 × (standard) and 3.04 × (the boldest). We then determined the pixel luminance for the print rendered at

<table>
<thead>
<tr>
<th>Boldness</th>
<th>0.27</th>
<th>0.72</th>
<th>1.48</th>
<th>1.89</th>
<th>3.04</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-height</td>
<td>0.88</td>
<td>0.93</td>
<td>1.10</td>
<td>1.18</td>
<td>1.33</td>
</tr>
<tr>
<td>RMS contrast</td>
<td>0.24</td>
<td>0.72</td>
<td>1.52</td>
<td>2.05</td>
<td>3.05</td>
</tr>
</tbody>
</table>

4. During the calibration procedure a fixation target randomly jumped to nine locations that were regularly spaced in a grid pattern (3 × 3) on the monitor. Observers were instructed to follow the target as accurately as possible, as it jumped from one location to the next. According to manufacturer’s criterion, a calibration was considered as “successful” if an observer’s fixation pattern formed a regular grid.
1× and 3.04× boldness that would yield the same RMS contrast as that of print of 0.27× boldness, taking into account the difference in the number of pixels comprising the letters, as shown in Eq. (2). Reading speeds were then determined for print of 1× and 3.04× boldness with the gray levels of the letters adjusted such that the RMS contrast of the letters matched those of the 0.27× boldness rendered in black (the original condition).

\[
\text{Number of pixels}_{0.27}\times \text{original luminance} = \text{Number of pixels}_{3.04}\times \text{new luminance}_{3.04}\times
\]

(2)

3. Results

Reading speed (in words per minute, wpm) is plotted as a function of nominal print size (x-height, in deg), for the two eccentricities, and for each of the six observers in Fig. 3. To estimate the CPS, we fit each set of data relating reading speed with print size using the two-line fit as described in Section 2. The intersection of the two lines represents the estimated CPS. Averaged across the six observers, the mean CPS are 0.12 (range = 0.08–0.15°) at the fovea and 1.63 (range = 1.21–1.93°) at 10° eccentricity. These values are consistent with those reported in the literature (Chung, 2002; Chung, Legge, & Cheung, 2004; Chung, Mansfield, & Legge, 1998).

3.1. Main experiment: Effect of letter-stroke boldness on reading speed

Fig. 4 summarizes the reading speeds obtained for different stroke boldness (0.27×, 0.72×, 1×, 1.48×, 1.89× and 3.04× the standard boldness) at the fovea and 10° eccentricity, and for the two nominal print sizes (0.8× CPS and 1.4× CPS). Each panel presents data for one observer. Consistent across all observers and as expected, reading speeds are higher at the fovea than at 10° eccentricity (repeated-measures ANOVA: \(F_{(df=1,5)} = 40.2, p = 0.0014\)), and higher for 1.4× CPS than for 0.8× CPS (repeated-measures ANOVA: \(F_{(df=1,5)} = 60.3, p = 0.0006\)). The main question here is whether

![Fig. 3. Reading speed (words per minute, wpm) is plotted as a function of print size (deg) for the six observers at the fovea (top panels) and 10° eccentricity in the inferior visual field (bottom panels). The straight lines through each set of data represent the two-line fit for estimating the critical print size (see text for details).](image1)

![Fig. 4. Reading speed (wpm) is plotted as a function of stroke boldness (stroke-width relative to the standard) for the six observers at the fovea (top panels) and 10° eccentricity in the inferior visual field (bottom panels). In each panel, smaller symbols represent reading speed obtained for 0.8× CPS and larger symbols represent reading speed obtained for 1.4× CPS. Error bars represent ±1 SEM.](image2)
stroke boldness affects reading speed. Fig. 4 clearly demonstrates that reading speed is affected by stroke boldness (repeated-measures ANOVA: $F_{(df=5,25)} = 13.0$, Greenhouse-Geisser adjusted-$p = 0.0009$). However, contrary to our prediction, across the six observers, none of the stroke boldness yields a consistent advantage of reading speed over the standard boldness. In fact, reading speed appears to be similar for a wide range of boldness values, at both the fovea and 10° eccentricity.

To facilitate the quantification of the effect of boldness on reading speed, we normalized the reading speed obtained for each stroke boldness to that for the standard boldness, for each individual observer and each condition. Fig. 5 shows the group-averaged normalized reading speeds as a function of stroke boldness, plotted as unfilled (fovea) and filled (10° eccentricity) symbols. Error bars associated with each symbol represent the 95% confidence intervals. If the error bars include a normalized reading speed of 1, then the reading speed for that stroke boldness does not differ from that for the standard boldness, at the $p = 0.05$ level. Fig. 5 illustrates that the effect of stroke boldness on reading speed is different between the fovea and the periphery, as confirmed by the significant interaction effect between these two factors (repeated measures ANOVA: $F_{(df=5,25)} = 3.89$, $p = 0.0095$). At the fovea, reading speed is invariant for a range of stroke boldness, from $0.72\times$ to $1.89\times$ the standard boldness, and drops for the two extreme stroke boldness, $0.27\times$ and $3.04\times$ the standard boldness. Averaged between the two print sizes, the drop in reading speed is approximately 23.3% from that obtained for the standard boldness. At 10° eccentricity, reading speed also remains similar for a range of stroke boldness, but this range shifts toward the thinner font (less bold), from $0.27\times$ to $1.48\times$ the standard boldness. At this eccentricity, reading speed falls below that of the standard boldness when the stroke boldness is thicker than $1.48\times$, implying that peripheral reading speed is more susceptible to the detrimental effect of bolder print. Averaged between the two print sizes, reading speed drops by 21.5% and 51% for stroke boldness of $1.89\times$ and $3.04\times$, respectively. Recall that we predicted faster reading speed for bolder print, at least in the periphery. Our results here clearly show that bolder print does not offer any advantage on reading speed, at the fovea and in the periphery. In fact, the detrimental effect of using bolder print is stronger in the periphery than at the fovea. Another interesting result is that reading speed in the periphery seems to be more tolerant of thin letter-strokes, as the reading speed for the least bold print is virtually the same as that for print of standard boldness. Most importantly, these effects do not change when we reanalyzed our data using a different criterion, 50% of words correctly read, to define reading speed (results not shown). The interpretation of these results will be discussed in the Discussion section.

![Fig. 5](image-url)
3.2. Control experiment: Equating the x-height

In the main experiment, reading speeds for the different boldness conditions were obtained using the same nominal print size. However, the actual x-height was smaller for the thinnest stroke boldness than for the standard boldness, and larger for the thickest stroke boldness than for the standard boldness (see Table 1). Fig. 6 plots the normalized reading speeds for the standard, the thinnest (0.27×) and the thickest (3.04×) boldness as obtained from the main experiment (gray bars), and when the print sizes were adjusted to equate for the x-height (white bars). If the lower reading speeds that we observed for the 0.27× and the 3.04× boldness were due to the difference in the actual print size (x-height) relative to the standard, then print rendered at the standard boldness but matching the x-height of the 0.27× or the 3.04× boldness print should yield reading speeds comparable with those of the main experiment. In other words, each pair of the gray and white bars for a given condition in Fig. 6 should yield the same height. When the error bars, representing the 95% confidence intervals, are taken into account, normalized reading speeds for the control condition (equating x-height) are similar to those of the original thinnest stroke boldness, but the normalized reading speeds are very different between the control condition and the original thickest stroke boldness. This result suggests that at least for the bolder print, the drop in reading speed could not be attributed to the change in print size associated with changes in stroke boldness.

3.3. Control experiment: Equating the RMS contrast of letters

In Fig. 7, the gray bars represent the normalized reading speeds obtained for the thinnest (0.27×), the standard and the thickest (3.04×) boldness in the main experiment. The white bars represent normalized reading speeds when the pixel luminance of letters of the standard and the thickest boldness were reduced to match the RMS contrast of that of the thinnest boldness rendered at the original contrast. If reading speeds measured for print of different boldness were determined solely by the RMS contrast, then we would expect that reading speeds measured using print matched in RMS contrast as the thinnest boldness would yield the same reading speed. In other words, the white bars should be of the same height as the leftmost gray bar (with horizontal line pattern) in each panel. This was not what we found. Reading speeds are still lower when the RMS contrast of the print was matched to that of the thinnest letter-strokes, especially for print of the thickest letter.

Fig. 6. Results for the control experiment examining the effect of letter height. Gray bars represent the normalized reading speeds (averaged across the six observers) obtained from the main experiment, for print rendered at (from left to right) the standard (1×, for comparison), the thinnest (0.27×) and the thickest (3.04×) stroke boldness. White bars show the normalized reading speeds when standard-boldness print was adjusted in size to match the actual letter height (see definition in text) of the print rendered at the thinnest (0.27×) and the thickest (3.04×) stroke boldness. Here, the comparison is to see if after equating for the letter height, the pair of the white and gray bars for each condition becomes similar in height.
strokes. This finding implies that at least for the bolder print, the drop in reading speed could not be attributed to the difference in the RMS contrast associated with changes in stroke boldness.

4. Discussion

By measuring reading speed for text rendered in a range of stroke boldness, we found that for a given print size, reading speed is optimal at the standard stroke boldness, and that rendering letter-strokes bolder does not improve reading speed, despite the overwhelming subjective preferences of boldface print by people with normal or low vision. These results are found at the fovea, as well as at 10° eccentricity. When the stroke boldness is very small (text rendered in thin strokes) or very large (text rendered in thick strokes), reading speed drops below that for the standard boldness.

4.1. Foveal reading

Fig. 5 shows that at the fovea, reading speed is invariant for a range of stroke boldness, from 0.72× to 1.89× the standard boldness, and drops at the two extreme stroke boldness, 0.27× and 3.04× the standard boldness. These results are consistent with the report of Paterson and Tinker (1940), who found no difference in reading speed for boldface and ordinary print in a group of 200 readers. Luckiesh and Moss (1940) also reported a very small difference (2–3%) in reading speed, even when the stroke boldness increased by 69%. Our study tested a larger range of stroke boldness, yet we are unable to find a boldness that improves reading speed beyond that for the standard boldness. If boldface text does not improve reading speed, then why is it subjectively preferred by so many people with normal or low vision? One possibility is that boldface text may be more comfortable to read, so that readers are able to read for a longer period when text is printed in boldface, compared with the standard typeface. Future studies are required to test if this is true.

When the letter-stroke becomes very thin (boldness of 0.27×) or very thick (boldness of 3.04×), foveal reading speed drops by approximately 23.3% below that for the standard boldness. For
the boldest condition, the reduction in reading speed can be explained by at least two possibilities. First, when the stroke-width of letters increases to 3.04 × the standard, some cues (or features) that are useful for letter identification may vanish. For instance, the intra-letter spaces within letters e, a, m, w and y almost disappear completely (see Fig. 1), compared with the less-bold versions of the font. This could increase confusions between letters, such as between c and e, a or o and o (Bouma, 1971), and thus directly reduce RSVP reading speed (Legge, Mansfield, & Chung, 2001). Second, the inter-letter spaces are also reduced as the stroke boldness increases, which could make it more difficult for observers to segment individual letters, a necessary step preceding word recognition (Pelli, Farell, & Moore, 2003). Again, this would lead to a degradation in letter recognition performance which could in turn, slow down reading. As for the thinnest stroke-width condition, the reduction in reading speed can simply be due to the low RMS contrast of the letters. As shown in our control experiment (Fig. 7), when we reduced the RMS contrast of text rendered in standard boldness, reading speed decreased substantially, implying that the RMS contrast of letters is an important factor for achieving optimal reading speed.

4.2. Peripheral reading

Our results obtained in the periphery are surprising on at least three accounts. First, contrary to many reports by, and advice offered to low vision patients, especially those with central vision loss who thus have to rely on their peripheral vision, bolder print does not improve reading speed. Second, the degradation effect of bold print on reading speed is more severe in the periphery than at the fovea, implying that the periphery is less tolerant to the thicker letter-strokes. This second point contradicts the fact that the spatial contrast sensitivity function shifts toward lower spatial frequencies in the periphery, compared with the fovea (Virsu & Rovamo, 1979), which should have facilitated the identification and reading of boldface print. We speculate that this effect could be due to the reduced edge-to-edge spacing for the two boldest conditions. Considering that letter crowding, the reduced ability in identifying individual letters when they are in close proximity to one another, is more substantial in the periphery than at the fovea (Bouma, 1970; Levi, 2008), it is reasonable to suppose that the reduced edge-to-edge spacing among letters affects reading more in the periphery than at the fovea. Previously, we examined the effect of letter spacing on reading for the standard Courier font (Chung, 2002), and determined that when the inter-letter spacing is very close, reading speed drops below the optimal reading speed. In that study, spacing was defined as center-to-center separation but we could determine the edge-to-edge spacing between letters. Here, we measured the edge-to-edge spacing between letters for the two boldest conditions (1.89 × and 3.04 × the standard boldness), and found that the spacings were equivalent to what would have been labeled as 0.88 × and 0.72 × the standard (center-to-center) spacing according to the definition in Chung (2002). The result of Chung (2002) showed that reading speed was virtually unchanged for 0.88 × the standard spacing at the fovea and 10° eccentricity, but dropped by approximately 22% when the spacing was reduced to 0.72 × the standard spacing. Our result showed a greater drop in reading speed for print rendered at the equivalent letter spacing but with bolder letter strokes, suggesting that even though letter spacing limits reading speed, it is not the only limiting factor.

The most interesting result in the periphery is likely to be the fact that reading speed for the thinnest letter-stroke condition is not different from that for the standard boldness. The RMS contrast of letters rendered at this boldness is very low, yet reading speed is not affected. We speculate that this lack of an effect on reading speed is due to the fact that the edge-to-edge spacing between letters increases when the letter-strokes become thinner (because we kept the center-to-center spacing between letters constant for different stroke-boldness), thus decreasing any crowding or spatial interaction effect arising from neighboring letter-strokes. In other words, the degrading effect of thin letter-strokes on reading speed is counteracted by the increase in reading speed due to the larger letter spacing between letters, with the net result being that reading speed appears to be unaffected by stroke-boldness when the boldness decreases from the standard value to the thinnest value.

4.3. Caveats

A few caveats should be kept in mind while evaluating our interpretation. First, as we stated in the Introduction, printed text has existed since 1455 (Meggs, 1998), therefore we expect that the various typographic characteristics of any given font are already optimized to provide the highest legibility for the standard version of the font. Also, our observers, although still young, have spent all their lives reading and seeing print of standard boldness, akin to receiving extensive training on the standard boldness. Therefore, they might have learned to optimally process print of standard boldness, compared with print of other boldness. These two factors might explain why the standard boldness is the most optimal one for reading. An interesting question is to determine if extensive training with fonts of other boldness (such as bolder print) could improve reading performance. Further experiments are needed to answer this question.

Second, although our motivation for testing in the periphery stemmed from our quest for methods that could improve reading speed for people with central vision loss, our finding might also bear significance for normal reading. In normal reading where eye movements are allowed, it is well known that readers can acquire partial word information from the word right of the currently fixated word (e.g. Rayner et al., 1982; Schotter, Angele, & Rayner, 2012; for a review, see Rayner, 1998, 2009). This parafoveal preview benefit is typically of the order of 30–50 ms. If bolder print can enhance the visibility of an upcoming word when a reader is not fixating the word, as in the case where the word is presented outside the fovea (in the parafovea (1.2–5° from the fovea) or periphery (beyond 5° from the fovea): Polyak, 1941; Rayner, 2009), then the benefit of parafoveal preview might even be greater. Although we did not find a benefit of using bolder text in the periphery in this study, it remains a possibility that boldface print may enhance the parafoveal preview benefit and improve reading speed in page reading.

Third, our study was based only on the Courier font. This font has a standard letter-stroke boldness of 0.165 × the height of the lowercase letter, similar to other frequently used fonts such as Times New Roman (average stroke-width = 0.124 × the height of the lowercase letter x) or Arial (average stroke-width = 0.151 × the height of the lowercase letter x). However, Courier is a fixed-width font, therefore, sentences or words rendered in Courier have a lower density of “ink pixels” per unit space (i.e. more blank area). Further studies will be necessary to show if our results could be generalized to other more “compact” (higher density of “ink pixels” per unit space) fonts. Based on a review of previous studies (see Section 1) that have examined the effect of boldness on legibility or reading speed at the fovea, it is highly likely that our main finding would stand even for other fonts, at least at the fovea.

Lastly, there is a common practice in typography called “optical scaling”, which refers to the subtle alterations made to glyph shapes depending on the physical size in order to keep fonts legible despite a change in physical size. For instance, when the print size is very small, instead of simply scaling the template of letters, typographers often widen the intra-letter spaces, increase the x-height or increase the enclosed part of a letter. In this study,
because our goal was to examine the effect of letter-stroke boldness on reading, we kept all other font characteristics scaled according to print size. Therefore in reality, the effect of boldness on reading, especially for small print, may be slightly different from what we report here, although we expect such differences would be small quantitative effects.

4.4. Conclusion

Reading is a daily activity that many of us can do effortlessly. The ability to read fluently depends on many factors including early sensory influences, eye movement control, high-level cognitive and linguistic factors. The main motivation of this study stemmed from our interest in seeking a simple method to modify text characteristics that would be beneficial to people with visual impairment. As such, we used a method to measure reading speed that minimizes the requirement to make reading eye movements (RSVP), and we also minimize the influences of cognitive and linguistic factors by using a within-subject comparison, that is, each observer was tested with all the conditions and our primary interest was to determine how reading speed changes with the different testing conditions (print size, testing eccentricity and stroke width boldness). We showed that by reducing or increasing the boldness of letter-strokes (referred to as weight in typography), reading speed at the fovea is not affected by a wide range of boldness until the letter strokes become very thin (0.27× the standard stroke-width) or very thick (3.04× the standard stroke-width). At 10° eccentricity in the periphery, reading speed is even more tolerant of thin letter-strokes, as reading speed for the thinnest stroke-width condition is not different from the reading speed for the standard boldness. However, in the periphery, reading speed falls off from the optimal reading speed at a boldness of 1.89× the standard, compared with 3.04× at the fovea, suggesting that peripheral reading is less tolerant to bold print. Considering the subjective preferences for reading boldface print indicated by people with visual impairment, our results confirm that subjective preferences for reading boldface print can affect performance in reading.

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