49.1: *Invited Paper:* Psychophysics of Reading: Implications for Displaying Text

Gordon E. Legge and Sing-Hang Cheung
Department of Psychology, University of Minnesota, Twin Cities, Minnesota

Abstract
Our psychophysical approach has the goal of explaining the dependence of reading performance on text parameters in terms of our understanding of spatial vision. In this presentation, we will focus on the impact of three attributes of characters (contrast, size and bandwidth), introduce the explanatory concept of the visual span, and discuss implications for text displays.

1. Introduction
Despite our contemporary fascination with graphics, reading text continues to be one of the most important functions of human vision. For text to be legible on electronic displays, it must lie within the envelope of *reading* vision. This envelope is bounded by critical values of several important text variables including character contrast, character size, and character bandwidth (or sampling density).

Until recently, reading usually involved text, printed in high-contrast black letters on white paper, viewed in good lighting, and processed line-by-line. Under these conditions, reading is fast and effortless because the key parameters of text lie well within the envelope of reading vision. Only people with impaired vision would require a magnifier to bring text within their envelope.

Modern technology has pushed the display of text way beyond the traditional format of print on paper. Consider three very different examples—1) large, high-resolution video displays, capable of containing a full page of text, but often including complex graphics, animations, and hyperlinks; 2) small text displays on PDAs or mobile phones, containing only 6 or 8 lines of 20 characters, viewed in a wide variety of environmental contexts; and 3) very low-resolution displays, perhaps less than 16 x 16 samples in size, comprising experimental prosthetic retinal implants for people with severe eye disease. The wide range of users, environments, display types, and text layouts takes advantage of the envelope of reading vision, but understanding the limitations of these modern displays relies on an understanding of the boundaries of this envelope.

2. Methods
We have used reading speed as our primary measure of performance. Reading speed can be scored objectively, is reproducible, and is sensitive to visual factors.

Measuring reading speed can be made akin to the widely used threshold methods of Psychophysics by pushing subjects to their fastest performance. This is done by presenting text on a computer screen for decreasing exposure times until the exposure time is too short for the subject to read accurately. We have used three variants of this approach: 1) In the *drifting-text* method, a single line of text drifts from right to left across a display screen at a controlled rate, and the subject reads the text aloud. The drift rate is adjusted to find the maximum legible speed. 2) In the *RSVP* method (Rapid Serial Visual Presentation), individual words are presented sequentially at the same location on a display screen. The RSVP rate is controlled by adjusting the exposure time for each word. 3) In the *flashcard* method the subject reads aloud standardized sentences of a fixed length and format, presented for a specified exposure time. If the entire flashcard is read correctly, a shorter exposure time is used on the next trial.

We have also developed a chart-based method for measuring reading speed, called the MNREAD Reading Acuity Chart, intended for clinical applications.

3. Results
In a numbered series of 20 journal articles <http://vision.psych.umn.edu/~legge/series.html>, we have reported on the impact of many text variables and eye variables on reading performance. In the present paper we review results on three key parameters especially important to the envelope of reading vision.

3.1 Contrast
Under optimal conditions, normal vision is remarkably tolerant to luminance contrast reduction. Reading speed is little affected by a 10-fold reduction from 100% contrast to 10% contrast. Only when contrast drops below 10% and approaches the threshold for letter recognition (typically between 1% and 2%) does reading speed decline rapidly. Accordingly, even displays with rather poor contrast rendering can support fast reading. The impressive tolerance of normal vision to reduced contrast is often diminished in disease (e.g., cataracts), or in aging eyes or even in normal vision under low illumination, or in the presence of veiling glare on a display screen.

3.2 Size
Angular character size is the relevant visual measure of print size because it determines retinal image size. For high-contrast print, reading speed is independent of angular character size down to a critical value (often termed "critical print size") of about 0.25 deg (15 min-arc)—roughly equivalent to the size of newsprint at a 40 cm viewing distance. People with normal acuity can read tinier print, but with severely decreasing speed as they approach their acuity limit (typically 5 min-arc or less). (Reading speed also slows down for very large characters, exceeding about 3 deg in size).

3.3 Interaction between Size and Contrast
Reading performance is remarkably flexible, sustaining high speed over a 10-fold range of character sizes and a 10-fold range of contrasts. But these variables do not act independently. For characters near the critical print size, the critical contrast is larger, and vice versa. This trade-off at the corner of the envelope of reading vision may have subtle consequences for display design. Imagine, for example, a text display with long lines of characters near the critical print size. Suppose the display's contrast is diluted by some source of external veiling light, compelling the reader to reduce the viewing distance from a normal 40 cm to a closer 20 cm. Even if the person is able to focus text at this near distance, binocular-convergence demands and the need for change

ISSN/0004-0966X/04/3502-1359-$1.00+.00 © 2004 SID

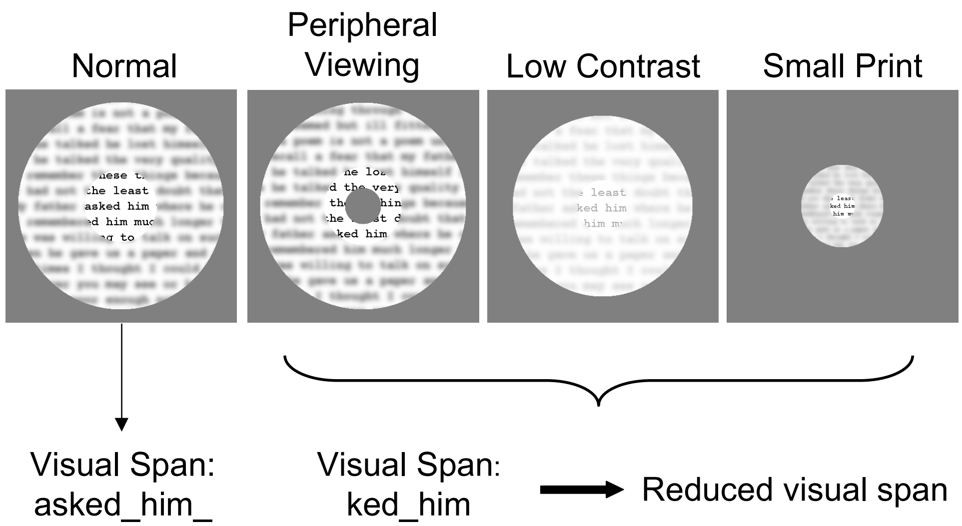

Figure 1. Information about text in the visual span for a) normal vision, b) vision with a central scotoma, c) near contrast threshold, and d) near the acuity limit.

of focus between the middle and ends of the lines, may result in slower reading or eyestrain.

3.4 Spatial Resolution

In one of our early studies [2], we measured reading speed as a function of the bandwidth of low-pass-filtered text. We discovered that a minimum bandwidth of 2 cycles/letter is required for reading. This result implies that a minimal reading display would require only 4x4 samples per character. This meager requirement does apply for tiny letters near the acuity limit, and provides hope that very coarse retinal prosthetic displays may be useful for reading. But we also found that the sampling requirements for larger characters are greater, and can exceed 20x20.

4. Visual Span as an Explanatory Concept

The effects of character size, contrast and bandwidth in letter recognition and reading have been tied to basic measures of spatial vision, especially the shape of the contrast sensitivity function (CSF) for vision. The concept of the *visual span* helps bridge the gap from these measures to reading.

The *visual span* for reading is the number of letters on a line of text that can be recognized accurately on one fixation. Figure 1a illustrates that the normal visual span is about 10 letters wide. Outside this region, decreasing spatial resolution of the retina reduces the accuracy of letter recognition. Figure 1b illustrates reading with a central blind spot (scotoma), a condition often resulting from age-related macular degeneration. People with this condition must use peripheral vision for reading. Our measurements indicate that the visual span shrinks in size in peripheral vision. Similarly, the right two panels in Figure 1 imply that the visual span also decreases for letters near contrast threshold or near the acuity limit.

The upper panel of Figure 2 illustrates how we measure the visual span. In a single trial, a random string of three letters (trigram) is briefly presented (typically 100 ms). The subject reports all 3 letters of the trigram. Trigrams are presented at different horizontal locations, with position indicated by the number of letter slots left or right of fixation. For instance, in Figure 2, tgu is positioned with g at slot +5. We use strings of letters rather than isolated letters because of their closer approximation to English text.

Across a block of trials, percent correct is accumulated for each letter slot. We refer to the resulting plot of letter accuracy vs. letter position as a *Visual-Span profile* (Figure 2, lower panel). These profiles usually peak at the midline and decline in the left and right visual fields. The right vertical scale of the graph in Figure 2 shows the transformation from percent correct letter recognition to information transmitted in bits. We quantify the size of the visual span by computing the area under the profile, more specifically, by summing across the information transmitted in each slot. The 13 slots in this sample profile transmit a total of 50.63 bits. Lower or narrower visual span profiles will transmit fewer bits of information.

In recent experiments, we have measured visual-span profiles and reading speeds for wide ranges of character contrast and size. In all cases, there is a close coupling between the area under the visual span and reading speed. Qualitatively, these findings suggest that when the contrast or size of text characters falls outside the boundary of the envelope of reading vision, reading speed slows down because of a reduction in the number of letters that can be recognized on each eye fixation. Smaller visual spans mean that the reader advances through text with shorter and more numerous saccadic eye movements, thereby taking longer to read the text. We have also developed a computational model that forges a quantitative link between letter recognition, characterized by empirical visual-span profiles, and reading speed [1].

5. Conclusion

Reading is remarkably tolerant to a wide range of display characteristics and viewing conditions because normal vision is tolerant to wide variations in key stimulus parameters, including

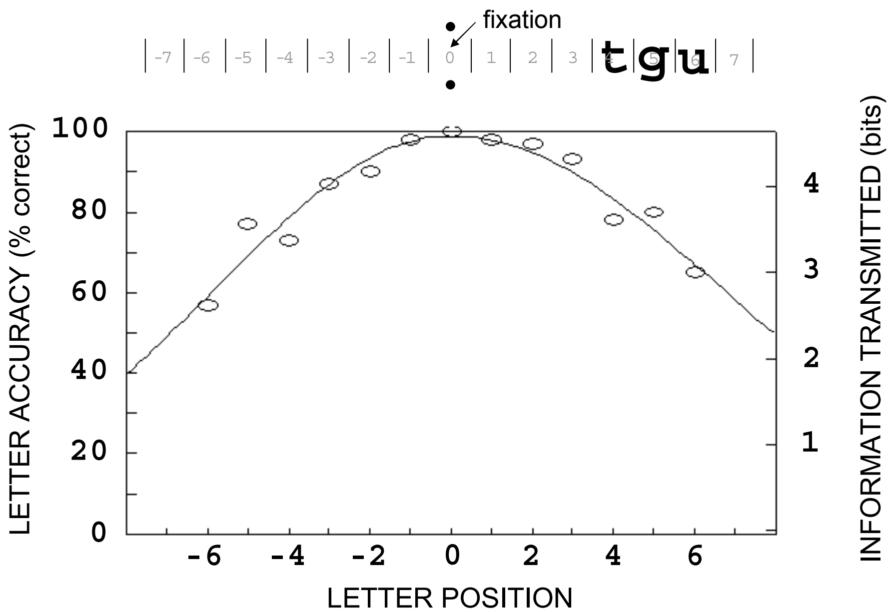

Figure 2. Illustrates the method for measuring the visual span (upper) and the resulting visual-span profile (lower).

character contrast and size. Modern technology can exploit the large envelope of reading vision by designing displays that are useful for a wide range of tasks and environmental conditions. Knowledge of the boundaries of the reading envelope, and how those boundaries can change due to eye disease or environmental conditions, can be used to predict legibility of text. When text parameters fall outside the envelope of reading vision, reading slows down because the reader's visual span shrinks in size.

6. Acknowledgement

Our research is supported by NIH Grant EY 02934.

7. References

[1] G.E. Legge, J.S. Mansfield, and S.T.L. Chung, "Psychophysics of reading. XX. Linking letter recognition to reading speed in central and peripheral vision," *Vision Research,* vol. 41, no. 6, Mar. 2001, pp. 725-734.

[2] G.E. Legge, D.G. Pelli, G.S. Rubin, and M.M. Schleske, "Psychophysics of reading. I. Normal vision," *Vision Research,* vol. 25, no. 2, 1985, pp. 239-252.