Typographic variables for digital low vision reading:

Print size and display size matter: magnification is usually necessary.

High contrast is often essential.

Bright displays and contrast reversal are desirable.

Inter-line and inter-word spacing may help.

Font effects are small, but fixed width fonts may be helpful when reading near the acuity limit.

Reading Digital with Low Vision

Gordon E. Legge

Abstract

Reading difficulty is a major consequence of vision loss for more than four million Americans with low vision. Difficulty in accessing print imposes obstacles to education, employment, social interaction and recreation. In recent years, research in vision science has made major strides in understanding the impact of low vision on reading, and the dependence of reading performance on text properties. The ongoing transition to the production and distribution of digital documents brings about new opportunities for people with visual impairment. Digital documents on computers and mobile devices permit customization of print size, spacing, font style, contrast polarity and page layout to optimize reading displays for people with low vision. As a result, we now have unprecedented opportunities to adapt text format to meet the needs of visually impaired readers.

Keywords
low vision, reading, readability, legibility, digital typography, typography

1 Introduction

The term *low vision* was coined in the 1950s by eye-care clinicians to convey the idea that vision can vary between the extremes of Sighted and Blind. *Low vision* refers to any chronic form of vision impairment not correctable by glasses or contact lenses that adversely affects everyday function. The boundary between normal vision and low vision is sometimes based on the inability to read newsprint at a standard viewing distance of 40 cm (16 inches) with best optical correction. This definition is used because most people with low vision have problems with reading texts designed for people with normal vision (Elliott et al., 1997; Owsley et al., 2009).

Letter acuity is the traditional clinical measure of vision, dating from the eye chart introduced by the Dutch ophthalmologist Herman Snellen in 1862. Four notable values on the Snellen scale of print size illustrate the range of reading vision. A Snellen acuity of 20/20 is the conventional standard for normal vision, and refers to letter sizes at the acuity limit subtending 5 minutes of arc (min-arc) of visual angle.

At a reading distance of 40 cm, an x-height of 0.58 mm subtends 5 min-arc. Typical newspaper print has an x-height of about 1.45 mm, just 2.5 times larger than acuity letters, the font size that a person with 20/20 vision can just barely see. One criterion for low vision is an acuity less than 20/60, meaning the acuity letters for 20/60 vision are more than three times larger than the standard for normal vision, and larger than typical newspaper print. The criterion for legal blindness is 20/200 or less (acuity letters at least 10 times larger than the normal limit). With high magnification, people with acuities as low as 20/2000 (acuity letters 100 times larger than 20/20 letters) can read. This wide range of reading acuities emphasizes that low vision, even very low vision, is compatible with reading, provided that adequate magnification is available.

The World Health Organization (2014) estimated that there are 285 million people worldwide with vision impairment, 39 million blind[1] and 246 million with low vision.[1] These figures include many people in less developed countries whose impaired vision is due to uncorrected refractive errors or untreated cataracts. According to the National Eye Institute (2014), there are between 3.5 and 5 million Americans with low vision, and the number is rising as the U.S. population ages. Because the leading causes of visual impairment in the United States are age-related eye diseases—macular degeneration, glaucoma, diabetic retinopathy and cataract—the prevalence of impaired vision rises steeply with age. Reading poses problems for almost everyone with low vision because the print size in everyday text is too small.

Traditional hard copy reading is not inclusive of people who are blind or have low vision. Marshall McLuhan (1962) in his famous essay *The Gutenberg Galaxy* referred to the invention of movable type as bringing about the "tyranny of the visual."[2] After Gutenberg's invention, hard-copy printed materials became increasingly available and literacy increased. Success in society became highly dependent on the ability to read, requiring good visual acuity. The "tyranny of the visual" has persisted for centuries, and has excluded many people with impaired vision from the literate mainstream. Since not much could be done to make print accessible, low-vision reading received little attention.

In the early 20th century, the concept of "sight saving" was an additional deterrent to reading with low vision. It was thought that use of the eyes would accelerate eye disease; sight should be "saved" and used sparingly. This concept may have originated with the Myope School in London. Children with myopia were thought to be at risk because high myopia could lead to retinal detachment. It was believed that this risk could be avoided by not reading. The sight-saving philosophy held sway in the United States during the first half of the 20th century, and generalized from myopia to low vision (Jackson, 1983). Many children with low vision were not taught to read visually and not prescribed reading magnifiers. Only in the 1960s did "sight saving" begin to give way to a "sight utilization" philosophy in education. The latter emphasizes the importance of optimizing the functional value of low vision.

The association between reading and myopia has long been a topic of study and debate. Causal explanations linking myopia in children to reading have focused on accommodative strain, residual defocus, and the fine detail in text stimuli which lack the distribution of coarse and fine features found in natural images (cf., Wallman & Winawer, 2004). Current intense research on myopia is focused on its increasing prevalence, especially in east Asia where it has reached epidemic proportions. There is recent evidence that time spent outdoors is protective against the onset of myopia, independent of the amount of reading and other indoor activities. One possible explanation is that bright light outdoors stimulates the release of the neurotransmitter dopamine in the eye which in turn inhibits excessive eye growth. (Myopia is a mismatch between the refractive power and the length of the eye.) For a nontechnical overview of the relationship between myopia and outdoor activity, see Dolgin (2015).

The modern electronic era has softened the "tyranny of the visual," first by moving text from hard copy where it is difficult or impossible to read with low vision onto video screens where it can be manipulated visually, and then into digital representations which can be customized. Digital documents on computers and mobile devices permit easy manipulation of print size, contrast polarity, font, color, and layout. High-tech digital image enhancement methods for low vision are also under study (Moshtael et al., 2015).

Digital text can also be converted to auditory or tactile (braille) formats. For example, screen-reading software converts digital text into

1. The World Health Organization defines people with acuities less than 20/400 as "blind," but, as indicated above, some people with acuities as low as 20/2,000 can read visually, given high magnification.

2. This quotation was brought to my attention by Cattaneo & Vecchi (2011).

synthetic speech. A major development in nonvisual text accessibility has been the inclusion of synthetic speech software (VoiceOver) as a standard component in Apple's iOS and Mac operating systems.

In short, the migration of text into digital formats brings with it enormous opportunities for enhancing text accessibility for people with impaired vision.

2 From Paper to Screens

Prior to the digital age, the primary method for facilitating low-vision reading was magnification, and the primary technology was optics. Optical magnification continues to be an important part of low-vision reading rehabilitation. Table 1 lists some highlights in the development of low-vision reading technology in the pre-digital era.

Table 1

Some highlights in the history of low-vision reading technology prior to the digital age (adapted from Goodrich et al., 2008).

Year	Event
1270	Marco Polo discovered older people in China using magnifying glasses for reading.
1637	First magnifying aid for visual defects; René Descartes "described a solid glass cone with a plano front surface and a concave back surface."
1829	Louis Braille published his invention of a tactile code for reading.
1908	The Myope School in London was the first class for children with low vision.
1909	Moritz von Rohr, employed by Carl Zeiss, designed a telescopic lens to correct high myopia.
1913	Edward Allen, Director of Perkins Institute, opened the first U.S. class for children with low vision.
1916	The Clear Type Publishing Company produced a series of books in 36 point font.
1924	The American Foundation for the Blind began supplying telescopic lenses and referring clients to eye-care practitioners.
1935	William Feinbloom published "Introduction to the principles and practice of sub-normal vision correction" in the *Journal of the American Optometric Association*
1947	The American Printing House for the Blind began regular publication of large print books.
1969	Samuel Genensky and colleagues at the Rand Corporation reported on their development of a closed circuit television magnifier for low vision.
1976	Eleanor Faye published her book on *Clinical Low Vision*.
1977	Louise Sloan published her book on *Reading aids for the partially sighted: a systematic classification and procedure for prescribing*.

There are three general forms of magnification for reading—enlarge the print size on the page, reduce the viewing distance, and use a magnifier. Some published materials are available in "large print" formats. It is recommended that large print materials should be at least 16 to 18 points

(Arditi, 1999). The vast majority of published material is not available in large print. Even when large-print publication is an option, there are practical limitations on the sizes of pages and books. For this reason, large print rarely exceeds 20 pt. For many people with low vision, 20-pt print provides insufficient magnification.

The simplest method of magnification is to reduce viewing distance. Since angular character size (and, correspondingly, retinal image size) is inversely related to viewing distance, reduction of the viewing distance by a factor of N accomplishes N-fold magnification. For instance, viewing the newspaper from 20 cm rather than 40 cm (a factor of two) is equivalent to magnifying print size by a factor of two. But this approach requires the reader to focus for the nearer distance. Young people who have a wide range of accommodation, or people who are myopic (short-sighted), may be able to focus at distances of 10 or 20 cm. Most people, especially older people with presbyopia (the absence of accommodation, encountered by almost everyone over 50), will require a lens to focus print at short viewing distances. Lenses used for this purpose are termed *magnifiers*.

Optical magnifiers for reading come in three general types—hand-held, spectacle-mounted or stand magnifiers that rest on the page. Enlargement of the characters in a local region of text by a magnifier brings about the need to move the magnifier across the lines of text. This process is sometimes termed *page navigation* and imposes demands on eye or head movements and manual dexterity. For reviews of properties and principles for prescribing low-vision magnifiers, see Bailey, Bullimore, Greer and Mattingly (1994) and Sloan (1977).

Optical magnifiers are effective reading aids for people with mild forms of low vision. For people with acuities of less than 20/100, requiring magnification of 6X or more, optical magnifiers become difficult to use because of the restricted field of view and the increasing demands of page navigation.

Figure 1

A. Topaz Desktop Video Magnifier (Freedom Scientific). B. Amigo Portable Low Vision Electronic Magnifier (Enhanced Vision).

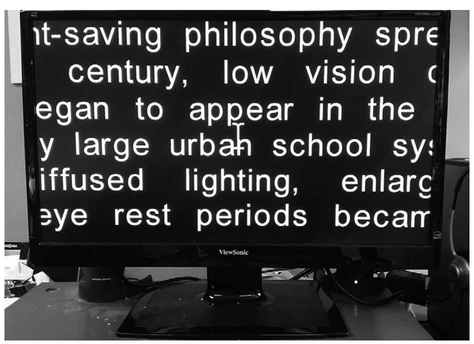
A major step in alleviating the problems associated with high-power optical magnifiers was to move text from small print on a page to highly magnified print on a television screen (Genensky, 1969). Figure 1 illustrates the display of text on a closed-circuit TV (CCTV) magnifier for a reader with very low acuity. The device includes a video camera, pointed downward, imaging a page of text lying on a movable X-Y table. The camera zoom is adjustable, allowing for high magnification, up to 64 times or more (ratio of character size on the screen to character size on the hard copy page.) The user can view different portions of the page by moving the table left/right or forward/back beneath the camera. In the example shown, the user has adjusted magnification so that the x-height on the screen is 1.3 inches, about 19 times larger than the characters on the page (Courier 10 pt). This user views the screen from a distance of 13 inches, with the result that the angular character size is almost 6º.

Notice that this low-vision reader prefers bright letters on a dark background rather than the conventional dark letters on a white background. Some people with low vision have higher acuity and read better with reversed-contrast text. CCTV magnifiers are designed to include options for reversing contrast polarity.

The original CCTV magnifiers were desktop devices. A recent development has been the advent of portable electronic magnifiers. An example is shown in Figure 2. These are handheld devices with a built-in LCD screen, a range of zoom, and the capability for contrast reversal. The user moves the magnifier across a page containing text. There are now many portable electronic magnifiers on the market. The American Foundation for the Blind (AFB) lists technology resources for people with vision loss at http://www.afb.org/info/living-with-vision-loss/using-technology/12. In a review of low-vision reading aids, Virgili et al. (2013) found that there is some limited evidence that desk-mounted or hand-held electronic reading aids yielded faster reading than stand or hand-held optical magnifiers.

Figure 2

Magnified text on a computer screen using the screen-magnification software ZoomText (Ai Squared).



The CCTV magnifiers are devices for magnifying hardcopy print. They deal with text in analog form.

A big leap forward toward accessibility of digital text for low vision was the advent of computer software for screen magnification. Figure 2 shows text magnified by the software program ZoomText on a computer display. Like the CCTV magnifiers, screen magnification software is designed with a wide range of zoom and the capacity for contrast reversal. The user scrolls through the text by moving the mouse or by taking advantage of the program's auto scrolling capability.

There is growing evidence that people with low vision are taking advantage of digital displays for reading. In an internet-based survey of 132 people with impaired vision (26% with no vision and 74% with low vision), Crossland et al. (2014), found that 81% used a smartphone. Of the smartphone users, 51% used the camera and screen for magnification. Gill et al. (2013) studied 27 subjects with stable age-related macular degeneration. They compared reading speeds for matched print size on paper, an Apple iPad and a Sony eReader. Reading speeds were slightly faster on the iPad than paper, and slightly faster on paper than the eReader. The authors attributed the differences to the bright, high-contrast display of the iPad. Morrice et al. (2015) compared the reading speeds of 100 low-vision subjects on a CCTV magnifier, and apple iPad and the subject's preferred optical magnifier. Reading speeds did not differ significantly across the three conditions. The authors emphasized the significance for rehabilitation of the use of a mainstream technology (the iPad) for low-vision reading magnification.

Once text is in digital form and of sufficient print size, we can ask how other text properties affect low-vision reading.

3 Measuring Reading Vision

If we want to measure the impact of text properties on reading, we need a method for measuring visual reading ability. Miles Tinker long ago introduced reading speed as a metric. For a review of his many contributions to understanding the effects of typographic variables on normally sighted reading, see Tinker (1963). A great deal of recent psychophysical research on reading has used reading speed because it is straightforward to measure objectively, is sensitive to changes in both eye condition and text properties, and is functionally significant to readers. For a discussion of methods of measuring reading speed and a comparison to other metrics for measuring reading performance, see Legge (2007, Ch. 2). For a review of clinical tests for assessing visual aspects of reading, see Rubin (2013).

Figure 3 shows the MNREAD reading-acuity chart designed by my colleagues and me (Mansfield et al., 1993; Mansfield & Legge, 2007). The chart is printed on two sides, and is composed of 19 sentences in a progression of print sizes differing by about 26% (0.1 log unit) per step. At 40 cm viewing distance, print sizes range from 20/400 to 20/6. 20/6 letters are more than 3 times smaller than 20/20 letters, tinier text than anyone can read. For low-vision testing requiring letters larger than 20/400, shorter viewing distances can be used (20 cm or even 10 cm) yielding corresponding increases in angular print size. Sentences on the chart are matched for geometric layout (each sentence is formatted on three lines with the same aspect ratio), and linguistic properties including high-frequency vocabulary. There are exactly 60 characters in each MNREAD sentence. The sentences have been pilot tested to ensure uniform readability.

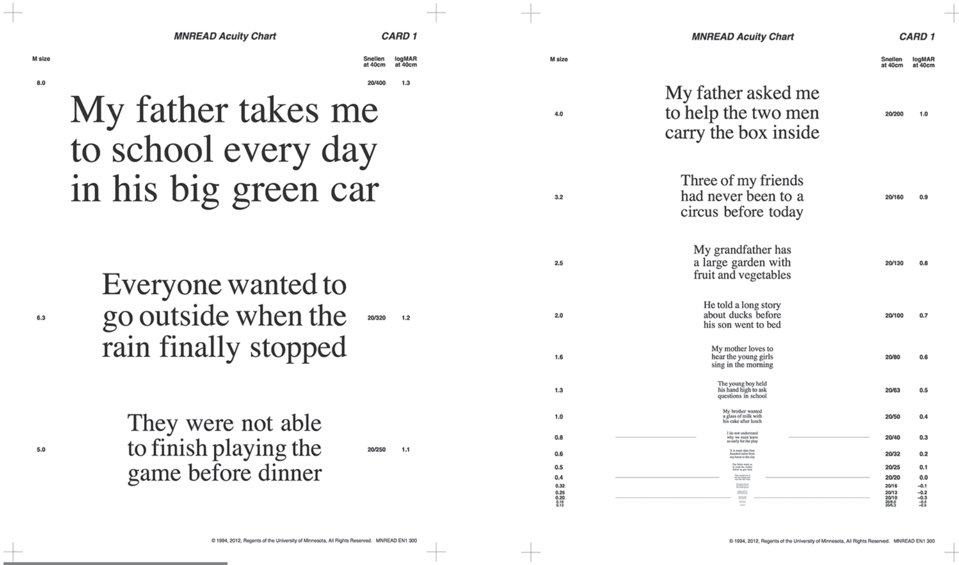


Figure 3

Two sides of the MNREAD acuity chart used for testing reading vision (Precision Vision).

In the test, subjects are instructed to read the sentences aloud as quickly and accurately as possible. They are timed with a stopwatch, and errors are recorded. These measurements are converted to reading speed in words per minute as a function of print size.

Figure 4 shows sample data for a normally sighted subject (A) and a low-vision subject (B). Reading speed in words/minute is plotted as a function of print size on a log scale.

Note that print size may be expressed as a physical measure on the page in units of mm or points (1 pt = 1/72 inch), or as the visual angle subtended in units of degrees (º) or minutes of arc (min-arc). Angular print size takes into account both the physical size of the characters and the viewing distance. Representing print size in terms of visual angles makes sense for vision researchers because angular size determines retinal-image size. Acuity letters on the 20/20 line of an eye chart subtend 5 min-arc. The "logMAR" unit represents angular print size as the logarithm (base 10) of print size divided by the size of 20/20 letters. This means that print sizes of 20/20, 20/200, and 20/2000 have logMAR values of 0, 1.0 and 2.0 respectively.

The curves in Figure 4 exhibit a typical form characterized by the subject's Reading Acuity (RA), Critical Print Size (CPS) and Maximum Reading Speed (MRS). RA is the smallest print that can be read. CPS is the inflection point in the curve, indicating the smallest print that can be read at maximum reading speed. MRS is the reading speed on the plateau, 225 words/minute for subject A with normal vision in Figure 5. As discussed in the next section, low-vision subjects often have larger values of RA and CPS, due to their lower acuity, and also lower maximum reading speed (42 words/minute for subject B in Figure 4.)

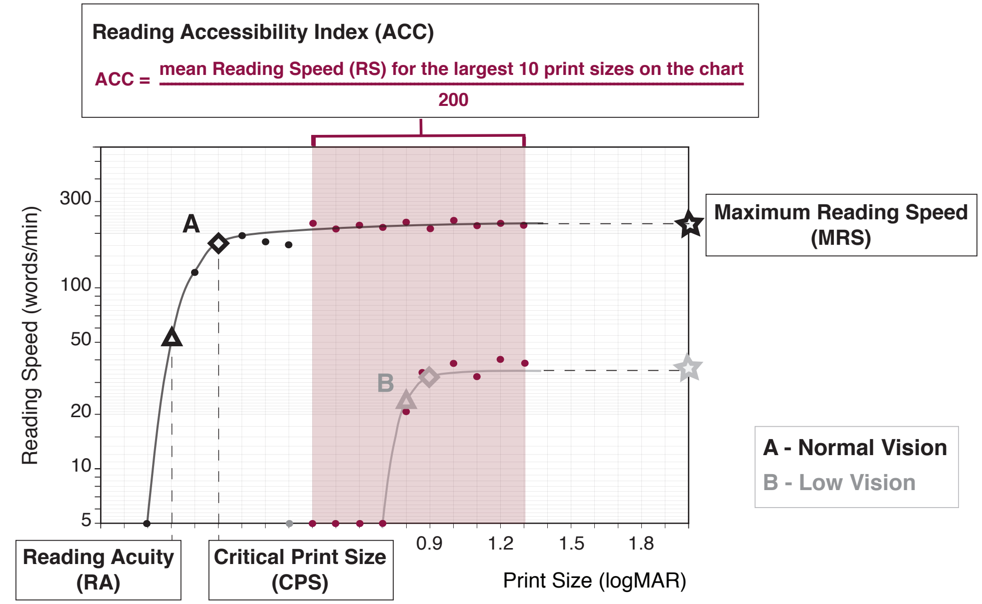


Figure 4

Sample MNREAD plots of reading speed vs. print size for a subject with normal vision (A) and a subject with low vision (B). Adapted from Calabrese et al. (2016). The triangle marks Reading Acuity (RA), the diamond marks Critical Print Size (CPS), and the star marks Maximum Reading Speed (MRS). The dots indicate reading speeds at different print sizes on a logarithmic scale.

Figure 4 also illustrates the computation of a summary parameter called the Reading Accessibility Index (ACC). It is the average reading speed, computed over the print size range from 0.4 to 1.3 logMAR, normalized by the mean value of 200 words/minute for a group of normally sighted, young adults (Calabrese et al, 2016). This range of print sizes encompasses the vast majority of print encountered in contemporary texts (Legge & Bigelow, 2011). The ACC is intended as a single-valued measure of the accessibility of print and depends on both the subject's range of visible print sizes and the speed of reading within the visible range. An average normally sighted reader would have an ACC value of 1.0. In Figure 4, subject A has an ACC value of 1.12, representing performance slightly better than the normal mean. Subject B with low vision has an ACC value of 0.12, representing severely reduced reading accessibility. Perhaps subject B's range of visible print and/or speed could be improved with an optical or electronic magnifier, thereby increasing the reading accessibility value.

4 Impact of Text Variables on Low-Vision Reading

The impact of many text variables on low-vision reading has been studied. For a review, see Legge (2007). According to an online publication by the American Council of the Blind (2011), the most important text variables are print size, spacing, contrast and font style. All of these are modifiable by digital devices.

Print Size:

First, let's consider how print size affects reading speed for people with normal vision. This information can serve as a baseline for understanding deficits associated with low vision.

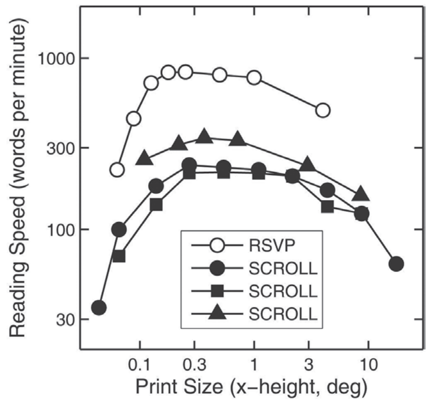


Figure 5 presents data from several experiments showing how print size affects reading speed for people with normal vision. Reading speed is plotted vertically against print size, measured as x-height in degrees of visual angle over a wide range. The curves rise steeply at the small-print end to a critical print size, then flatten out for an intermediate range of print sizes, and then decline more slowly for very large print sizes.

The key result is that there is a large range (10-fold) of print size for which people with normal vision can achieve maximum reading speed—extending from the critical print size of 0.2° to 2°. This range corresponds to x-heights from 4 points to 40 points at a reading distance of 40 cm. We refer to this as the *fluent range* of print size. Legge & Bigelow (2011) presented evidence supporting the hypothesis that the distribution of print sizes in historical and contemporary published works falls within this behaviorally-defined fluent range of print size. For reasons of economy and space, production of text has favored the small print end of the fluent range. The challenge for low vision is the lack of accessibility of print in this fluent range, especially toward the small-print end.

Figure 5

Reading Speed (words per minute) is plotted as a function of angular print size (x-height in degrees). Data are taken from four experiments using RSVP (open circles), and scrolling text (filled circles, filled squares, triangles). The data points are means across subjects. Reprinted from Legge & Bigelow, (2011).

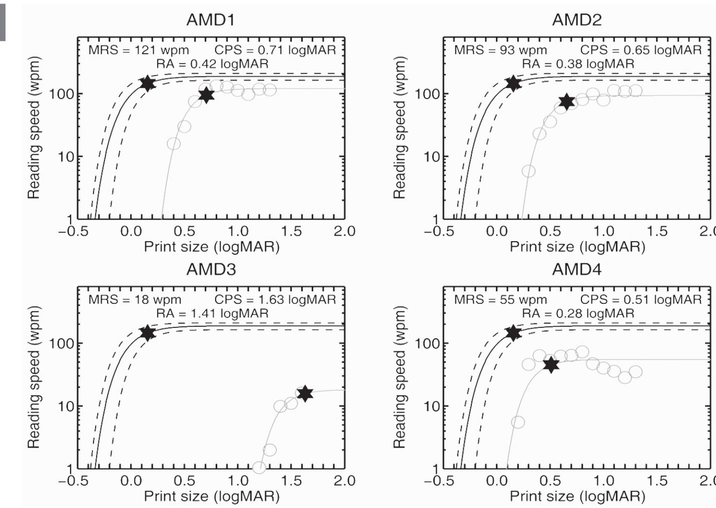
A side comment about this figure: the open circles are from a study that had reading speeds that were much higher than the other three studies. The difference is due to the use of the Rapid Serial Visual Presentation (RSVP) method for measuring reading speed. In the RSVP method, individual words are presented sequentially at the same location on a display screen. The RSVP rate is controlled by adjusting the exposure time for each word. RSVP reading speeds are typically much higher than speeds for regular page reading (Forster, 1970; Rubin & Turano, 1992).

Figure 6 illustrates the impact of print on reading speed in low vision, measured with the MNREAD chart.

The red curves in the four panels show reading speed measurements for individual subjects with age-related macular degeneration (AMD), the commonest form of low vision in the United States. The upper white curves show the average data from a group of 15 age-matched normally sighted older adults (mean age 70 years). There are two important things to notice in the figure. First, the AMD subjects have larger critical print sizes (CPS), to achieve their maximum reading speed; this means they need magnified print for reading. The extent of the difference in CPS between the normal controls and the AMD subject can guide a clinician in deciding how much magnification is required for a reading magnifier.

Figure 6

Reading speed (words/minute) is plotted as a function of angular print size. The grey curves in the four panels show slower reading speed for four people with AMD, while the black curves show the average data for a group of normally sighted age-matched controls. The stars mark Critical Print Size.



Second, even with adequate magnification, the AMD subjects do not achieve normal reading speeds; the flat portions of the red curves lie below the normal curves. Several causes of this reduction of maximum reading speed in AMD have been explored, including instability of eye fixations (Crossland et al., 2004) and reduced visual span for reading (Cheong et al., 2008).[3]

To achieve magnification of digital text, people with low vision often use large computer displays and/or screen magnification software. But what about the visual accessibility of text on portable digital devices with small displays?

Table 2 summarizes some measurements of print size on portable devices. Based on recommendations for large print books, a font

Table 2

Type Sizes on Portable Digital Devices

Type of text	x-height mm	x-height pt	x-height deg (reading distance, cm)
Bababekova et al. (2011): Means across subjects and smartphones			
Text Msg	1.6	4.6	0.25 (36.2)
Web pg	1.1	3.1	0.2 (32)
Houston et al. (2011): iPhone 4 C (2X mag, Horizontal)			
Text Msg	3	8.6	0.42 (40)
Web Pg	3	8.6	0.42 (40)
Phone Keypad	5.4	15.4	0.75 (40)
C.A. Bigelow (2016, personal communication): Nook GlowLight+ (Georgia font)			
Smallest text	1.1	3.1	0.16 (40)
Largest text	10.0	28.4	1.42 (40)
C.A. Bigelow (2016, personal communication): iPhone 6s+ iBooks (Georgia font)			
Smallest Text	0.9	2.6	0.13 (40)
Largest Text	3.9	11.1	0.55 (40)

3. The visual span for reading is the number of adjacent letters in text that can be recognized during a single eye fixation (O'Regan et al., 1983; Legge et al., 2001). For normally sighted readers, the visual span is about ten letters, but it can be much smaller in cases of low vision.

size of at least 18 to 20 pt is required for low vision. This corresponds to roughly 9 pt x-height in this table. Values near or above this value are highlighted in red.

Bababekova et al. (2011) surveyed the font sizes and reading distances of more than 100 young normally sighted cell phone users for text messaging and web browsing. On average they held the phones a little closer than the standard 40 cm, 36 and 32 cm respectively. The corresponding angular x-heights of the cell phone print were close to the critical print size (CPS) for normally sighted readers of 0.2º, and the font point size of the print was much smaller than recommended for large print applications.

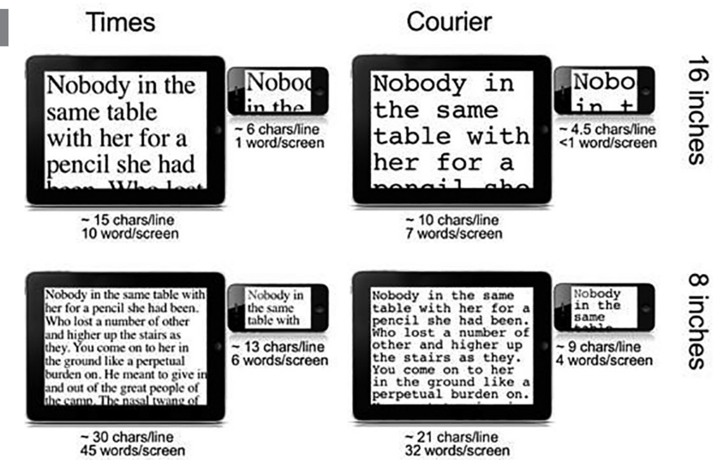
Houston et al., (2011) evaluated print sizes on six types of cell phones. Only the iPhone 4c in its 2X mode generated text that might be viable for low vision. They did their testing in the landscape orientation. For text messaging and web browsing, the print was 8.6 pt in x-height, not far from the 9-pt minimum x-height for large print. For symbols on the phone keypad, the print size was 15.4 point.

Charles Bigelow (personal communication) measured e-reader print sizes on the Nook GlowLight Plus (e-paper display at 300 pixels per inch), and also on the iPhone 6s Plus (Retina HD LCD display at 401 pixels per inch). Both e-readers offer at least 10 user-selectable font sizes. Using the Georgia font, and depending somewhat on the particular book, the Nook's smallest print size x-height is approximately 1.1 mm (equivalent to 6.5 pt font size), less than the CPS for normal vision for a 40 cm viewing distance, and its largest print size x-height is approximately 10.0 mm (equivalent to 60 pt font size), almost three times the low-vision guideline for large type. On the iPhone 6s Plus iBooks e-reader, also using the Georgia font, the smallest print size x-height is approximately 0.9 mm, less than the CPS for normal vision and the largest print size x-height is approximately 3.9 mm (equivalent to 23 pt font size) which meets the low-vision guideline.

Keep in mind two additional user strategies for dealing with print size: First, small devices can be held closer to the eye, thereby increasing the angular print size, but with the added demand for near focus. Second, these devices generally allow pinch to zoom to provide larger print. But, because of their limited screen real estate, magnification is constrained by the number of large characters that can be displayed.

For many people with low vision, reduced acuity means that the required print size is much larger than a font size of 20 points, even with a short viewing distance. The small size of displays on mobile devices poses a major challenge. Four interacting factors may determine the viability of reading with such displays--print size, number of characters per line, line separation and font. Figure 7 illustrates these interactions in the case of a sample low-vision reader.

Figure 7



This figure simulates 2° text displayed on an iPad 3 and an iPhone 5 at viewing distances of 16" (top row) and 8" (bottom row). Only the iPad at 8" exceeds 12 characters per line and 10 words per screen for both Times (left panel) and Courier (right panel).

Suppose this reader has a critical print size of 2° and is considering an iPhone 5 or iPad 3 for reading. If empirical testing reveals that she needs at least 12 characters per line and 10 words per screen for acceptable reading, then only the iPad (viewed from 8 inches) exceeds these minimum values for both Times and Courier (*Figure 7*). This illustrates the interacting effects of display geometry, acuity, viewing distance, print size and font.

Spacing

Spacing has been of interest in studies of low-vision reading because of the crowding phenomenon. Crowding refers to the interfering effects of one target on the identification of a nearby target in the visual field. The spatial extent of crowding increases in peripheral vision (Bouma, 1970), meaning that target stimuli need to be farther apart for recognition. Crowding is a major cause of the reduced visual span in peripheral vision (Pelli et al., 2007; He et al., 2013). Macular degeneration, the leading cause of low vision in the United States, can result in the development of blind spots (scotomas) in central vision extending 5º or more and including the fovea. People with this condition must use peripheral vision for reading. It is reasonable to suspect that increased spacing between letters, words or lines would help their reading by reducing crowding.

Measurements of reading speed for normally sighted subjects have varied letter-letter spacing in a fixed-width font (Courier) from half of standard spacing to twice standard spacing (Chung, 2002; Yu et al., 2007). These studies found that reading speed peaks at the standard spacing. But does extra spacing help in low vision? In a limited experiment, Legge et al. (1985) tested two normal and four low-vision subjects. They read highly magnified text (6° or larger), with normal spacing, and 1.5x and 2x normal spacing. For all of the subjects, reading speed was highest for standard spacing and declined for extra spacing. Chung (2012) conducted a more extensive test with 14 subjects with central-vision loss, and found essentially the same result.

What about interline spacing? Two recent studies with low-vision subjects found either no benefit of extra line separation (Chung et al., 2008) or a very small advantage (Calabrese et al., 2010). But Blackmore-Wright et al. (2013) found that combining double line spacing and double between-word spacing was beneficial for subjects with macular degeneration.

Overall, the evidence indicates that increasing spacing between letters is not helpful, but extra-wide spacing between lines or words may have some benefits for some readers with low vision.

Figure 8

Losses of resolution in low vision. Samples of text are shown in six fonts. A blurring filter simulates viewing the samples in 18 point type, at a viewing distance of 40 cm (16") with four levels of declining acuity (standard sharpness followed by three increasing amounts of blurring). Which font appears to have best visibility as acuity declines?

Font Style

There have been many opinions about the most suitable fonts for low vision.

Figure 8 shows text samples from six fonts that have often been discussed in the context of low vision—Courier, Courier Bold, Times New Roman, Arial, Verdana and Tiresias LP. Recall that 18 pt is a recommended font size for large print. In Figure 8, digitally filtered versions of each font are shown, simulating the loss of resolution to be expected for 18 pt font size, viewed at 40 cm with four acuity levels (20/20, 20/120, 20/160 and 20/200.) While the blurring functions used for this simulation may not be perfectly calibrated, the qualitative outcome is clear. For the simulation of 20/200 vision, the separate lines are distinguishable, and also the spaces between words, but the characters are not legible. For an acuity of 20/120, the text is becoming readable, with legibility depending on the font.

In one of our studies, we showed that for low vision, reading speed is measurably faster for Courier than Times, with the difference increasing for reading near an individual's acuity limit (Mansfield et al., 1996).

The advantage of Courier may relate to space around narrow letters. The simulation in Figure 9 appears to confirm that Times is less tolerant to acuity reduction than Courier. Tarita-Nistor et al. (2013) tested 24 AMD subjects on the MNREAD test with four fonts—Times Roman, Arial, Courier and Andale. Near the acuity limit, performance was best with Courier and worst with Arial. The poorer performance with Arial was a surprise; it is a sans-serif font. The prevailing opinion has been that sans serif fonts are slightly more legible than serif fonts for low vision. The Guidelines for Large Print recommend Verdana and Arial.

It is widely held that bold print is desirable for low vision. In Figure 8, is Courier Bold more tolerant to blur than Courier? Bernard et al. (2013) measured reading speed (RSVP method) in central and peripheral vision for subjects with normal vision. They rendered their text in Courier, but varied the stroke thickness from 0.27 to 3.04 times the standard stroke width for the font. Contrary to expectation, stroke thickness greater than the standard value did not help reading, and excessively bold strokes resulted in slower reading. It remains to be determined empirically how stroke width affects low-vision reading.

Tiresias was designed specifically for low vision. It emphasizes space around narrow letters. Does it appear more tolerant to blur in Figure 8? Rubin et al. (2006) compared four fonts including Tiresias and Times Roman, for people with mild forms of low vision. The Tiresias font had a slight advantage in speed for fonts equated for nominal font point size, but when equating fonts for actual horizontal and vertical space occupied, the difference disappeared.

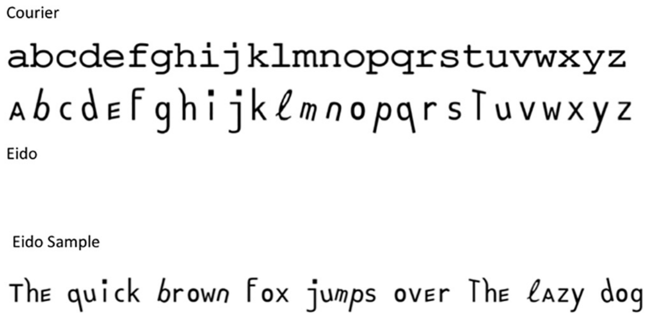
A review by Russell-Minda et al, (2007) concluded that there is little empirical evidence for an optimally legible font for low vision. In my book (Legge, 2007, Ch. 4), I concluded that

"… type designers have developed several commonly used fonts that are roughly comparable in terms of reading performance for normal vision, at least when angular character size is greater than some critical print size. For low vision, fixed-width fonts may yield faster reading, possibly because low-vision reading often occurs near the acuity limit."

Recently, Bernard et al. (2016) reported on the design of a font to enhance legibility for peripheral vision by reducing crowding between adjacent letters. Such a font might be helpful for people with central-field loss from macular degeneration. Bernard et al. designed their fixed-width font, named Eido (*Figure 9)*, based on three principles: reduce the image similarity between letters, reduce the complexity of the letters, and retain letter shapes that are familiar to readers. They compared Eido with Courier, matched for inter-letter spacing and x-height, in tests of reading speed, letter recognition, word recognition and reaction time for lexical decisions. Tests of flanked letter recognition indicated that Eido was successful in reducing crowding. But when they tested reading speed on normally sighted subjects with simulated central scotomas, they found no significant

Figure 9

Comparison of Courier and Eido Fonts from Bernard et al. (2016).



difference in reading speed or critical print size between Eido and Courier. It remains possible that subjects with central scotomas from macular degeneration or other diseases would benefit when reading with the Eido font.

Contrast and Lighting

The luminance contrast of text refers to the difference in light intensity between letters and their background.

Figure 10 illustrates variations in contrast level and contrast polarity of text. For normally sighted subjects, contrast polarity has little or no effect on reading speed, and only a weak effect on reading acuity (Calabrese et al., under review). But a subset of people with low vision read 10% to 50% faster with bright letters on a black background. This contrast-polarity effect is often due to abnormal light scatter in the eye, which reduces the effective retinal-image contrast; for example, an eye with cataract. The asymmetry occurs because a white background with black text produces more light scatter in the eye than a dark page with white print. For this reason, some people with low vision prefer digital displays that offer contrast reversal for text.

People with normal vision can identify letters at extremely low contrasts, down to 1% of maximum contrast. Maximum reading speed can be sustained down to a critical contrast of 5% to 10% of maximum (Legge et al., 1987, 1990). This is why high-contrast print is not usually necessary for fluent reading.

People with low vision typically have poorer contrast sensitivity. For some of them, reading speed decreases for any reduction from maximum text contrast. Crossland et al. (2010) reported that the maximum contrast on the Amazon Kindle and Sony e-Reader are both about 63%. Although these contrast levels are satisfactory for people with normal vision, they would be problematic for some low-vision readers. For this reason, digital devices with the highest contrast displays are especially valuable in low vision.

Figure 10

The 14 lines of Shakespeare's Sonnet CXVI are rendered with seven contrast levels for each of the two contrast polarities. Numbers refer to the Michelson contrast between the letters and the background in the original photograph, where a value of 100% represents maximum contrast. Reprinted from Legge (2007, Fig. 3.1.)

There is evidence that some people with low vision benefit from brighter illumination of text than normally sighted readers. For a review, see Legge (2007, Ch. 4). Bowers et al. (2001) measured reading speed as a function of print size at six illumination levels (from 50 to 5,000 Lux) for 20 subjects with AMD. They found significant improvements in reading acuity, critical print size and maximum reading speed over this range, with most of the improvement occurring for 2,000 Lux or less. They reported that 2,000 Lux is substantially higher than typical values of 50 Lux for page illumination in the home, and 500 Lux in the eye clinic. Their findings confirm that AMD patients frequently benefit from elevated lighting while reading.

Ambient lighting can, however, have adverse effects on digital reading. The contrast of text on a display can decrease due to veiling light from windows, sunshine or other bright lights. The brighter the display, the less the contrast will be diluted by glare sources. So, bright digital displays are better for low vision than dimmer displays.

In short, people with low vision have reduced contrast sensitivity, and a more pressing need for high-contrast text. Reading will often benefit from a brighter display, and from care in controlling veiling light from external glare sources.

5 Conclusions

To summarize the impact of text variables on low-vision reading:

Print size and display size matter. Magnification is usually necessary.

High contrast is often essential.

Bright displays and contrast reversal are desirable.

Inter-line and inter-word spacing may help.

Font effects are small, but fixed width fonts may be helpful when reading near the acuity limit.

Marshall McLuhan famously proclaimed that "the medium is the message." For people with low vision, the digital medium for displaying text is indeed the message; digital reading has the potential to enhance access to print for people with low vision.

Acknowledgments

This manuscript was based on a presentation made at the symposium Reading Digital at the Rochester Institute for Technology, Rochester New York, April 2012. I am grateful to Charles Bigelow for inviting me to the symposium. I wish to thank J.-B. Bernard for providing examples of the Eido font (Figure 9), Aurelie Calabrese for providing Figure 4, Greg Goodrich for discussion of the history of low vision and Rachel Gage for help in assembling the figures. The Preparation of this manuscript was supported by NIH grant EY002934.

References

American Council of the Blind (2011) *Best Practices and Guidelines for Large Print Documents Used by the Low Vision Community.* http://www.acb.org/large-print-guidelines

Arditi, A. (1999). *Making text legible: Designing for people with partial sight.* New York: Lighthouse International. Retrieved November 20, 2004 from http://www.lighthouse.org/print_leg.htm.

Bababekova, Y., Rosenfield, M., Hue, J. E., & Huang, R. R. (2011). Font size and viewing distance of handheld smart phones. *Optometry & Vision Science, 88*(7), 795-797 710.1097/OPX.1090b1013e3182198792.

Bailey, I. L., Bullimore, M. A., Greer, R. B., & Mattingly, W. B. (1994). Low vision magnifiers--their optical parameters and methods for prescribing. *Optometry & Vision Science, 71,* 689-698.

Bernard, J.-B., Kumar, G., Junge, J., & Chung, S. T. L. (2013). The effect of letter-stroke boldness on reading speed in central and peripheral vision. *Vision Research, 84*(0), 33-42.

Bernard, J.-B., Aguilar, C., & Castet, E. (2016). A new font, specifically designed for peripheral vision, improves peripheral letter and Word recognition, but not eye-mediated reading performance. *PLoS ONE, 11*(4), e0152506.

Blackmore-Wright, S., Georgeson, M. A., & Anderson, S. J. (2013). Enhanced text spacing improves reading performance in individuals with macular disease. *PLoS One, 8*(11).

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226,* 177-178.

Bowers, A. R., Meek, C., & Stewart, N. (2001). Illumination and reading performance in age-related macular degeneration. *Clinical & Experimental Optometry, 84*(3), 139-147.

Calabrese, A., Bernard, J. B., Hoffart, L., Faure, G., Barouch, F., Conrath, J., et al. (2010). Small effect of interline spacing on maximal reading speed in low-vision patients with central field loss irrespective of scotoma size. *Investigative Ophthalmology & Visual Science, 51*(2), 1247-1254.

Calabrese, A., Owsley, C., McGwin, G., & Legge, G. E. (2016). Development of a reading accessibility index using the mnread acuity chart. *JAMA Ophthalmology, 134*(4), 398-405.

Cattaneo, Z., & Vecchi, T. (2011). *Blind Vision: The neuroscience of visual impairment*: MIT Press.

Cheong, A.M.Y., Legge, G.E., Lawrence, M., Cheung, S-H., & Ruff, M. (2008). Relationship between visual span and reading performance in age-related macular degeneration. *Vision Research, 48,* 577-588.

Chung, S. T. L. (2002). The effect of letter spacing on reading speed in central and peripheral vision. *Investigative Ophthalmology & Visual Science, 43*(4), 1270-1276.

Chung, S. T. L., Jarvis, S. H., Woo, S. Y., Hanson, K., & Jose, R. T. (2008). Reading speed does not benefit from increased line spacing in AMD patients. *Optometry & Vision Science, 85*(9), 827-833.

Chung, S. T. L. (2012). Dependence of reading speed on letter spacing in central vision loss. *Optometry & Vision Science, 89*(9), 1288-1298.

Crossland, M. D., Culham, L. E., & Rubin, G. S. (2004). Fixation stability and reading speed in patients with newly developed macular disease. *Ophthalmic & Physiological Optics, 24*(4), 327-333.

Crossland, M. D., Macedo, A. F., & Rubin, G. S. (2010). Electronic books as low vision aids. *British Journal of Ophthalmology, 94*(8), 1109.

Crossland, M. D., R, S. S., & Macedo, A. F. (2014). Smartphone, tablet computer and e-reader use by people with vision impairment. *Ophthalmic & Physiological Optics, 34*(5), 552-557.

Dolgin, E. (2015). The myopia boom. *Nature, 519*, 276-278.

Elliott, D. B., Trukolo-Ilic, M., Strong, J. G., Pace, R., Plotkin, A., & Bevers, P. (1997). Demographic characteristics of the vision-disabled elderly. *Investigative Ophthalmology & Visual Science, 38*(12), 2566-2575.

Forster, K. I. (1970). Visual perception of rapidly presented word sequences of varying complexity. *Perception and Psychophysics, 8*, 215-221.

Genensky, S. M. (1969). Some comments on a closed circuit TV system for the visually handicapped. *Optometry & Vision Science, 46*(7), 519-524.

Gill, K., Mao, A., Powell, A. M., & Sheidow, T. (2013). Digital reader vs print media: the role of digital technology in reading accuracy in age-related macular degeneration. *Eye (Lond), 27*(5), 639-643.

Goodrich, G.L., Arditi, A., Rubin, G., Keeffe, J., & Legge, G.E. (2008). The low vision timeline: An interactive history. *Visual Impairment Research, 10,* 57-75.

He, Y., Legge, G. E., & Yu, D. (2013). Sensory and cognitive influences on the training-related improvement of reading speed in peripheral vision. *Journal of Vision*, *13*(7) http://www.journalofvision.org/content/13/7/14.full

Houston, K. E., Stumpf, C. J., & Perras, B. G. (2011). Smartphone visual acuity requirements and accessibility options for the visually impaired. *Visibility, 5*(1), 10-13.

Jackson, R. M. (1983). Early educational use of optical aids: A cautionary note. *Education of the Visually Handicapped, 15*(1), 20-29.

Legge, G.E. (2007). *Psychophysics of Reading in Normal and Low Vision*. Mahwah, NJ & London: Lawrence Erlbaum Associates. ISBN 0-8058-4328-0

Legge, G. E., & Bigelow, C. A. (2011). Does print size matter for reading? A review of findings from vision science and typography. *Journal of Vision, 11*(5).

Legge, G.E., Mansfield, J.S., & Chung, S.T.L. (2001). Psychophysics of reading. XX. Linking letter recognition to reading speed in central and peripheral vision. *Vision Research*, *41*, 725-734.

Legge, G.E., Rubin, G.S., Pelli, D.G., & Schleske, M.M. (1985). Psychophysics of reading. II. Low vision. *Vision Research, 25,* 253-266.

Legge, G.E., Parish, D.H., Luebker, A. & Wurm, L.H. (1990). Psychophysics of reading. XI. Comparing luminance and color contrast. *Journal of the Optical Society of America, A7*, 2002-2010.

Legge, G.E., Rubin, G.S., & Luebker, A. (1987). Psychophysics of reading. V. The role of contrast in normal vision. *Vision Research, 27,* 1165-1171.

Mansfield, J. S., Ahn, S. J., Legge, G. E., & Luebker, A. (1993). A new reading acuity chart for normal and low vision. In *Ophthalmic and visual optics/Noninvasive assessment of the visual system: summaries* (p. 232-235). Washington, DC : Optical Society of America. (Technical digest series ; v. 3)

Mansfield, J.S., Legge, G.E., & Bane, M.C. (1996). Psychophysics of reading. XV. Font effects in normal and low vision. *Investigative Ophthalmology & Visual Science, 37,* 1492-1501.

Mansfield JS, & Legge GE. (2007). The MNREAD acuity chart. In G.E. Legge *Psychophysics of Reading in Normal and Low Vision*, pp. 167-191. Mahwah, N.J. & London: Lawrence Erlbaum Associates

McLuhan M. (1962). *The Gutenberg Galaxy: The making of typographic man*. Toronto: University of Toronto Press.

Morrice, E., Johnson, A. P., Marinier, J.-A., Overbury, O., & Wittich, W. (2015). Use of the Apple iPad as a reading tool in comparison to other magnification devices: What we have learned from 101 low vision clients. *Visibility, 9*(3 & 4), 10-11.

Moshtael, H., Aslam, T., Underwood, I., & Dhillon, B. (2015). High Tech Aids Low Vision: A Review of Image Processing for the Visually Impaired. *Translational Vision Science & Technology, 4*(4), 6.

National Eye Institute (2014). National Plan for Eye and Vision Research. Retrieved from: http://www.nei.nih.gov/strategicplanning/np_low.asp. Accessed March 6, 2014.

O'Regan, J. K., Levy-Schoen, A., & Jacobs, A. M. (1983). The effect of visibility on eye-movement parameters in reading. *Perception and Psychophysics, 34*, 457-464.

Owsley, C., McGwin, G., Jr., Lee, P. P., Wasserman, N., & Searcey, K. (2009). Characteristics of low-vision rehabilitation services in the United States. *Archives of Ophthalmology, 127*(5), 681-689.

Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision, 7*(2), 20 21-36.

Rubin, G. S. (2013). Measuring reading performance. *Vision Research Testing Vision: From Laboratory Psychophysical Tests to Clinical Evaluation, 90*(0), 43-51.

Rubin, G. S., Feely, M., Perera, ., Ekstrom, K., & Williamson, E. (2006). The effect of font and line width on reading speed in people with mild to moderate vision loss. *Ophthalmic & Physiological Optics, 26*(6), 545-554.

Rubin, G. S., & Turano, K. (1992). Reading without saccadic eye movements. *Vision Research, 32*, 895-902.

Russell-Minda, E., Jutai, J. W., Strong, J. G., Campbell, K. A., Gold, D., Pretty, L., et al. (2007). The legibility of typefaces for readers with low vision: A research review. *Journal of Visual Impairment & Blindness, 101*(7), 402-415.

Sloan, L. L. (1977). *Reading aids for the partially sighted: a systematic classification and procedure for prescribing*. Baltimore, MD: Williams & Wilkins.

Tarita-Nistor, L., Lam, D., Brent, M. H., Steinbach, M. J., & Gonzalez, E. G. (2013). Courier: a better font for reading with age-related macular degeneration. *Canadian Journal of Ophthalmology, 48*(1), 56-62.

Tinker, M. A. (1963). *Legibility of print*. Ames: Iowa State University Press.

Virgili, G., Acosta, R., Grover, L. L., Bentley, S. A., & Giacomelli, G. (2013). Reading aids for adults with low vision. *Cochrane Database of Systematic Reviews, 10*, CD003303.

Wallman, J., & Winawer, J. (2004). Homeostasis of eye growth and the question of myopia. *Neuron, 43*(4), 447-468.

World Health Organization (WHO) Media Centre. Visual Impairment and Blindness Fact Sheet No. 282. Available at: http://www.who.int/mediacentre/factsheets/fs282/en/. Accessed on February 13, 2014

Yu, D., Cheung, S.-H., Legge, G.E., & Chung, S.T.L. (2007). Effect of letter spacing on visual span and reading speed. *Journal of Vision, 7,* 1-10. http://journalofvision.org/7/2/2/

Author

Gordon E. Legge is a Distinguished McKnight University Professor in the Department of Psychology at the University of Minnesota, and head of the Minnesota Laboratory for Low-Vision Research. He is recognized for applying the principles and methods of visual science to explain the difficulties encountered by people with low vision in reading, object recognition, and spatial navigation. He is a member of the editorial board of the Journal of Vision and was a member of a National Research Council committee on the redesign of U.S. currency, including introduction of large-print numerals on newly designed bills to help people with low vision. In 2007, he summarized three decades of his research in his book, *Psychophysics of Reading in Normal and Low Vision*.