

Does print size matter for reading? A review of findings from vision science and typography

Gordon E. Legge

Department of Psychology, University of Minnesota,
Minneapolis, MN, USA



Charles A. Bigelow

School of Print Media, Rochester Institute of Technology,
Rochester, NY, USA



The size and shape of printed symbols determine the legibility of text. In this paper, we focus on print size because of its crucial role in understanding reading performance and its significance in the history and contemporary practice of typography. We present evidence supporting the hypothesis that the distribution of print sizes in historical and contemporary publications falls within the psychophysically defined range of fluent print size—the range over which text can be read at maximum speed. The fluent range extends over a factor of 10 in angular print size (x-height) from approximately 0.2° to 2°. Assuming a standard reading distance of 40 cm (16 inches), the corresponding physical x-heights are 1.4 mm (4 points) and 14 mm (40 points). We provide new data on the distributions of print sizes in published books and newspapers and in typesetters' specimens, and consider factors influencing these distributions. We discuss theoretical concepts from vision science concerning visual size coding that help inform our understanding of historical and modern typographical practices. While economic, social, technological, and artistic factors influence type design and selection, we conclude that properties of human visual processing play a dominant role in constraining the distribution of print sizes in common use.

Keywords: critical print size, type size, x-height, reading speed

Citation: 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):8, 1–22, <http://www.journalofvision.org/content/11/5/8>, doi:10.1167/11.5.8.

Introduction

Reading is of fundamental importance in modern culture. It is mediated by strings of symbols on a page or display screen. The size and shapes of these symbols are crucial factors determining the legibility of print. In this paper, we focus on print size because of its key role in understanding reading performance and its significance in the history and contemporary practice of typography. We consider the ecological hypothesis that the distribution of print sizes in common use falls within the psychophysically defined range of print sizes for fluent reading. Here, we use the term “ecological” to refer to the variation in printed text throughout our culture.

Our goal is to review key ideas on the distribution and effects of print size from the two very different disciplinary perspectives of vision science and typography. These two disciplines focus on the same graphical–visual phenomena—text—but from different viewpoints. Typography presents a plethora of features and forms with aesthetic and practical significance, but typographical explanation tends to be historical and anecdotal. Psychophysics provides quantitative studies of forms, patterns, dots, lines, and gratings that are simpler than typographic characters, but psychophysical theories rarely address potential connections between artistic designs and established properties of visual processing. Examples of vision

science studies of artistic and literate forms include the interpretation of the block portraits by artist Chuck Close by Pelli (1999), the analysis of Mona Lisa's smile by Livingstone (2000), and the proposed linkage between letter topology and visual contour analysis by Changizi, Zhang, and Shimojo (2006).

Outline of the paper

We begin laying the groundwork for our ecological hypothesis by discussing metrics for print size used by typographers and vision scientists. Confusion over definitions of print size has been an impediment to communication between the two disciplines, but common ground is necessary to understand our hypothesis. Next, we present psychophysical data on reading performance, demonstrating that fluent reading is restricted to a broad but limited range of print sizes. The essential claim of our ecological hypothesis is that print sizes in most contemporary and historical publications fall within this fluent range. Before describing two tests of the ecological hypothesis, we devote a section of the paper to reviewing current explanations from vision science for the extent of the fluent range. In our first test of the hypothesis, we survey contemporary newspapers, hardcover novels, and paperbacks to determine whether the observed distribution of print sizes falls within the fluent range. In our second

test of the hypothesis, we survey type size specimens from the 15th, 16th, and 18th centuries to assess variations in type size usage post-Gutenberg.

Print size metrics and terminology

A major difference between typography and vision science is the reliance of typographers on the physical size of type on the page and the reliance of vision scientists on angular size of print (often measured in minutes of arc or degrees of visual angle). The angular measure depends on both the physical size of the print and the subject's viewing distance. Angular size is preferred by vision scientists because it determines retinal image size. The conversion is straightforward:

$$\begin{aligned} \text{Angular size in degrees} \\ = 57.3 \times \text{physical size/viewing distance,} \end{aligned} \quad (1)$$

where the physical size and viewing distance must be measured in the same units (typically, millimeters, centimeters, or inches). This equation is an approximation, which holds when the physical size is significantly smaller than the viewing distance, almost always the case for print size.

(a) Conversions between physical units

Conversions between

Points and millimeters

Point size = $2.86 \times$ size in mm

Size in mm = $0.35 \times$ point size

Points and inches

Point size = $72 \times$ size in inches

Size in inches = $0.0138 \times$ point size

(b) Conversion to visual angle (VA) in degrees from physical print size (for a viewing distance of 40 cm = 16 inches)

Conversion to visual angle (degrees) from

Millimeters

VA = $0.143 \times$ size in mm

Points

VA = $0.05 \times$ size in points

(c) Conversion from visual angle (VA) in degrees to physical print size in millimeters or points (for a viewing distance of 40 cm = 16 inches)

Conversion from visual angle to

Millimeters

Size in mm = $7 \times$ VA

Points

Size in points = $20 \times$ VA

(d) Useful rules of thumb

For a viewing distance of 40 cm = 16 inches

1.4 mm = 4.0 pt, subtends 0.20°

10 points = 3.5 mm, subtends 0.5°

Visual angle in degrees = point size/20

For instance, suppose the height of the lowercase letter “x” in a newspaper column is 1.4 mm (physical size), and the reader views the newspaper from a typical reading distance of 40 cm (16 inches). The angular height of “x” at the eye is 0.2° (equals 12 arcmin). If the reader reduces the viewing distance from 40 cm to 20 cm, the angular character size doubles to 0.4° , but the physical character size, of course, does not change.

Typographers measure physical type size to determine how many text characters fit in a line, column, page, or screen of fixed dimensions and also to estimate apparent character size at a typical viewing distance.

The common typographic measure is the *point*, which has had different definitions over the centuries in different countries. The digital PostScript point is $1/72$ inch (approximately 0.35 mm). The traditional Anglo-American point is slightly smaller ($1/72.27$ inch) and the traditional European Didot point somewhat larger (approximately 0.38 mm), but the traditional definitions have largely been supplanted by the PostScript point. Unless stated otherwise, we use “point” to denote the PostScript point.

Table 1 includes conversions between three metrics of print size and also conversions between physical and angular measures of print size.

x-height and other measures of print size

Vertical measures of type size are generally taken between virtual guidelines that define the major horizontal alignments of a typeface (**Figure 1**). These are the

Table 1. Print size conversions. (Although points are frequently used as measures of the body size of print, this table refers strictly to physical conversions. For instance, an x-height of 1.4 mm is equal to an x-height of 4 points (a), although the corresponding body size might be 8 points or more.)

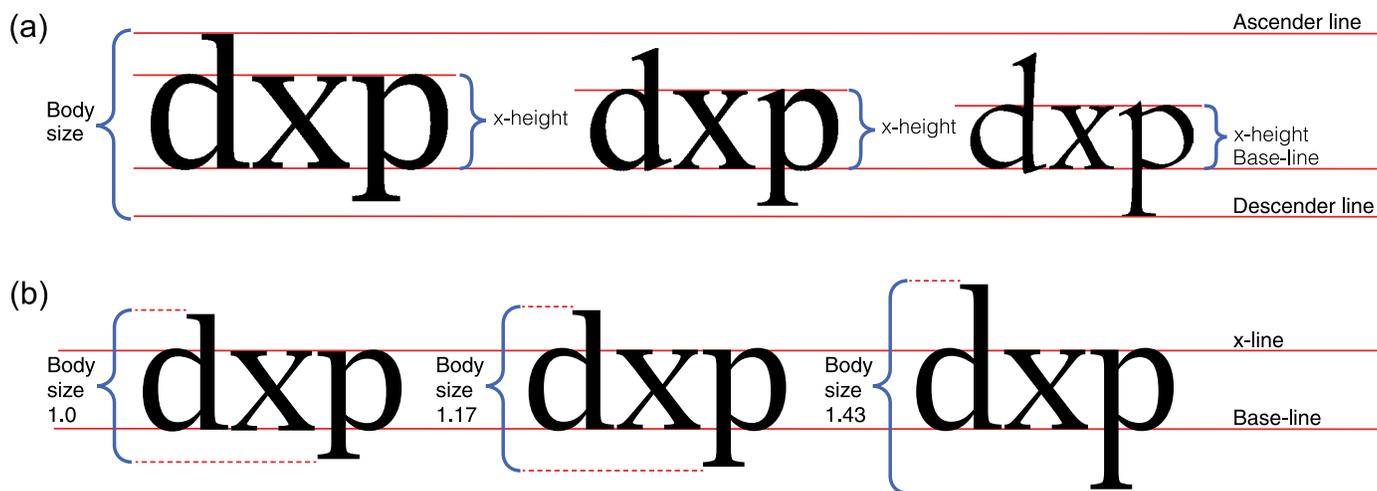


Figure 1. (a) Three typefaces with the same body size but different x-height fractions (in parentheses), from left to right: Lucida Bright (0.53), Times Roman (0.45), Centaur (0.37). The letters are aligned at the baseline. The white “gaps” between ascenders or descenders and their respective guidelines are components of the body size. (b) Three versions of a typeface, Lucida Bright, with the same x-height but different ascender–descender lengths, corresponding to the proportions of the three typefaces of (a). From left to right, the approximate body size progression is: 1.0, 1.17, 1.43.

baseline, on which most letters sit; the *capital line*, which coincides with the tops of most capital letters, such as “H” or “Z”; the *x-line*, which coincides with the tops of lowercase letters such as “x” or “z”; the *ascender line*, which coincides with the tops of strokes ascending above the x-line, as in “b” or “f”; and the *descender line*, which coincides with the bottoms of strokes descending below the baseline, as in “p” or “g.”

The traditional measure of type is *body size*. Originally the physical height of the cast metal “sorts” that carried the faces of the letters in a font, body size is now defined as the distance from the ascender line to the descender line plus a small additional space or *gap*, which serves to separate ascenders and descenders of adjacent lines. Body size is a global measure of a font, but very few individual letters actually extend from the ascender to the descender line.

The *capital height* is the distance from the baseline to the capital line. Most capitals, occasionally excepting “J” and “Q,” fit between those two guidelines (with slight overhangs and/or underhangs by round or pointed letters).

The *x-height* is the distance from baseline to x-line. Half the lowercase letters fit between baseline and x-line (with slight overhangs and underhangs), while the other half have an ascender or descender, or, rarely, both (the dot of lowercase “j” at ascender height in some fonts, lowercase “f” with both ascender and descender in many italic fonts, and the “thorn” letter “þ” with both ascender and descender in fonts with Icelandic letters).

The x-height of printed text is measured as a physical size, like the 1.4-mm x-height in the example above, but it may also be measured as a decimal fraction of body size. Conversion of x-height fraction to physical size is

straightforward, using the same units (e.g., points or millimeters) for body size and physical x-height:

$$\text{Physical x-height} = \text{x-height fraction} \times \text{body size.} \quad (2)$$

For example, the x-height fraction of Times New Roman is 0.45, slightly less than half the body size, so 12-point Times New Roman has an x-height of 5.4 points. The equivalent body in millimeters is 4.2 mm, with an x-height of 1.9 mm.

Type historians and bibliographers often measure body size, x-height, and capital height in millimeters (Vervliet, 2010). German type manufacturers have used capital height in millimeters as well as in (Didot) points (Gorissen, 1980). Digital fonts defining characters in Cartesian grids have been based on capital height (Karow, 1993) or on body size (Microsoft, 1995). To research typographic legibility, Tinker (1963) measured body size in Anglo-American points, following standard American typographic practice at the time.

Commercial word-processing and office software typically use body size measurements in points, while specialized page layout software may offer a choice of point systems (PostScript, Anglo-American, Didot) or user-defined points.

In this paper, we use x-height as a basic measure, for the following reasons:

1. Lowercase predominates in most English texts—94.5% in a large sample of text studied by Jones and Mewhort (2004). In addition, 96% of lowercase letters have graphical features at the x-height, so x-height

features are approximately 16 times more common in text than capital height features.

2. It is easier to measure physical x-height than body size, because graphical features (e.g., arches, serifs, and terminals) cluster along the baseline and x-line, whereas body height is more difficult to measure because ascenders and descenders are more sparsely distributed. A few character pairs like “ly” and “ph” have an adjacent ascender and descender for slightly easier measurement of body size, but in most roman fonts, only letter “j” has a total height near body size (average around 96%).
3. The x-height region (the horizontal band between baseline and x-line) contains most of the black area of text type. Legros and Grant (1916) calculated the graphical form of an average lowercase character by measuring the features of lowercase letters weighted by the frequency of letter occurrence. In their “mean resultant character,” the x-height region constituted 87% of the total black area, while ascenders constituted 10% and descenders 3%. The black area of the lowercase in modern fonts is similarly distributed. In the digital fonts in Figure 1, the proportions of x-region black area to the total black area of the lowercase alphabet are: Centaur, 81%; Times New Roman, 85.5%; Lucida Bright, 87.5%.
4. Although not proven by rigorous laboratory studies, typographic opinion (Williamson, 1966) and informal observation indicate that x-height is a more salient determinant of perceived type size than is body size. For a given body size, the apparent sizes of typefaces are influenced by their x-heights: Faces with larger x-height fractions appear to be bigger than those with smaller fractions (Figure 1a). Conversely, types with the same x-heights but different body sizes appear to be approximately the same size.

Because x-height is not a constant fraction of body size, it cannot be accurately calculated from body size alone. Karow (1993) measured the x-heights of 1049 roman typefaces and found that the x-height fraction ranged from 0.28 to 0.58, with a mean of 0.46. In our sample of text typefaces of recent books and newspapers (see below), we found that the x-height fraction of 51 seriffed fonts ranged from 0.36 to 0.55, with a mean of 0.45 and standard deviation of 0.045.

Letter width

A traditional typographic measure of horizontal print size of a font is the length of the 26 letters of the lowercase alphabet, placed side by side, measured in points (Arnold, 1969; Linotype, 1940) or millimeters (Gorissen, 1980). For example, the Linotype Corporation’s typeface, Corona, had a lowercase alphabet length of 155 points when cast in metal on a Linotype machine at a 12-point

body size (Linotype, n.d.). The mean letter width was close to 6 points.

Most digital typefaces today are scaled linearly, but traditional cast metal types often did not scale linearly, with alphabet lengths decreasing less in proportion to body size as type was scaled down. The above-mentioned Corona type at 6 point had an alphabet length of 103 points rather than the 77.5 points expected from linear scaling. The proportionally greater alphabet length included more space between letters as well as slightly wider letterforms.

The x-height provides a good estimate of mean letter width. For proportionally spaced typefaces, mean letter widths vary from design to design, but for seriffed faces used in running text, mean width is strongly correlated with x-height. We calculated mean letter widths (weighted by letter frequencies in text) for 23 digital seriffed fonts used for the majority of our 650 running text samples (analysis of print size for these samples is discussed later) and found a correlation of 0.94 between x-height and mean width, which was 0.47 of body size.

When capitals are excluded, the mean lowercase letter width is close to x-height. In our running text samples, the ratio of mean lowercase widths to corresponding x-heights ranged from 0.96 (Times New Roman, a narrow face) to 1.09 (Corona, a wide face). The mean ratio for all faces in our sample was 1.03. In general, no single letter in a font has width equal to mean letter width, but as a rule of thumb for text faces, x-height is a close approximation to mean lowercase width.

Arditi (1996) has studied the impact of the height-to-width ratio (H/W) of letters on acuity. He found that tall, thin letters ($H/W > 1.0$) are more legible than short, wide letters ($H/W < 1.0$).

When the horizontal center-to-center separation between letters in text is a pertinent measure, it is important to distinguish between *fixed-width* fonts (also termed fixed-pitch or mono-spaced fonts), such as Courier, and proportionally spaced fonts (sometimes termed *variable-width* fonts) such as Times New Roman. In fixed-width fonts, each letter is allocated the same horizontal distance, regardless of the letter’s width—an “i” occupies the same horizontal real estate as an “m.”

Fixed-width fonts were first widely used on typewriters in the late 19th century, and despite the obsolescence of typewriters, such fonts continue to be widely used in two disparate fields today: computer programming and movie screenwriting. The script of nearly every Hollywood blockbuster is written in fixed-width Courier, which provides a convenient, predictable metric. Each standard script page corresponds to roughly 1 min of movie time, so the number of pages gives producers an estimate of the length and production cost of a movie. Moreover, the very plainness of the font gives imagination free rein. Movies dazzle the senses with beautiful actresses, dashing heroes, stirring music, sensational sound tracks, and astonishing special effects, none of which can be conveyed in print, so

scripts are purposely plain, to permit movie studio readers to imagine the stories solely on the basis of unadorned description and dialogue.

For fixed-width fonts, the physical widths have been measured as characters per inch or characters per centimeter. Pica typewriter type, for instance, measured 10 characters per inch or 4 characters per centimeter, and in digital type, fixed-width Courier still measures 10 characters per inch at 12 points, equivalent to pica size.

In a proportionally spaced font, the horizontal space is proportional to the traditional design of the individual character. An “m” is approximately three times as wide as an “i,” for example. A practical advantage of proportionally spaced fonts is that more characters can be printed in the same horizontal line width. An aesthetic advantage of proportionally spaced fonts is that the pattern of strokes appears regularly spaced, and at small sizes, the texture appears even (Bigelow, 1989).

Angular measure

Vision scientists usually specify print size in angular units, frequently using angular x-height. Full stimulus description also requires indication of the viewing distance and font. There is approximate proportionality between angular print size and retinal image size, such that a character subtending 1° of visual angle in central vision has a size of 0.28 mm on the retina (Drasdo & Fowler, 1974). Acuity and other facets of visual performance related to print size are presumed to be more closely related to retinal image size than physical size on the page.

In some psychophysical studies of reading performance, print size has been defined as horizontal center-to-center spacing in degrees between adjacent letters (cf., Legge, Pelli, Rubin, & Schleske, 1985). As we will discuss below, center-to-center spacing between letters turns out to be a highly relevant measure when considering the influence of crowding on letter recognition and reading.

In clinical vision applications, angular character size is often expressed using metrics from visual acuity testing including Snellen notation, logMAR, and decimal notation. For definitions and conversions, see Legge (2007, Appendix A).

Conversion from print size on the page in points or millimeters to visual angle requires specification of the reading distance. A “standard” reading distance of 40 cm (16 inches) for hardcopy text is often adopted for this conversion. Of course, reading distances vary across individuals and reading modalities. For instance, Shieh and Lee (2007) studied preferred reading distances and found a mean close to 50 cm for both electronic paper and video display terminals (VDTs), greater than their reported value of 36 cm for books and paper. They found a very weak but significant dependence on character size, from 2.4-mm to 4.3-mm characters. (These authors used

capital height as character size for Latin letters. Equivalent x-heights would have ranged approximately from 1.6 mm to 2.9 mm.)

Range of print size for fluent reading

The legibility of print depends on physical characteristics of text and also on task demands, viewing conditions, and the vision status of the reader. Several physiological and behavioral methods have been used for measuring legibility. For reviews, see Legge (2007, Ch. 4) and Tinker (1963, Ch. 2). The two most common legibility metrics involve measurement of acuity for the letters of the text (or, equivalently, the greatest viewing distance at which the text can be read) and reading speed. These two metrics may have different applications. For instance, a typeface may be designed to optimize legibility at the acuity limit for use in highway signage. Other typefaces may be more suitable for fluent reading of continuous text in books or newspapers.

Reading speed in words per minute was introduced by Tinker (1963) as a metric for measuring the legibility of print. Reading speed has been widely used in recent years as a psychophysical measure of the visual component of reading. One of two methods is usually adopted. In one, subjects are asked to read short passages of text aloud as quickly and accurately as possible, and the time taken and number of words read correctly are converted to reading speed. In the other, text is presented in an automated fashion on a computer—either scrolling horizontally across the screen as in a TV text crawl or as a rapid sequence of words at one location on the screen (Rapid Serial Visual Presentation, RSVP)—and the presentation rate is increased until the subject is unable to read the text. The fastest presentation rate yielding a criterion reading accuracy (e.g., 80% of words are read correctly) is then taken as the maximum reading speed. Simple text is used so that vocabulary and syntax do not limit performance. Reading speed has been found to be a reproducible measure and to be sensitive to the physical characteristics of print and also the vision status of subjects. For a discussion of methods for measuring reading speed and comparison of reading speed to other metrics for measuring legibility, see Legge (2007, Ch. 2).

The data in Figure 2 illustrate a key result: There is a 10-fold range of print size from approximately 0.2° to 2° for which people with normal vision can achieve maximum reading speed. This range corresponds to x-heights from 1.4 mm (4 points) to 14 mm (40 points) at a reading distance of 40 cm. We refer to this as the *fluent range* of print size. An important goal of this paper is to evaluate the ecological hypothesis that asserts that the distribution

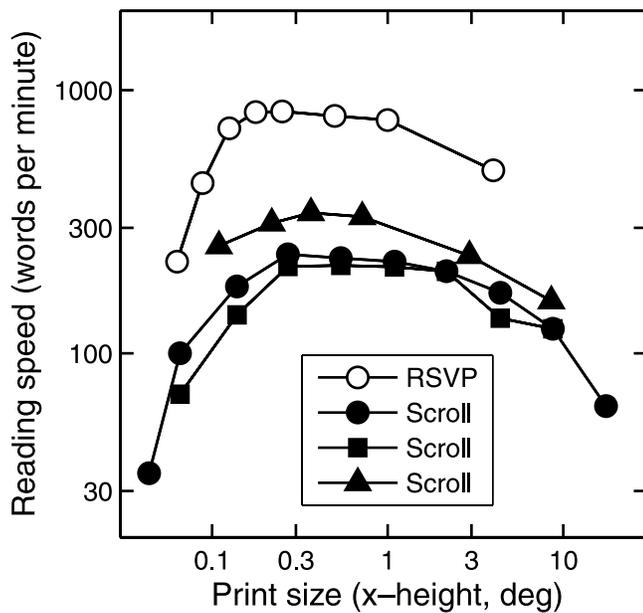


Figure 2. Reading speed (words per minute) vs. print size (x-height in degrees). Data are replotted from four experiments. Legge et al. (2007) used the RSVP method (open circles). The other three studies used scrolling text—filled circles: Legge et al. (1985), matrix sampling; filled squares: Legge et al. (1985), blur; and triangles: Akutsu et al. (1991). The data points are means across subjects. RSVP is known to yield much higher reading speeds than scrolling text, accounting for the vertical shift in the curve for Legge et al. (2007). See the text for more details.

of print sizes in newspapers and books lies within the fluent range.

Two of the data sets in Figure 2 are from experiments reported by Legge et al. (1985). They were interested in the influence of several text characteristics on reading speed, including the number of samples per character (“matrix sampling”) and low-pass filtering (“blur”). In both cases, they measured reading speed over a very wide range of print sizes. The data from these two experiments in Figure 2 represent asymptotic values for which the sampling density and blur no longer limited reading performance. In their study, four normally sighted subjects read aloud as text scrolled across a display screen. The drift rate was increased to determine maximum reading speed. Print size varied over a 400:1 range from 0.06° (≈ 3.6 arcmin) to 24° . (This size range is equivalent to seeing 6-inch letters from viewing distances ranging from 16 inches to about one tenth of a mile.) A third data set is taken from a study by Akutsu, Legge, Ross, and Schuebel (1991) with 16 subjects, also using scrolling text. The fourth data set is taken from a study by Legge et al. (2007) with five subjects, using the RSVP method for measuring reading speed. Notable in Figure 2, the reading speeds in Legge et al.’s (2007) study (open circles) were much higher than those in the other three studies. The difference is due to the use of the RSVP method for measuring

reading speed. RSVP reading speeds are typically much higher than speeds for static or scrolling text. For example, Rubin and Turano (1992) reported an average reading speed of 1171 words/min for RSVP text compared with 303 words/min for static text. However, despite the difference in peak reading speeds for RSVP and scrolling text, the range of print sizes for best performance is approximately the same.

Collectively, the speed vs. print size curves in Figure 2 demonstrate a broad plateau for intermediate character sizes for which reading speed is fairly constant, a sharp decline in reading speeds for smaller characters, and a more gradual decline for very large characters.

There is a smallest print size below which reading speed begins to decline sharply, termed the *critical print size* (CPS). The CPS typically lies in the range from about 0.15° to 0.3° depending on the individual, stimulus factors such as font (Mansfield, Legge, & Bane, 1996), and the methods for measuring reading speed or for estimating the CPS. For instance, Legge et al. (1985) estimated the critical print size (the specific term was not used in the paper) to be about 0.3° center-to-center spacing, equivalent to an x-height of 0.22° . Chung, Mansfield, and Legge (1998), using a different method for measuring reading speed (the RSVP method), found the average CPS of six subjects to be 0.17° x-height (range of 0.14° to 0.24°). Across studies, a consensus value for the critical print size for normally sighted readers is 0.2° x-height (Legge, 2007).

At a viewing distance of 40 cm (16 inches), Times New Roman type, with an x-height fraction of 0.45 and a visual x-height of 0.2° , is equivalent to a physical body size of 9 points.

The concept of a critical print size for reading has long been recognized, although the term is relatively new. Huey (1908/1968, Ch. 21) recommended an x-height no less than 1.5 mm for printed texts, corresponding to an angular character size of 0.21° at a reading distance of 40 cm. Tinker (1963) investigated the effect of type size on reading speed, measuring reading rates for body sizes from 8 to 12 points. We converted Tinker’s findings to angular measure, assuming a 40-cm viewing distance and the x-height fraction of 0.396 for Tinker’s Granjon test font. The fastest reading speed was for an x-height of 0.21° (1.5 mm, 11 point body), with a decline at 0.19° (x-height = 1.36 mm, 10-point body), a slight rise at 0.17° (x-height = 1.2 mm, 9-point body), and a significant decline at 0.15° (x-height = 1.09 mm, 8-point body). Tinker’s findings are consistent with a critical print size of about 0.2° .

It is important to distinguish critical print size from letter acuity and reading acuity. Critical print size is the smallest character size for which reading is possible at maximum speed. Letter acuity (often called Snellen acuity) is measured with unrelated test letters and represents the smallest angular size for identifying letters with unconstrained viewing time. Reading acuity refers to

the measurement of visual acuity using a test chart containing sentences or words typeset as in text. The critical print size is at least two times larger than acuity letters for normally sighted subjects, and the difference is often much larger for people with low vision (Legge et al., 1985; Whittaker & Lovie-Kitchin, 1993). The distinction between acuity size and critical print size is important for the design of text displays and for the prescription of low-vision magnifiers. If a reading magnifier is prescribed to enlarge letters to the acuity limit, rather than to the critical print size, the person's reading will be effortful and unnecessarily slow.

Reading speed also declines for big print. This decline is not as sharply defined or well studied as the CPS, but the decline commences for letters larger than 1° to 3° with a representative value of 2° (Akutsu et al., 1991; Legge et al., 2007, 1985). To give an example of familiar characters that subtend about 2° , the large sans-serif digits on the lower right corner of the reverse side of the recently issued U.S. \$20 currency bills are about 13 mm in height and subtend nearly 2° at a viewing distance of 40 cm.

Production of large-print text, or the use of optical or electronic devices to enlarge the visual angle of conventional text, is of great importance in low vision. The topic of print size is nearly synonymous with magnification in the context of low vision.

Chart-based tests have been developed for clinical assessment of the impact of print size on reading vision including the Sloan M cards (Sloan & Brown, 1963), the Radner reading test (Radner et al., 1998), the Colenbrander reading cards (<http://www.ski.org/Colenbrander/General/references.html#LVtools>), and the MNREAD Reading Acuity Chart (Mansfield, Ahn, Legge, & Luebker, 1993; Mansfield & Legge, 2007). The MNREAD chart consists of 19 sentences with identical format (a block of text of fixed aspect ratio in the Times Roman font containing 60 characters on 3 lines) in a progression of print sizes in steps of 0.1 log unit (26% change in x-height). Sizes range from the smallest print Snellen 20/6.3 (x-height = 0.184 mm or 1.6 arcmin) through the 20/20 line (x-height = 0.0.582 mm or 5 arcmin) to the largest print Snellen 20/400 (x-height = 11.6 mm or 100 arcmin). The Snellen ratios and arcmin values are calibrated for a 40-cm viewing distance and can be scaled for larger or smaller viewing distances. The subject's reading time is recorded for each sentence, and the results are used to construct a plot of reading speed vs. print size. This plot can then be used to estimate the subject's reading acuity, critical print size, and maximum reading speed.

Explaining the dependence of reading speed on print size

In this section, we consider theoretical explanations for the shape of the reading speed vs. print size curve.

Readers who are primarily interested in tests of the ecological hypothesis and connections to typography may wish to skip on to the next section.

Three types of explanations have been proposed—limitations imposed by eye movement control, the spatial frequency representation of letters in the visual pathway, and the role of crowding in limiting the visual span for reading.

Oculomotor limitations

Legge et al. (1985) first demonstrated the shape of the speed vs. print size curve and suggested that oculomotor limitations might play a role. They used a scrolling text method to measure reading speed. The decline in performance for large characters might have occurred because smooth-pursuit eye tracking had trouble keeping up with the high angular velocities associated with rapidly drifting large characters. Reduced reading speed for very small characters might also have an oculomotor origin. Kowler and Anton (1987) found that fixation times increase prior to short saccadic eye movements ($<1^\circ$), presumably because of the demands of saccade planning. Subsequent research has shown that factors other than oculomotor limitations must play a role in determining the large print and small print boundaries of the fluent range. This is because the qualitative shape of the curve is the same for RSVP reading in which the role of eye movements is minimized. Yu, Cheung, Legge, and Chung (2007) specifically compared critical print size for RSVP reading and eye movement reading (their “flashcard” method). They found no significant difference in CPS for the two methods.

Spatial frequency representation of letters

The properties of the human contrast sensitivity function may have an impact on the print size dependence of reading speed. Legge, Rubin, and Luebker (1987) showed that print size interacts with text contrast in affecting reading speed. Reducing text contrast first pushes down reading speed for very large and very small print and, when the contrast gets very low, forces down performance at intermediate print size as well. The result is to produce a peak in the curve with high performance for middle-size characters and lower performance for small and large characters. This shape is reminiscent of the contrast sensitivity function (CSF) for sine-wave gratings (Campbell & Robson, 1968) and suggested that contrast sensitivity at different spatial frequencies might play a role in the print size dependence of reading speed. To explore this possibility, Legge et al. created a CSF for reading as follows. They converted print size in degrees to spatial frequency in cycles per degree by assuming that two cycles per character width were important for letter recognition (cf., Ginsburg, 1978; Parish & Sperling, 1991; Solomon & Pelli, 1994).

For instance, for 0.5° characters, the corresponding spatial frequency was 4 c/deg. They defined a threshold contrast for reading as the text contrast required for a speed of 35 words/min. They then plotted the reciprocal of this threshold value as contrast sensitivity for reading as a function of the spatial frequency associated with each print size. They compared this CSF for reading with a sine-wave grating CSF obtained under similar viewing conditions including 4-Hz flicker to roughly mimic the temporal dynamics of reading (4 fixations/s). The resulting CSFs for reading were very similar in shape to the corresponding sine-wave grating CSFs (Legge et al., 1987, Figure 7). These findings suggested that print size effects in reading are related to the spatiotemporal contrast sensitivity of vision. More specifically, the slow decline in reading speed for very large letters may be due to a corresponding decline in contrast sensitivity for low spatial frequencies. The more rapid decline in reading speed for very small letters may be associated with the steep falloff in contrast sensitivity at high spatial frequencies.

Subsequent studies sought to determine the most critical spatial frequencies for letter recognition at different angular print sizes and the potential relationship to underlying spatial frequency channels. Solomon and Pelli (1994) used a noise-masking method to measure spatial frequency tuning curves for letter recognition. For 1° Bookman letters, the tuning curve peaked at 3 cycles per letter. Subsequent studies by Chung, Legge, and Tjan (2002), Majaj, Pelli, Kurshan, and Palomares (2002), and Oruç and Landy (2009) have shown that the peak frequency, for letter recognition, expressed as cycles per letter, decreases from this value for smaller letters and increases for larger letters. Extrapolating from the findings of Majaj et al., Legge (2007, Ch. 3) estimated that the peak frequency for a print size of 0.16° is 1.7 cycles per letter, and for a print size of 16° , it is 7.7 cycles per letter. These results imply that letters of large angular size are identified by channels encoding edge features or other higher frequency components of the letters' spectra. Identification of letters near the critical print size depends on coarser features (lower frequencies in units of cycles per letter).

This size dependence of the perceptual representation of letters may correspond to a distinction in typography made by Carter (1937/1984). Contrasting small and large print, he wrote: "Legibility is all that matters in 6- to 12-point types; so that their successful design is a technical, and not in the ordinary sense an artistic achievement. ... In the design of founts from 20- to 72-point the artist comes into his element." We interpret Carter to mean that for small type sizes, where only low spatial frequencies in cycles per letter are important for perception, fine artistic details are not evident, whereas for large sizes, where high-frequency components are used, fine lines, sharp corners, and crisp serifs are aesthetically appreciated. Bigelow (1989) argued that different typographic aesthetics apply to different type scales (sizes). Aesthetics of

texture prevailed at small sizes, of pattern in the middle sizes, and of form at the large sizes.

Carter found that when type punches were hand-cut at print size, the x-height fractions of small type sizes were larger than x-height fractions at large sizes, a phenomenon he termed "optical scale." To paraphrase his argument, craft lore in concert with the visual system of the designer/punchcutter drove adjustments in letterform proportions and details to optimize appearance at different print sizes or scales.

In digital typography, nearly all type sizes are linearly scaled from a single master font. The traditional cutting of different x-heights and features for different print size has largely been abandoned. Instead, typographers and graphic designers tend to choose different typefaces for different print sizes, as we demonstrate below in surveys of book and newspaper typefaces. A few recent digital typeface families do, however, offer variant designs for different print sizes. The differences are subtle at text sizes but can be seen when the letterforms are enlarged. In Figure 3, the x-height of a typeface variant designed for 8.5 point size is 6% greater than the x-height for 22 point, while the mean lowercase width for 8.5 points is 15% greater than the mean for 22 point.

From the perspective of vision science, the typographic concept of *optical scale*, i.e., variant designs for small and large fonts, pertains to the components of the spatial frequency spectra of letters used by the visual pathway in recognition. Tiny letters are recognized with low spatial frequencies (in cycles per letter) representing coarse letter features and, hence, the emphasis in design on bold strokes and simple forms. Large letters are recognized with higher spatial frequencies (cycles per letter) and, hence, the greater attention to the finer details in font design.

A priori, spatial frequency tuning properties for reading might differ from those for letter recognition. Although it is generally accepted that letter recognition precedes word recognition as a stage in reading, other factors influence reading speed including oculomotor control and linguistic context. It is possible that these factors are influenced by the spatial frequency content of text. Chung and Tjan (2009) have measured the effects of contrast and spatial frequency band on reading speed. When text contrast was low enough to affect reading speed, they found spatial frequency tuning similar to letter recognition, that is, the peak frequency in cycles per letter shifted to lower values for smaller print size. For high-contrast text, the spatial frequency tuning was less pronounced, and the authors attributed limitations on reading speed to non-visual factors.

The role of narrowband spatial frequency channels in mediating letter recognition and reading remains controversial (for a discussion, see Legge, 2007, Ch. 3). Majaj et al. (2002) propose that a single channel mediates letter recognition for a given print size, but the peak frequency of the relevant channel (in cycles per letter) depends on

“Optical Scale” in type design

72 point	Recommended size	Alphabet at recommended size
	8.5 point “Caption”	abcdefghijklmnopqrstuvwxyz
	10 point “Small Text”	abcdefghijklmnopqrstuvwxyz
	12 point “Regular”	abcdefghijklmnopqrstuvwxyz
	18 point “Subhead”	abcdefghijklmnopqrstuvwxyz
	22 point “Display”	abcdefghijklmnopqrstuvwxyz

Figure 3. Optical scale. A digital typeface (Arno Pro) implemented as five fonts designed for printing at five different body sizes. The “caption” size (8.5-point body size and smaller) has a bigger x-height, greater width, thicker details, and looser spacing than the design for “display” body size (22-point body size and larger).

print size. Chung and Tjan (2009) and Chung et al. (2002) contend that channels need not be invoked to explain the size-dependent shift in peak frequencies for letter recognition and reading. They argue that the effects can be explained without reference to channels per se but in terms of the distinctive information in different portions of the letter spectra and the weighting of this information by the subject’s contrast sensitivity function. Oruç and Landy (2009) have challenged the relevance of the CSF in determining the print size dependence of peak spatial frequency in letter recognition. They studied letter recognition for stimuli embedded in high levels of external white visual noise, a condition that flattens the contrast sensitivity function. This flattening might be expected to reduce the size-dependent shift in peak frequency of the tuning curves, but it did not.

Visual span and crowding

The third type of explanation for the shape of the speed vs. size curve deals with the visual processing of letter strings rather than individual letters. The *visual span* is the number of adjacent letters that can be recognized reliably without moving the eyes (O’Regan, 1990). It has been proposed that the size of the visual span imposes a bottom-up sensory limitation on reading speed (Legge et al., 2007; Legge, Mansfield, & Chung, 2001). Legge et al. (2001) introduced a psychophysical method for measuring the size of the visual span. Subjects are shown briefly presented strings of three unrelated letters (trigrams) at several positions left and right of the point of fixation (Figure 4, top). Clusters of letters are used rather than

single letters because of their closer approximation to text and because interfering effects of adjacent letters (crowding) may be an important determinant of reading speed. In a trigram trial, the subject reports the three letters aloud in left-to-right order and is scored right or wrong for each letter. After a block of several hundred trials, the accumulated results are plotted as letter identification accuracy (percent correct) as a function of distance

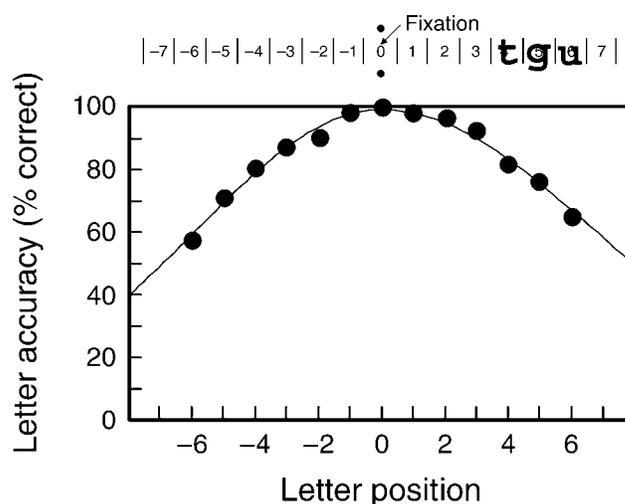


Figure 4. Measuring the visual span with the trigram method. (Top) The figure illustrates schematically that trials consist of the presentation of trigrams, random strings of three letters, at specified letter positions left and right of fixation. (Bottom) Example of a *visual span profile*, in which letter recognition accuracy (percent correct) is plotted as a function of letter position for data accumulated across a block of trials.

left and right of fixation. These plots, termed visual span profiles, usually peak at fixation where letter recognition accuracy is very high and decrease monotonically left and right of fixation. An example of a visual span profile is shown in Figure 4 (bottom).

The size of the visual span can be quantified as the area under the profile or as the distance left and right of fixation for which letter recognition accuracy exceeds some criterion level of performance such as 80% correct. For instance, if letters in trigrams can be recognized with 80% accuracy or more for four letter positions left and right of fixation, but not at greater distances from fixation, as in Figure 4, we could say that the visual span is nine characters wide (the fixated letter plus four letters on either side of fixation.)

Several studies have examined how both reading speed and the size of the visual span depend on stimulus attributes of text. High correlations have been found between reading speed and the size of the visual span for variations in character size and contrast (Legge et al., 2007), character spacing (Yu et al., 2007), text orientation, i.e., vertical text compared with conventional horizontal text (Yu, Park, Gerold, & Legge, 2010), and the retinal eccentricity of text presentation (Legge et al., 2001). These high correlations mean that when the visual span gets small, reading speed slows down. In the case of print size, for example, the size of the visual span remains constant at its maximum value over the same range of print sizes for which reading speed is maximum (the “fluent range”). For letters smaller or larger than the fluent range, the visual span gets smaller and reading speed slows down. Intuitively, the idea is that as the visual span gets smaller, fewer letters can be recognized on each fixation, or in a given unit of time, and reading slows down because more “looks” at text are required to read. A theoretical framework for the role of the visual span in reading was presented as part of an ideal observer model of reading called Mr. Chips (Legge, Hooven, Klitz, Mansfield, & Tjan, 2002; Legge, Klitz, & Tjan, 1997). Simulation results showed that the model’s mean saccade length decreased as the model’s visual span size decreased. Given that a reduction in mean saccade length would normally correspond to a reduced reading speed, the model shows how a smaller visual span size would result in a slower reading speed.

Reading speed may be linked to the size of the visual span, but what determines the size of the visual span? Why does the visual span (measured as the number of highly recognizable letters around fixation) suddenly begin to decrease in size for letters smaller than the critical print size? Pelli et al. (2007) have made a persuasive case that crowding imposes the major limitation on the size of the visual span. An important and deep insight underlying their contention is that the limiting factor is not the size of the letters per se but the spacing between letters (assuming that the letters do not physically overlap).

Crowding refers to the observation that recognition of letters flanked by other letters (such as “g” in the trigram “tgu”) is much harder to recognize in peripheral vision than single letters with no flankers (Bouma, 1970; Woodworth, 1938). Bouma (1970) measured percent correct letter recognition as a function of distance from the fovea for letters of a fixed size (the x-height was 14 arcmin). Target letters were presented alone or flanked on both sides with an “x” as in “xax.” Recognition accuracy was severely reduced by the flankers. The interfering effect extended over a large distance from the target letter, roughly equivalent to half the distance from the target to the point of fixation. Pelli et al. (2007) described the spacing over which crowding effects extended from a given letter to a neighboring letter and defined the critical spacing S within which crowding would result in a reduction to 80% or less letter recognition. They referred to the relationship between this critical spacing S and retinal eccentricity ϕ as the *Bouma law*:

$$S = S_0 + b\phi, \quad (3)$$

where ϕ is the distance of a target letter from fixation in degrees, S is the critical spacing in degrees, S_0 is the critical spacing near fixation with a value roughly 0.1° to 0.2° , and b is a constant named for Bouma. When adjacent letters are closer than the critical spacing, there will be crowding, and letter recognition will suffer.

In reading, letters in the text extend leftward and rightward away from the currently fixated letter. Letters farther from fixation are at greater eccentricity ϕ with larger critical spacing S . When the distance from fixation is large enough, adjacent letters fall within the critical spacing for the retinal eccentricity in question, and letter recognition performance suffers from crowding. It is this crowding that limits the size of the visual span. When print size gets small, the spacing between letters also gets small and the constant S_0 in Bouma’s law begins to dominate. Below a critical print size, the spacing between all letters in the text string falls within the critical spacing for crowding. When this occurs, the visual span shrinks rapidly and reading slows down. In short, according to Pelli et al. (2007), the critical print size for reading is not a consequence of the size of the letters per se, but a result of the center-to-center spacing between adjacent letters falling within the critical spacing for crowding.

This discussion of crowding and spacing might seem to imply that extra-wide spacing between letters in text would reduce crowding, increase the size of the visual span, and result in faster reading. However, empirical study has shown that extra-wide spacing does not enlarge the visual span nor increase reading speed (Yu et al., 2007).

To briefly summarize the findings reviewed in this section, oculomotor factors do not determine the boundary print sizes for the fluent range. It is likely that the spatial

frequency dependence of contrast sensitivity plays a role in the reduction of reading speed for very small and very large letters, but it remains uncertain why peak frequencies (cycles per letter) for letter recognition are size dependent. It appears likely that the size of the visual span is an important determinant of reading speed, and crowding is a primary determinant of the size of the visual span.

Print sizes in use in typography

We now address the ecological hypothesis that type designers and typographers have adapted the range of print sizes used in newspapers and books to fall within the fluent range, that is, that typography and type design have implicitly been driven by the properties of human vision.

The hypothesis that the range of commonly used print sizes is determined by visual competence is part of a larger hypothesis that writing symbols have evolved in response to visual pressures rather than writing pressures (Changizi et al., 2006). These authors found that the distribution of topological configurations of contours commonly found in writing systems corresponds to the distribution found in natural images, implying that written forms have been designed to take advantage of visual mechanisms that evolved for perception in the natural world. There is historical evidence, however, of shifting compromises between economic pressures for faster writing, resulting in rapidly executed cursive scripts with fewer hand motions and pen lifts, versus visual pressures for clearer text, resulting in slowly executed formal scripts with more hand motions and pen lifts. Bigelow and Day (1983), Frutiger (1989), and Noordzij (2005) argue that historical transformations from formal to cursive script involve simplification and reduction of stroke structure in response to the motor pressures of fast handwriting.

To test the ecological hypothesis, we conducted surveys of the print size distributions in four contemporary text sources—running text in printed newspapers, headlines in printed newspapers, and text in hardcover and paperback fiction books.

For the newspaper surveys, we looked at font size metadata contained in portable document format (PDF) files of the front pages of 360 U.S. newspapers that had been posted to a common website, the “Newseum.org” (<http://www.newseum.org/todaysfrontpages/>). This method was faster and more precise than measuring physical print size, with the limitations that “ink spread” in print on paper could not be measured but may have increased print sizes slightly and that prepress modifications of the digital pages may have slightly reduced print sizes. For running text size, we chose the most common size on the front page. For headline size, we first measured the largest size on each front page and later measured

smallest size and subhead size. Confirmation of values for selected running text sizes was obtained by visual inspection of print newspaper samples with a 60× power digital measuring microscope.

Data for 200 hardcover novels published since the year 2000 were gathered visually with a calibrated handheld loupe, and data for 100 paperback novels published during the same time period were also gathered visually with a handheld loupe.

Table 2 provides the summary statistics of the book and newspaper studies. The x-heights are given in degrees of visual angle assuming a 40-cm reading distance, as well as in millimeters (mm) and points (pts). Most noteworthy, all of the values of visual angle fall within the psychophysically defined fluent range of print sizes, confirming the hypothesized link between typographic practice and visual function.

Newspapers

Figure 5 shows the frequency distributions of x-heights for newspaper and book running text. The newspaper distributions are tightly clustered, with a mean visual angle of 0.23° in a range from 0.20° to 0.26° (1.41–1.85 mm). These values lie close to the small-print end within the fluent range of print sizes. For paperback books, the mean visual angle is 0.24°, and distribution is clustered like that of newspapers but with a somewhat smaller range (1.41–1.76 mm). For hardcover books, the physical mean print size is slightly greater than for paperbacks, but the rounded mean visual angle of 0.24° is the same as for paperbacks. The hardcover size range is more loosely distributed in a greater range (1.41–1.94 mm). For all three kinds of publication, the range of values lies within the lower end of the fluent range of print sizes. Evidently, newspaper and book typographies are compatible with the critical print size for normal vision.

Text type	Range	Mean	Standard deviation
Books (hardcover fiction)	0.20°–0.28° VA (1.41–1.94 mm) [4.0–5.5 pts]	0.24° VA (1.68 mm) [4.77 pts]	0.01 (0.10) [0.28]
Books (paperback fiction)	0.20°–0.25° VA (1.41–1.76 mm) [4.0–5.0 pts]	0.24° VA (1.66 mm) [4.65 pts]	0.01 (0.10) [0.25]
Newspaper running text	0.20°–0.26° VA (1.41–1.85 mm) [3.98–5.25 pts]	0.23° VA (1.64 mm) [4.65 pts]	0.01 (0.07) [0.2]

Table 2. Running text print sizes (x-heights) in books and newspapers. (x-height values are degrees of visual angle (° VA) assuming a reading distance of 40 cm, followed by millimeters in parentheses (mm) and points in brackets [pts].)

Contemporary book & newspaper print sizes

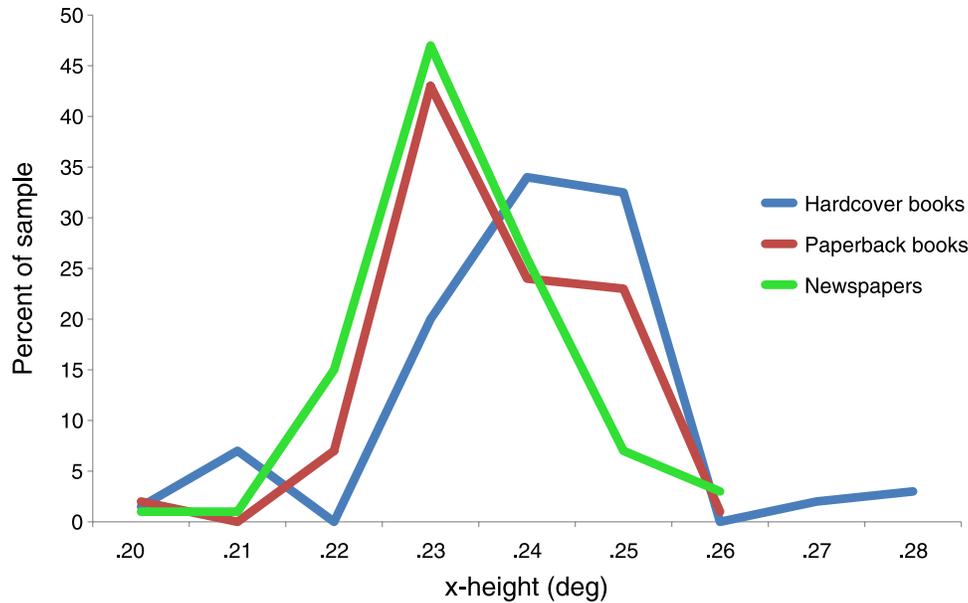


Figure 5. Frequency distributions of x-heights in hardcover novels, paperback novels, and daily newspapers. Distribution frequencies are shown as percentages, e.g., an x-height of 0.23° constitutes 47% of the hardcover novel sample.

DeMarco and Massof (1997) made similar measurements on 100 U.S. newspapers.¹ For front page running text, they found a median value of 1.74 mm and a range of 1.5 to 1.9 mm. Their values are slightly larger than ours, probably due to their measure of o-height, which is roughly 5.5% greater than the flat x-height we used. The remainder of the difference may be due to ink spread on newsprint in their study, whereas we measured type size in digital files. It is also possible that there was a slight increase in average newspaper type sizes during the 14-year interval between DeMarco and Massof’s study and ours, but newspaper type sizes appear to have been stable over several decades. Arnold (1969) reported on a 1968 study that the most common body size in newspaper running text (44% of the newspapers) was 9 points. Assuming a newspaper type x-height fraction of 0.5, mean x-height rounds to 1.59 mm, only slightly smaller than the value of 1.64 mm we obtained.

DeMarco and Massof also measured the sizes of print in several other sections of their newspapers. The smallest print was found in stock listings, typically not intended for fluent reading, with a median print size of 1.13 mm (0.17°).

We mentioned earlier that different typefaces have different x-height fractions (ratios of x-height to body size). Typographers tend to choose typefaces with larger x-height fractions for smaller body sizes, probably to increase the apparent size of type while decreasing the physical body size. We found evidence for this in our newspaper study, where the x-height fraction of the fonts had an inverse correlation of 0.71 with body size. The

smaller the body size, the bigger the x-height fraction of the font.

Headlines are the largest print in newspapers. They are intended to attract the attention of potential purchasers at a distance on the street and, for readers holding the paper at typical reading distance, also function as guides to the organization and contents of a page.

The first row in Table 3 shows the summary statistics for the x-height sizes of the largest headlines on the front

Text	Range	Mean	Standard deviation
Newspaper headlines (largest)	0.56°–4.42° VA (3.96–31.2 mm) [11.22–88.44 pts]	1.71° VA (12.06 mm) [34.19 pts]	0.46 (3.26) [9.25]
Newspaper headlines (smallest)	0.45°–1.05° VA (3.18–7.4 mm) [9.0–21.0 pts]	0.76° VA (5.38 mm) [15.24 pts]	0.14 (0.98) [2.77]
Newspaper subheads	0.26°–0.9° VA (1.85–6.35 mm) [5.25–18.0 pts]	0.43° VA (3.06 mm) [8.67 pts]	0.11 (0.78) [2.22]
Newspaper running text	0.2°–0.26° VA (1.41–1.85 mm) [3.98–5.25 pts]	0.23° VA (1.64 mm) [4.65 pts]	0.01 (0.07) [0.2]

Table 3. Headline print sizes (x-heights) in newspapers. (x-height values are in degrees of visual angle (° VA) assuming a reading distance of 40 cm, followed by millimeters in parentheses (mm) and points in brackets [pts].)

page of the newspapers in our study. The mean x-height of 1.71° (12.06 mm) lies below the upper boundary of the fluent range of about 2° . The second row shows the summary for the smallest headlines, and the third row shows the summary for subheads—smaller than headlines but bigger than subsequent running text. For comparison, the fourth line of the table repeats the findings of newspaper running text sizes of [Table 2](#).

Overall, the mean sizes for running text in newspapers of 1.64 mm (0.23°) and for the largest front page headlines of 12.06 mm (1.71°) lie comfortably within the psychophysically defined fluent range for reading from 0.2° to roughly 2° . We note, however, that approximately 20% of the headlines exceed 2° of visual angle, a violation of the ecological hypothesis. There are two mitigating factors. First, the decline in reading speed for print sizes larger than 2° is much more gradual than the sharp decline at the critical print size, lessening the impact on reading performance. Second, the largest headlines are very short texts; in our sample, the largest 10% of headline text ranged in length from one to six words, with a mean of 3.2 words. Slower reading of these very short texts would not have much overall effect on newspaper reading.

In [Table 3](#), notice the spread of mean print sizes for the four categories of text. There are steps of approximately two-fold increase in print size from running text to subheads, to the smallest headlines, and then to the largest headlines. These large steps may help maximize perceptual differences in size of functionally salient categories of text. This finding is subject to some limitations: Newspaper headline and subhead sizes vary depending on the importance or sensationalism of the news on a given day; we measured only front page headlines, but those on inner pages may be smaller; we measured largest and smallest headlines, but there were intermediate sizes that would smooth out the size distribution.

The distribution span of headlines is larger than for running text: 3.96 mm to 31.2 mm (0.56° to 4.42° VA), roughly three factors of two. Approximately 80% of our headline sample had x-height sizes equal to or smaller than 2° , and only 1% of the sample were larger than 3° . Overall, these data show that most newspaper headlines fall within the psychophysically defined fluent range of print sizes.

Books

Next, we consider the findings for hardcover and paperback novels summarized in [Table 2](#). For hardcover novels, mean print size (0.24° VA) is slightly larger than newspaper running text and the range of x-height sizes is broader, from 0.2° to 0.28° VA (1.4 to 1.9 mm). All of these texts lie within the fluent range for readers using a 40-cm reading distance.

Print sizes in paperback novels show a mean size (0.24° VA) equal to hardcover novels and slightly greater

than that of newspapers. The size range is 83% of that of hardcover novels and 63% of that of newspapers.

It is worth noting that the common mass-market paperback page has little more than half the area of the typical hardcover page, but mean type size in paperbacks is reduced by only a few percent. To economize on paper costs, paperback publishers reduce page margins and spacing between lines of type, but reduce type body only around 12%, and use typefaces with bigger x-height fractions of the body, so mean print size (based on x-height) in paperbacks is nearly the same as that of hardcover novels.

Vision vs. economics

Digital typography can render print sizes to fractional point sizes at no additional cost, and small and large print sizes are equally inexpensive to render, excepting the cost of the substrate (newsprint, gloss paper, etc.). Newsprint is a major cost of newspaper production, so we might expect print sizes to be reduced in order to conserve paper. Yet, the x-heights in our newspaper survey did not fall below 1.4 mm and 0.2° of visual angle (at 40 cm) and appear to have been more or less stable for 40 years. Even the smallest sizes of newspaper financial listings and classified ads, as reported by DeMarco and Massof (1997) and supported by our own findings, do not approach digitally feasible minimum type sizes and are not even as small as the smallest type sizes produced 200 years ago.

The smallest print sizes in paperback books, likewise subject to paper conserving economies, also do not fall below the critical print size. Therefore, it appears that neither technology nor economics are determinants of minimum print sizes, but rather, it is the visual factor of critical print size that determines the minimum sizes in usage.

The data from our survey of contemporary books and newspapers largely confirm the ecological hypothesis. Virtually all running text, intended to carry narrative information, lies within the fluent range for reading from 0.2° to 2° and most newspaper headlines fall into this range as well.

Print size in historical perspective

Next, we turn to a second test of the ecological hypothesis by considering print size practice in historical perspective. Is print size usage across the centuries consistent with the fluent range for reading? In particular, do printed books and typefounders' specimens provide evidence that the fluent range for reading from 0.2° to 2° has remained stable from the mid-1400s to the present?

It is generally supposed that the 5000 years of human literacy is too short a period for the evolution of specialized visual or brain mechanisms for use in reading and writing (cf., Dehaene, 2009, p. 119). Instead, it is likely that preexisting brain mechanisms are deployed to handle reading and that these mechanisms are tuned when an individual learns to read. For example, human brain imaging studies have revealed a brain region that appears to be especially responsive to visual words and is implicated in the transformation from visual word forms to their phonetic and semantic representations. This region is located in the left hemispheric ventral region near the boundary of the occipital and temporal lobes, more specifically, the left fusiform gyrus. This region has been termed the “visual word form area” or VWFA (Cohen et al., 2000, 2002). In a recent fMRI study, He et al. (2009) have shown that a functional brain module of this type emerges over the course of 1-month instruction in reading for illiterate Chinese adults.

If we consider the population distribution of visual acuities and, presumably, critical print sizes, it is possible that economic, technological, and demographic factors have had an influence on the fluent range over the period of print. These factors include the growing literacy rate arising from greater availability of cheaper books, greater access to education, greater longevity in the population, and better access to refractive corrections for reading (glasses, contacts, or surgical correction).

Refractive correction and the fluent range of print sizes are linked because the ability to read 0.2° print requires well-focused retinal images. Spectacles were certainly available for use in reading by the early 14th century (Dreyfus, 1995; Wade, 2007). Dreyfus suggests that the availability of inexpensive spectacles to correct for refractive errors, including presbyopia, may have had an impact on the economics of printed book production: Spectacles enabled smaller print to be read, allowing the production of books with fewer and smaller pages and thus lower prices. It is also possible that spectacles and magnifying lenses facilitated the design and cutting of movable type with small print sizes (Carter, 1969; Dreyfus, 1995). Wade (2007) points out that an understanding of the refractive properties of the eye came substantially after the introduction of spectacles, awaiting the 17th century insights of Kepler and Descartes. An understanding of presbyopia, the age-related shrinkage in the range of visual accommodation, came even later with the work of Wells at the end of the 18th century and Donders in the 19th century (Wade, 2007).

In developed countries, most people now have access to refractive corrections, enabling them to read newspaper and book print, but this is not true worldwide. The World Health Organization estimates that about 150 million people worldwide have impaired vision due to uncorrected refractive errors, close to the estimated 161 million people worldwide with uncorrectable visual impairment (WHO, 2004, 2006). Overall ocular health in developed

countries is undoubtedly better today than in past centuries, and it is possible that the distribution of visual acuity across the population (either corrected or uncorrected) has shifted slightly toward higher levels. This possible increasing population acuity may be partially offset by the increase in reading by older individuals. People in their 70s and beyond who are not afflicted with age-related eye disease show only a modest decline in visual acuity under clinical testing conditions but are more vulnerable to acuity reduction in poor lighting, in glare, or with low-contrast print (Haegerstrom-Portnoy, Schneck, & Brabyn, 1999).

From the above considerations, it remains possible that the small-print end of the fluent range ($\sim 0.2^\circ$) has decreased over the centuries with the improving ocular hygiene of the reading public, but our survey of historical sources (discussed below) implies that any changes have been small.

To see if there have been significant changes in type size ranges since the beginning of printing in Europe, we measured type sizes in the 15th, 16th, and 18th centuries. In all these studies, we focused on seriffed roman types, which first appeared in 15th century Italian Renaissance printing and provide unbroken continuity through the centuries, up to and including the text types in our surveys of recent books and newspapers, all of which are seriffed romans. Table 4 shows summary statistics.

Fifteenth century Italian roman types

For the 15th century, we measured x-heights of roman types in books printed from 1469 to 1501 in the Italian

Sample	Range	Mean	Standard deviation
Fifteenth century Italian text types	0.25°–0.36° VA (1.8–2.5 mm) [5.1–7.09 pts]	0.30° VA (2.1 mm) [5.95 pts]	0.03 (0.18) [0.51]
Sixteenth century French text types	0.11°–0.35° VA (0.8–2.5 mm) [2.27–7.09 pts]	0.23° VA (1.66 mm) [4.7 pts]	0.06 (0.43) [1.22]
Sixteenth century French display types	0.42°–2.38° VA (3.0–17.0 mm) [8.5–48.9 pts]	0.8° VA (5.67 mm) [16.07 pts]	0.53 (3.79) [10.74]
Eighteenth century foundry text types	0.11°–0.35° VA (0.75–2.38 mm) [2.13–6.75 pts]	0.22° VA (1.54 mm) [4.37 pts]	0.06 (0.41) [1.16]
Eighteenth century foundry display types	0.35°–2.0° VA (2.47–14.11 mm) [7.0–40.0 pts]	0.81° VA (5.68 mm) [16.1 pts]	0.44 (3.13) [8.87]

Table 4. Print sizes (x-heights) in historical books and type foundry specimens. (x-height values are in degrees of visual angle ($^\circ$ VA) assuming a reading distance of 40 cm, followed by millimeters in parentheses (mm) and points in brackets [pts].)

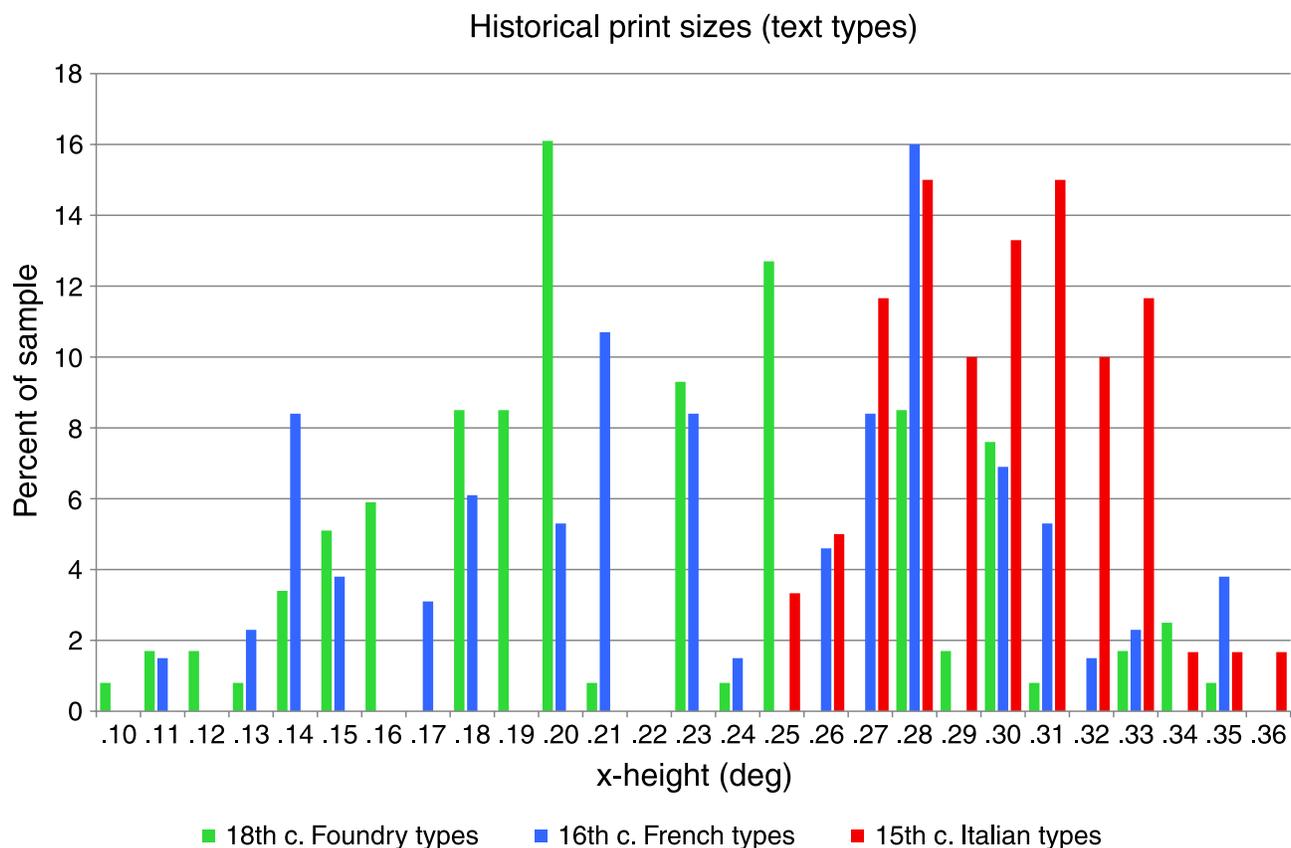


Figure 6. Distribution of roman text sizes (x-heights) in books and type specimens from the 15th, 16th, and 18th centuries. Fifteenth century Italian types cluster at the large end of the range, while 16th century French types span nearly the whole range, and 18th century English and French types extend the small end of the range.

Renaissance, when “roman” types were first created and became the model for most subsequent printing types. The corpus comprised 110 book pages compiled by Haebler (1927), which included 60 examples of roman type (the others in black-letter rotunda or Greek types). Although the sample is small, it includes eighty different printers whose output is representative of the period. The smallest x-height we found was 1.8 mm (0.25°) and the largest was 2.6 mm (0.36°). The size range is narrow but lies comfortably within the fluent reading range. The mean size was 0.30° of visual angle and 2.1 mm. The distribution of sizes is shown in Figure 6.

Several hypotheses may be advanced for the large mean size and narrow range of roman types in 15th century Italian printing. A technical hypothesis is that early printing was graphically noisy. Rough paper surfaces, variable ink densities, soft-type metal alloys, and difficulties in casting and printing meant that small details were not reproduced clearly. Hence, larger type sizes, easier to produce and print, may have been favored, at least in the roman form. Early printers did, however, use black-letter “rotunda” types in sizes down to 1.5 mm in x-height (0.21°) (Haebler, 1927) and perhaps down to 1.4 (0.20°) or slightly smaller (Carter, 1969). Black-letter types, small

and large, were supplanted by roman in 16th century Italy, France, and England (Ferguson, 1989; Vervliet, 2010).

A vision-related hypothesis can also be based on a few first-hand accounts from 14th and 15th century readers. Ullman (1960) cites letters from 14th century Italian humanist scholars with aging eyesight (Petrarch and Coluccio both in their 60s), who, before printing came to Italy, sought manuscript books in larger text sizes of semi-roman handwriting, which they believed was easier to read. Coluccio complained of difficulty reading a manuscript written in black letter with an x-height of 1 mm (0.14°), equivalent to 6-point type today. Scholarly readers in the era of printing may have had similar preferences. Updike (1937) quotes a scholar, circa 1480, praising the types of the printer, Nicolas Jenson with these words “The characters themselves are so methodically and carefully finished by that famous man [Jenson] that the letters are not smaller or larger or thicker than reason demands or than may afford pleasure.” Jenson’s three roman types in our study had a mean x-height of 2.12 mm or 0.3° of visual angle. Dreyfus (1995) states that most decisions on type size were probably influenced by economic considerations and that “cheap and serviceable spectacles” may have enabled usage of smaller type sizes,

which in turn reduced paper costs and expanded the book market.

Sixteenth century French roman types

Our next survey was based on measurements by Vervliet (2010) of 158 roman types including all the distinct forms and sizes of roman types cut and cast by French printers, punchcutters, or typefounders during the century and printed in books or specimen sheets. In the 16th century, type punchcutting and type founding became trades separate from printing, so typefounders' specimens provide additional data on type size distribution.

We hypothesized that the frequency of occurrence of variants within named size ranges would indicate relative popularity of the sizes, because in competitive publishing, typefounders would have produced sizes preferred by printers, who would have used types preferred by readers. Preferences were based on economics and religion as well as vision, according to Vervliet (2008), who notes that in the 16th century, paper costs constituted 75% of the cost of producing a book, so small print sizes were favored, particularly in Bible printing.

The distribution of type sizes is shown in Figure 6. In this survey, type x-heights ranged from 0.8 mm (0.11°) to 17 mm (2.38°), an extension at both ends of the range from the previous century. Only one typeface, less than 1% of the sample, was above the upper limit of the fluent reading range, but 27% of the types fell below the lower end of the fluent reading range.

We categorized type sizes as “text” or “display,” the former for running text, the latter for titles and headings. We used a physical x-height of 2.5 mm as a convenient demarcation between text and display categories, though the boundary is not strongly defined.

In the text range, peaks around 0.14° , 0.21° , and 0.28° of visual angle show that there were several types at or near those sizes. The 0.28° peak is slightly lower than the 0.30° mean size found in our 15th century sample. The size span between 0.21° and 0.28° includes more than half of the 16th century text sample. Outside of France, this same size and style range corresponds to “pica roman” type, said to have been the most widespread type of Elizabethan England (Ferguson, 1989).

The proliferation of small type sizes during the 16th century, when several sizes below 1.4 mm (0.20°) became available, suggests that technical limitation on small type was no longer a limiting factor on size. Carter (1937/1984) stated that these small type sizes were produced mainly for footnotes and marginal notes, but Vervliet (2008) found that several small types (x-heights from 0.11 mm to 0.15 mm, or approximately 6- to 8-point body size) were used in the printing of Protestant Bibles and religious texts, because small type sizes made books inexpensive, portable, small, and convenient for clandestine distribution,

all desirable book features during the Counter-Reformation. The visual disadvantage of non-fluent reading sizes was apparently countervailed by economic and social pressures.

Of the thirty display types with x-height greater than 2.5 mm (0.39°), only one had an x-height greater than 14 mm (2.0° , the upper end of the fluent reading range). The 16th century display type range resembles that of the 21st century American newspaper (Table 2), which suggests that sizes of display type read within arm's length have been more or less consistent for four centuries.

We examined type foundry specimen facsimiles from the 17th century (Dreyfus et al., 1963) but found no salient differences in size ranges from the 16th century. We note, however, that actual type usage in the 17th century may have shifted toward smaller text sizes, notably in small, popular books from the Elzevir publishers. Type size usage across these centuries is a matter that invites further investigation.

Eighteenth century foundry roman types

Our third survey of historical sizes measured x-heights of type specimens from three 18th century typefounders: Caslon (1786) and Fry (1786) both in London, and Fournier (1766) in Paris. These foundry specimens do not provide data on typeface size distribution in books but do encompass the range of sizes available to printers and publishers.

The small end of the size range was populated with more types than in previous centuries: 37% of the 18th century foundry types had x-heights with angular size below the critical print size of 0.2° , and some fonts were very small indeed. Fry advertised a “Diamond” roman as “The Smallest Letter in the World,” with an x-height of 0.74 mm subtending a visual angle of 0.10° , approximately 4 to 4.5 points in body size. Fournier showed a “Parisienne” roman with an x-height of 0.75 mm. Although notable technical achievements in letter cutting and casting, these small types, at half the critical print size, appear not to have been popular. A 19th century English publisher, Pickering, printed a series of miniature books, the “Diamond Classics,” in this small type size, but they were not widely emulated, and such a small size has rarely been used in 20th or 21st century publishing, not even in newspaper classified advertising and stock listings.

At the large end of the scale, Fournier showed a type with an x-height of 14.1 mm and a visual angle of 2.0° . Neither of the 18th century English typefounders showed x-height sizes above 12 mm or angular size above the 2.0° upper bound of the fluent reading range. A 19th century specimen from the Fry foundry (Chambers, 1986) showed five sizes from 14-mm to 36-mm x-height, but these large sizes were produced for placards and posters read at distances two or more times greater than for books, so the

visual angle subtended by these large types was probably not greater than the upper limit of the fluent range.

Summary of historical findings

In our historical survey, we found three main trends: (1) extension of type size range from a narrow cluster of fluent sizes in the 15th century to a broader range including several subfluent sizes in the 16th and 18th centuries; (2) nearly stable size range from the 16th to 18th century; (3) proliferation of type sizes in the subfluent range, from zero (for roman types) in the 15th century to 37% of the sample of typefounders' specimens in the 18th century.

If, as hypothesized, size ranges were constrained by technical limitations in the 15th century, when those limitations were no longer operant in the 16th century, three factors may have motivated or enabled smaller sizes: (a) economics—smaller type sizes enabled cheaper printing with less paper; (b) vision—eyesight improved by refractive correction enabled reading of smaller sizes by more of the population; (c) social change—books challenging established religious and political orders were preferentially small, requiring smaller type sizes.

Our surveys of type sizes from the 15th, 16th, and 18th centuries are consistent with the ecological hypothesis, with one exception: The proliferation of small sizes with visual angles below 0.2° in the 16th and 18th centuries appears to violate the hypothesis.

Critical print size is the lower bound of fluent reading but is not an absolute limit; reading below the critical print size slows but does not stop. Carter's (1937/1984) contention that small (subfluent) sizes were used not for running text but for notes suggests that slower reading speed was acceptable for short texts, presumably balanced by greater economy. The finding by Vervliet (2008) that, in the 16th century, subfluent sizes were used for running texts in religious printing suggests that economic and social advantages compensated for slowed reading.

Digital screens

We have been discussing print typography dating from the 15th century, but in the 21st century, reading has been shifting from print publications to the screens of computers, mobile phones, and e-reading devices. How do typefaces and type sizes on screens compare to those in print publications?

We observed that the mean x-height fraction of commonly used typefaces in our surveys increases from books to newspapers to screens (Table 5).

There is evidence that larger x-height fractions are associated with greater legibility on screens. Sheedy, Subbaram, Zimmerman, and Hayes (2005) tested on-screen, threshold legibility of capital letters, lowercase letters, and

Publication	Mean	Standard deviation
Hardcover book typefaces	0.42	0.04
Paperback book typefaces	0.43	0.03
Newspaper typefaces	0.48	0.03
Print typefaces adapted to screens	0.49	0.04
Digital typefaces designed for screens	0.52	0.03

Table 5. Mean x-height fractions of typefaces by publication form.

lowercase words composed in common screen fonts. For a given body size, they found that Verdana (x-height fraction = 0.55) was the most legible and Times New Roman (x-height fraction = 0.45) the least legible, with Arial (0.52) and Georgia (0.48) intermediate in legibility. The x-height fraction of a font, which is calculated independently of output resolution, does not always correlate exactly with physical size in pixels on screens, because intentional non-linearities in font rasterization may increase x-height at small body sizes. In Sheedy et al., the pixel x-heights at a body size of 18 pixels were given as follows: Verdana = 10 pixels, Arial = 9 pixels, Times New Roman = 8 pixels. These follow the respective x-height fractions of the fonts and match the legibility findings. Georgia, however, had an on-screen x-height of 10 pixels, whereas 9 would be expected from its x-height fraction of 0.48. In word recognition tests, Georgia was more legible than Arial or Times New Roman, indicating that x-height fraction in screen pixels is associated with legibility.

Sheedy et al. (2005) also found that when viewing distance was adjusted so that all fonts had the same angular viewing size, legibility was greater when fonts were rendered with more pixels, equivalent to higher resolutions. Larger x-height fractions encompass more pixels for the x-height at a given body size, which effectively increases resolution for the x-height region of the font and which may, therefore, be a factor in the finding of greater legibility for fonts with larger x-height fractions.

Screen type sizes in online newspapers

To investigate type sizes in use on screens in comparison to our studies of print media, we measured the sizes of headlines and running text on the websites of 30 U.S. daily newspapers. This sample included the websites of 21 of the 25 U.S. newspapers with largest print circulation.

Because web browsers enable readers to scale text to larger or smaller sizes, it is difficult to determine with certainty the type sizes that readers actually view. For our initial study, we used the default settings of the Safari browser, version 5.0.5, running under Macintosh operating

Sample	Range	Mean	Standard deviation
Home page headlines	9–17 pixels	11.33 pixels	1.95
	0.25°–0.46° VA	0.31° VA	0.05
Home page text	6–8 pixels	6.78 pixels	0.49
	0.16°–0.22° VA	0.19° VA	0.01
Article headlines	8–17 pixels	13.63 pixels	2.36
	0.22°–0.46° VA	0.37° VA	0.06
Article running text	6–9 pixels	7.53 pixels	0.78
	0.16°–0.25° VA	0.21° VA	0.02

Table 6. Screen font sizes in online news home pages and article pages.

system OS X 10.6 on a MacBook Pro with LCD screen resolution of 132 pixels/inch. To measure screen type sizes, we captured screen pixel images of headlines and text and counted the number of pixels in the letter x-heights. To calculate angular size, we used a viewing distance of 40 cm (16 inches). The results are summarized in Table 6.

In contrast to the front pages of print newspapers, the home pages of online newspapers contained few instances of running text. Instead, the home pages resembled complex tables of contents with multiple lists and sections. Brief headlines and accompanying short texts, ranging from a single phrase up to a few sentences, functioned as links to longer articles. Other short texts on the home pages included notices of reports and special sections, short headline lists, and lists of the most popular stories of the day, all linking to other sections of the site.

At a reading distance of 40 cm, the mean headline size was 0.31° of visual angle, well above the critical print size, but the mean text size was 0.19°, slightly below the critical print size, and the smallest text size was 0.16°, substantially below critical print size. This appears to violate our ecological hypothesis that running text will be at or above the critical print size, but because the texts on the home pages were short phrases or at most a few sentences, intended for skimming rather than extended reading, slower reading rates due to the small size would presumably not slow readers appreciably.

In the online articles, linked from the home page, the range of headline sizes was nearly the same as on the home page, but the mean size of 0.37° was greater than on the home page (0.31°). The size range of the running text of articles was broader than on the home page, and the mean size of 0.21°, while near the bottom of the fluent reading range, was above the critical print size.

In comparison to print newspapers, online news sites had much smaller headlines. On the home pages, the mean angular size of the largest headlines was 0.31°, less than a fifth of the mean largest headline of print newspapers. The mean article headline of 0.37° was less than a fourth of the print mean headline. We attribute the marked reduction in headline size to the different functions of headlines in print versus online. Print headlines are partly intended to

attract newspaper readers from greater than normal reading distances, whereas readers of online headlines are presumably within normal reading distance. Home page headlines are intended to invite the reader to click on the link to an article deeper in the site, and headlines beginning an article function more like book chapter titles, identifying the content of a page the reader has already reached, while also competing against other visual stimuli appearing on a computer screen.

Web pages do not need large headlines to attract readers but do need to hold readers' attention, because competing sites are only a few clicks away. Smaller sized headlines enable more stories to be put on the home page within the frame of a web browser window. The more articles on the home page, the more likely a reader will link to one or more of them and stay within the news site. Hence, there is pressure toward smaller type sizes in online news, not from the cost of paper as in print newspapers, but from the need to gain and hold a reader's attention. Although screen text is freed from the economics and limitations of rendering on an expensive analog substrate (paper), the economics of digital resolution, display screen real estate, and reader attention become important and, at least in our preliminary survey, drive text sizes below those in print.

Unlike print newspapers, in which technology and typography have developed and matured over hundreds of years, screen news is still a quickly evolving medium in which factors of vision and cognition have potentially greater influence than in print, thus inviting further study.

Discussion and conclusions

Print is the medium for visual reading. Print size has been of interest to typographers and to vision researchers. Typographers care about print size in the context of design requirements required for legibility, the layout of print on the page or screen, and the economics of document production. Typographers have long been aware that legibility depends on characteristics of vision, but they have rarely had the opportunity to make a firm theoretical connection between typeface designs and visual pattern recognition. In 1937, the typographic historian Harry Carter wrote: "The whole problem of adapting type-design to optical susceptibilities is a fascinating and a very difficult one. It is only possible to nibble at it without having proper experimental apparatus and ample time" (Carter, 1937/1984).

Vision researchers care about size because the underlying mechanisms for encoding pattern—spatial frequency channels or their neural counterparts, the receptive fields—vary in size. The contrast sensitivity function, introduced for use in display design by Schade (1956) and later used widely in vision science (cf., Campbell & Robson, 1968), provides a characterization of visual

pattern sensitivity across the range of sizes or scales. Recent theoretical developments on crowding indicate that character spacing, which usually covaries with print size, may be the operative variable (Pelli et al., 2007). Clinical vision researchers care about print size in the determination of visual acuity and in refractive correction (using the ubiquitous letter charts) and in the prescription of magnifiers for people with low vision.

Miles A. Tinker, in a large body of work including a classic series of 13 papers with Donald G. Paterson on “studies of typographical factors influencing speed of reading,” published between 1928 and 1936, used psychophysical methods to study the effects of text characteristics on legibility. This work is summarized in Tinker’s (1963) book *Legibility of Print*. Tinker’s work spoke more to typographers than to vision researchers. His focus was almost exclusively on the empirical dependencies and not the nature of visual processing underlying legibility. More specifically, his work preceded the insights on the visual representation of size in the second half of the 20th century. His measurements of the effects of print size, cited earlier in this paper, did not explore a wide range of sizes nor express the results in terms of visual angles. As such, his results on print size have not had much impact on vision research. To the extent that Tinker identified the fonts in his studies, and we are willing to make plausible assumptions about the viewing distances of his many subjects, it is possible to convert his typographic size measures into angular measures of x-heights and, thus, bring some of his data into closer correspondence with recent vision research, including some of the investigations in this paper.

A key consideration dividing the typographic and vision research communities has been the metric used for specifying print size. Typographers traditionally refer to the physical dimensions of print on the page, typically in points. Vision researchers prefer angular size of print in degrees or minutes of arc because visual angles determine retinal image size. Angular size of print requires careful specification of both physical print size on the page and the reader’s viewing distance. We find that measures of x-height provide a convenient metric, being familiar to both typographers and vision researchers. Easy transformations exist for conversion of x-height between physical size and visual angle (Table 1).

We have considered the ecological hypothesis that the distribution of print sizes commonly used in books and newspapers falls within the psychophysically defined range of fluent print sizes for reading. We recognize that it is difficult to prove a causal relation, but we have found some striking parallels. The range of print sizes for fluent reading can be defined as the range of print size over which text can be read at maximum speed. The fluent range extends over a factor of 10 in print size (x-height) from approximately 0.2° to 2° . Assuming a standard reading distance of 40 cm (16 inches), the corresponding x-heights are 1.4 mm (4 points) and 14 mm (40 points).

Supporting the ecological hypothesis, our analysis of print sizes in large samples of contemporary newspapers, hardcover novels, and paperback novels indicates that almost all running text and most display text (headlines and headings) fall into the fluent range.

We also tested the ecological hypothesis by asking whether font sizes used by printers or offered by typefounders from the 15th to 18th centuries lie within the fluent size range. From our review, most of the font sizes are within the fluent range, but we found a significant fraction of font sizes below the critical print size of 0.2° of visual angle. Our proposed explanations are, first, that the smaller, subfluent type sizes offered by typefounders were not generally used in texts for continuous reading but for notes or reference materials and, second, that when subfluent sizes were used for running text, principally in Bibles, it was the result of economic and social pressures outweighing the convenience of reading fluency. For contemporary publications, this explanation is borne out by, for example, the use of small sizes in non-running texts in classified newspaper advertisements, stock listings, and telephone directories, and for Bible printing in the 21st century, as in the 16th century.

The ecological hypothesis bears on several economic and technical issues related to the production of text. For example, because of the cost of paper, small type sizes are more economical than large sizes and small type sizes decrease costs for both publishers and book buyers and, thereby, expand the market for books. Therefore, we expect that, historically, there would be a trend toward use of smaller type sizes. We found this trend in our survey of 16th century typefaces and in 18th century typefounders’ specimens. We explain the absence of small types in the 15th century by claiming that the technology was not yet adequate for the making and printing of small sizes, but we observe that as technology improved, smaller sizes were produced in the 16th century. Although type sizes below the critical print size became available, they were not much used except for specialized publishing (Bibles and religious printing). This remains true today, when technology enables the development and printing of very small sizes, but sizes below the critical print size are not found in running text in books or newspapers.

We have argued that x-height is a major determinant of apparent type size. This may explain why as type body sizes are reduced to save paper costs, the x-height fractions of types may become larger. In particular, we would expect that the increase in x-height fraction will be strongest at or near the critical print size. We found this in newspapers, where there is a substantial inverse correlation (0.71) between body size and x-height fraction for running text. The inverse correlation is present but weaker in paperback books and weaker still in hardcover books. Book typographers have found that, for hardcover books, paper consumption is of lesser concern because readers expect a book of a certain size, thickness, heft, and number of pages (Williamson, 1966).

At the high end of the fluent reading range, we also found limits on type sizes in actual use. For running text in books, we found the mean size to be well below the high end of the fluent range, and historically, we found that font sizes for text are below the high end of the fluent range. For newspaper headlines, we found that 80% are within the fluent reading range. For the 20% of headlines above the fluent range, we note that most contain only a few words. Large headlines are not running text and do not involve extended reading.

While economics, ergonomics, technology, and functional role of print undoubtedly all influence the choice of print size for particular texts, we conclude that properties of vision constrain the choice to lie within a fluent range of print sizes.

Acknowledgments

We gratefully thank Denis Pelli for editorial guidance and comments on crowding; Aries Arditi and Rolf Rehe for constructive and insightful reviews; MiYoung Kwon and Dion Yu for help in preparing Figures 2 and 4; Kris Holmes for preparing Figures 1a and 1b and the graphic icon; Tiana Bochsler for help in assembling the manuscript; David Pankow, curator of the Cary Graphic Arts Collection, RIT, for assistance in historical studies; and Hendrik D. L. Vervliet for comments on 16th century types; The Font Bureau, Linotype, and Monotype Imaging for contributions of newspaper fonts. C.A.B.'s investigations were supported in part by the Melbert B. Cary, Jr. Professorship at RIT. G.E.L.'s work on this manuscript was supported by NIH Grant EY002934.

Commercial relationships: none.

Corresponding author: Gordon E. Legge.

Email: legge@umn.edu.

Address: 75 East River Rd., Minneapolis, MN 55455, USA.

Footnote

¹They reported their findings in Sloan M units (Sloan, 1977) that we have converted to millimeters. M size is defined as the physical height of a character that subtends 5 arcmin at the distance in meters indicated by the M value. For instance, 2M characters subtend 5 arcmin at a viewing distance of 2 m.

References

- Akutsu, H., Legge, G. E., Ross, J. A., & Schuebel, K. J. (1991). Psychophysics of reading: X. Effects of age-related changes in vision. *Journal of Gerontology*, *46*, 325–331.
- Arditi, A. (1996). Typography, print legibility, and low vision. In R. Cole & B. Rosenthal (Eds.), *Remediation and management of low vision* (pp. 237–248). St. Louis, MO: Mosby.
- Arnold, E. (1969). *Modern newspaper design*. New York: Harper & Row.
- Bigelow, C. (1989). Form, pattern, & texture in the typographic image. *Fine Print*, *15*, 75–82.
- Bigelow, C., & Day, D. (1983). Digital typography. *Scientific American*, *249*, 106–119.
- Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*, 177–178.
- Campbell, F. W., & Robson, J. G. (1968). Application of Fourier analysis to the visibility of gratings. *The Journal of Physiology*, *197*, 551–566.
- Carter, H. (1969). *A view of early typography*. Oxford, UK: Oxford University Press.
- Carter, H. (1984). Optical scale in type founding. *Printing Historical Society Bulletin*, *13*, 144–148. (Original work published 1937, *Typography* *4*, 2–8)
- Caslon, W. (1786). A specimen of printing types by William Caslon, letter-founder to His Majesty. In E. Chambers & A. Rees (Eds.), *Cyclopaedia* (vol. 3). London: J. F. & C. Rivington.
- Chambers, D. (1986). *Specimen of modern printing types by Edmund Fry, 1828*. London: Printing Historical Society.
- Changizi, M. A., Zhang, Q., Ye, H., & Shimojo, S. (2006). The structures of letters and symbols throughout human history are selected to match those found in objects in natural scenes. *The American Naturalist*, *167*, E117–E139.
- Chung, S. T., Mansfield, J. S., & Legge, G. E. (1998). Psychophysics of reading: XVIII. The effect of print size on reading speed in normal peripheral vision. *Vision Research*, *38*, 2949–2962.
- Chung, S. T., & Tjan, B. S. (2009). Spatial-frequency and contrast properties of reading in central and peripheral vision. *Journal of Vision*, *9*(9):1, 611–619, <http://www.journalofvision.org/content/9/9/16>, doi:10.1167/9.9.16. [PubMed] [Article]
- Chung, S. T. L., Legge, G. E., & Tjan, B. S. (2002). Spatial-frequency characteristics of letter identification in central and peripheral vision. *Vision Research*, *42*, 2137–2152.
- Cohen, L., Dehaene, S., Naccache, L., Lehericy, S., Dehaene-Lambertz, G., Henaff, M., et al. (2000). The visual word form area: Spatial and temporal characterization of an initial stage of reading in

- normal subjects and posterior split-brain patients. *Brain*, 123, 291–307.
- Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex? Functional properties of the visual word form area. *Brain*, 125, 1054–1069.
- Dehaene, S. (2009). *Reading in the brain*. New York: Viking.
- DeMarco, L., & Massof, R. (1997). Distributions of print sizes in U.S. newspapers. *Journal of Visual Impairment & Blindness*, 97, 9–13.
- Drasdo, N., & Fowler, C. W. (1974). Non-linear projection of the retinal image in a wide-angle schematic eye. *British Journal of Ophthalmology*, 58, 709–714.
- Dreyfus, J. (1995). The invention of spectacles and the advent of printing. In *Into print: Selected writings on printing history, typography, and book production* (pp. 298–310). Boston: David R. Godine.
- Dreyfus, J., Johnson, A., Carter, H., Carter, M., Hoeflake, N., & Parker, M. (1963). *Type specimen facsimiles*. London: Bowes & Bowes.
- Ferguson, W. C. (1989). *Pica roman type in Elizabethan England*. Aldershot, UK: Scolar Press.
- Fournier, P.-S. (1766). *Manuel typographique* (vol. 2). Paris: Fournier.
- Frutiger, A. (1989). *Signs and symbols* (A. Bluhm, Trans.). New York: Van Nostrand Reinhold.
- Fry, J. (1786). A specimen of printing types by Joseph Fry and Sons, letter-founders, Worship Street, Moorfields, London, 1785. In E. Chambers & A. Rees (Eds.), *Cyclopaedia* (vol. 3). London: J. F. & C. Rivington.
- Ginsburg, A. P. (1978). *Visual information processing based on spatial filters constrained by biological data* (vols. I and II). Ph.D. thesis, Cambridge University. Aerospace Medical Research Laboratory Report AMRL-TR-78-129. Dayton, OH: Wright-Patterson AFB.
- Gorissen, G. (Ed.) (1980). *E2 Berthold fototypes body types* (vol. 1). Berlin, Germany: H. Berthold.
- Haebler, K. (1927). *Italian incunabula*. Munich, Germany: Weiss & Co. Antiquariat.
- Haegerstrom-Portnoy, G., Schneck, M. E., & Brabyn, J. A. (1999). Seeing into old age: Vision function beyond acuity. *Optometry & Vision Science*, 76, 141–158.
- He, S., Liu, H., Jiang, Y., Chen, C., Gong, Q., & Weng, X. (2009). Transforming a left lateral fusiform region into VWFA through training in illiterate adults [Abstract]. *Journal of Vision*, 9(8):853, 853a, <http://www.journalofvision.org/content/9/8/853>, doi:10.1167/9.8.853.
- Huey, E. B. (1908/1968). *The psychology and pedagogy of reading*. Cambridge, MA: MIT Press.
- Jones, M., & Mewhort, D. (2004). Case-sensitive letter and bigram frequency counts from large-scale English corpora. *Behavior Research Methods, Instruments, & Computers*, 36, 388–396.
- Karow, P. (1993). *Typeface statistics*. Hamburg, Germany: URW.
- Kowler, E., & Anton, S. (1987). Reading twisted text: Implications for the role of saccades. *Vision Research*, 27, 45–60.
- Legge, G. E. (2007). *Psychophysics of reading in normal and low vision*. Mahwah, NJ & London: Lawrence Erlbaum Associates.
- Legge, G. E., Cheung, S. H., Yu, D., Chung, S. T., Lee, H. W., & Owens, D. P. (2007). The case for the visual span as a sensory bottleneck in reading. *Journal of Vision*, 7(2):9, 1–15, <http://www.journalofvision.org/content/7/2/9>, doi:10.1167/7.2.9. [PubMed] [Article]
- Legge, G. E., Hooven, T. A., Klitz, T. S., Mansfield, J. S., & Tjan, B. S. (2002). Mr. Chips 2002: New insights from an ideal-observer model of reading. *Vision Research*, 42, 2219–2234.
- Legge, G. E., Klitz, T. S., & Tjan, B. S. (1997). Mr. Chips: An ideal-observer model of reading. *Psychological Review*, 104, 524–553.
- Legge, G. E., Mansfield, J. S., & Chung, S. T. (2001). Psychophysics of reading: XX. Linking letter recognition to reading speed in central and peripheral vision. *Vision Research*, 41, 725–743.
- Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading: I. Normal vision. *Vision Research*, 25, 239–252.
- Legge, G. E., Rubin, G. S., & Luebker, A. (1987). Psychophysics of reading: V. The role of contrast in normal vision. *Vision Research*, 27, 1165–1177.
- Legros, L., & Grant, J. (1916). *Typographical printing-surfaces*. London: Longmans, Green & Co.
- Linotype (1940). *Specimen book Linotype faces*. Brooklyn, NY: Mergenthaler Linotype.
- Linotype (n.d.). *Corona*. Brooklyn, NY: Mergenthaler Linotype.
- Livingstone, M. S. (2000). Is it warm? Is it real? Or just low spatial frequency? *Science*, 290, 1299.
- Majaj, N., Pelli, D. G., Kurshan, P., & Palomares, M. (2002). The role of spatial frequency channels in letter identification. *Vision Research*, 42, 1165–1184.
- 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/non-invasive assessment of the visual system: Summaries, Technical digest series* (vol. 3, pp. 232–235). Washington, DC: Optical Society of America.

- Mansfield, J. S., & Legge, G. E. (2007). The MNREAD acuity chart. In *Legge, G.E.: Psychophysics of reading in normal and low vision*. Mahwah, NJ and London: Lawrence Erlbaum Associates.
- 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.
- Microsoft (1995). TrueType fundamentals. In *TrueType 1.0 Font Files Technical Specification, Revision 1.66, August 1995* (pp. 3–27). Redmond, WA: Microsoft. <http://www.microsoft.com/typography/SpecificationsOverview.mspx>.
- Noordzij, G. (2005). *The stroke theory of writing* (P. Enneson, Trans.). London: Hyphen Press.
- O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395–453). New York: Elsevier.
- Oruç, I., & Landy, M. S. (2009). Scale dependence and channel switching in letter identification. *Journal of Vision*, *9*(9):4, 1–19, <http://www.journalofvision.org/content/9/9/4>, doi:10.1167/9.9.4. [PubMed] [Article]
- Parish, D. H., & Sperling, G. (1991). Object spatial frequencies, retinal spatial frequencies, and the efficiency of letter discrimination. *Vision Research*, *31*, 1399–1415.
- Pelli, D. G. (1999). Close encounters—An artist shows that size affects shape. *Science*, *285*, 844–846.
- 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, <http://www.journalofvision.org/content/7/2/20>, doi:10.1167/7.2.20. [PubMed] [Article]
- Radner, W., Willinger, U., Obermayer, W., Mudrich, C., Velikay-Parel, M., & Eisenwort, B. (1998). A new reading chart for simultaneous determination of reading vision and reading speed. *Klin Monbl Augenheilkd*, *213*, 174–181.
- Rubin, G. S., & Turano, K. (1992). Reading without saccadic eye movements. *Vision Research*, *32*, 895–902.
- Schade, O. H. (1956). Optical and photoelectric analog of the eye. *Journal of the Optical Society of America*, *46*, 721–739.
- Sheedy, J., Subbaram, M., Zimmerman, A., & Hayes, J. (2005). Text legibility and the letter superiority effect. *Human Factors*, *47*, 797–815.
- Shieh, K. K., & Lee, D. S. (2007). Preferred viewing distance and screen angle of electronic paper displays. *Applied Ergonomics*, *38*, 601–608.
- Sloan, L. L. (1977). *Reading aids for the partially sighted: A systematic classification and procedure for prescribing*. Baltimore, MD: Williams & Wilkins.
- Sloan, L. L., & Brown, D. J. (1963). Reading cards for selection of optical aids for the partially sighted. *American Journal of Ophthalmology*, *55*, 1187–1199.
- Solomon, J. A., & Pelli, D. G. (1994). The visual filter mediating letter identification. *Nature*, *369*, 395–397.
- Tinker, M. A. (1963). *Legibility of print*. Ames, IA: Iowa State University Press.
- Ullman, B. L. (1960). *The origin and development of humanistic script*. Rome: Edizioni di Storia e Letteratura.
- Uddike, D. (1937). *Printing types: Their history, forms, and use* (vol. I). Cambridge, MA: Harvard University Press.
- Vervliet, H. D. L. (2008). *The palaeotypography of the French renaissance*. Leiden, The Netherlands: Brill.
- Vervliet, H. D. L. (2010). *French renaissance printing types: A conspectus*. New Castle, DE: Oak Knoll Press.
- Wade, N. J. (2007). Image, eye, and retina (invited review). *Journal of the Optical Society of America A: Optics, Image Science, and Vision*, *24*, 1229–1249.
- Whittaker, S. G., & Lovie-Kitchin, J. (1993). Visual requirements for reading. *Optometry and Vision Science*, *70*, 54–65.
- WHO (2004). *Fact sheet: Vision 2020: The right to sight, the global initiative for the elimination of avoidable blindness*. Downloaded from <http://vision2020.org>.
- WHO (2006). *Sight test and glasses could dramatically improve the lives of 150 million people with poor vision*. Downloaded from <http://vision2020.org>.
- Williamson, H. (1966). *Methods of book design*. Oxford, UK: Oxford University Press.
- Woodworth, R. S. (1938). *Experimental psychology*. New York: Henry Holt and Company.
- Yu, D., Cheung, S. H., Legge, G. E., & Chung, S. T. (2007). Effect of letter spacing on visual span and reading speed. *Journal of Vision*, *7*(2):2, 1–10, <http://www.journalofvision.org/content/7/2/2>, doi:10.1167/7.2.2. [PubMed] [Article]
- Yu, D., Park, H., Gerold, D., & Legge, G. E. (2010). Comparing reading speed for horizontal and vertical English text. *Journal of Vision*, *10*(2):21, 1–17, <http://www.journalofvision.org/content/10/2/21>, doi:10.1167/10.2.21. [PubMed] [Article]