Taylor & Francis
health**sciences**

Adjustable typography: an approach to enhancing low vision text accessibility

Aries Arditi*

Lighthouse International, New York, NY, USA

Millions of people have low vision, a disability condition caused by uncorrectable or partially correctable disorders of the eye. The primary goal of low vision rehabilitation is increasing access to printed material. This paper describes how adjustable typography, a computer graphic approach to enhancing text accessibility, can play a role in this process, by allowing visually-impaired users to customize fonts to maximize legibility according to their own visual needs. Prototype software and initial testing of the concept is described. The results show that visually-impaired users tend to produce a variety of very distinct fonts, and that the adjustment process results in greatly enhanced legibility. But this initial testing has not yet demonstrated increases in legibility over and above the legibility of highly legible standard fonts such as Times New Roman.

1. Introduction

Visual impairment, and in particular, low vision, are highly prevalent and potentially disabling conditions. Estimates of the size of the vision-impaired population vary with criteria used to define impairment (American Foundation for the Blind 1989), but, for the US, range between 10 million (National Advisory Eye Council 1983) and 14 million (Lighthouse International 1995). Since the leading causes of visual impairment (age-related maculopathy, cataract, glaucoma, diabetic retinopathy, and optic nerve atrophy) are diseases of old age, the bulk of the visually-impaired population is older. Only a very small portion of this group is functionally blind (i.e. has no pattern vision)—about 220,000, based on statistics cited by the American Foundation for the Blind (1989)—the vast majority of visually-impaired people have significant remaining vision, a condition known as low vision.

Reading difficulties are well-known to be among the most disabling functional problems experienced by those with age-related vision loss, and providing renewed access to text after vision loss is the cornerstone of most vision rehabilitation (Faye 1984). Successful rehabilitation primarily involves enhancement and exploitation of whatever usable visual function remains. The most direct method for enhancing vision is magnification, which, for a wide range of impairments, is usually accomplished by optical or, in the case of video magnifiers (also known as closed-circuit television systems or CCTVs), opto-electronic means.

---

*Author for correspondence: Arlene R Gordon Research Institute, Lighthouse International, 111 East 59th Street, New York, NY 10022-1202

High levels of magnification are not without problems, however. A serious drawback that must always be considered with respect to reading magnifiers is the size of the usable field. As magnification increases, the number of letters in the reading field decreases, which can reduce reading speed. When reading is extremely slow, comprehension may also be reduced. Thus in low vision, it is desirable to provide only the minimum magnification that results in comfortable reading. Enhancing legibility with typographic manipulations can reduce magnification requirements, allowing a larger reading field and hence more efficient reading.

There is a good deal of evidence from psychophysical experiments that typography can significantly impact what is known as *reading acuity*, the minimum size of print that can be read both in normal and low vision (reviewed in Tinker 1963 and Arditi 1996). Conversely, one can also use an observer's reading acuity as a yardstick of legibility by comparing acuity for different fonts within the same observer.

Indeed, reading acuity and equivalently, maximum reading distance, forms the basis for the most commonly used measure of legibility (Tinker 1963). Using this and other methods, many scientific studies and less formal investigations within the print and graphic design communities have found significant effects of font typography on legibility (McLean 1980; Rubinstein 1988; Mansfield *et al.* 1996). Specifically, the results have shown that font characteristics including stroke width (Arditi *et al.* 1995a; Berger 1944a,b), aspect ratio (Arditi *et al.* 1995b; Berger 1948; Soar 1955), inter-letter spacing (Arditi *et al.* 1995b; Arditi *et al.* 1997; Moriarty and Scheiner 1984; Whitaker *et al.* 1989), and the presence or absence of serifs (Arditi and Cho 2000), have some impact on text legibility.

Psychophysical data from our laboratory that have systematically varied one or two font parameters have found legibility differences between some fonts using the acuity criterion of legibility to be (reliably) as great as 0.2 log units, corresponding to a type size difference of about 58%. It is such data that motivated the question of whether enhancement of reading acuity would result from allowing users to adjust font parameters for best legibility.

Reading speed is another commonly used criterion for legibility, but is inherently noisy due to variations in word difficultly, context effects, etc. The only published quantitative data comparing low vision reading speeds for different fonts appear to be those of Mansfield *et al.* (1996), who found reading speeds to be 10% slower with Adobe Times Roman than with Adobe Courier (for normal participants, Times Roman provided the speed advantage by only 5%). Acuity differences between the fonts were much larger – 23% for participants with low vision. Other unpublished data from our laboratory show no significant differences in low vision reading speeds among four fonts, even between fonts which differ in acuity legibility by nearly a factor of two. Thus while we know that manipulating font parameters significantly affects reading acuity, gains in reading speed for low vision can be expected to be, at best, modest.

Illegible typography, however, is a continual complaint from people with low vision, and anything that can improve legibility may be beneficial. Given the steepness of the function relating reading speed to print size in the vicinity of the acuity limit, a small legibility enhancement could make the difference between not being able to read at all and reading effectively, albeit slowly. The work described here tests the feasibility of a prototype parametric font program that we call Font Tailor, that allows a person with impaired vision to customize a font (beyond merely increasing its size) for her own visual needs in real time, and thereby maximize

legibility and access to text. There have been other attempts to develop fonts for low vision (e.g. Silver *et al*. 2000, American Printing House for the Blind 2001), but none have been adjustable.

A parametric font is one in which global properties of the font as a whole may be altered by specifying suitable values of variables that affect the font as a whole, such as stroke width or serif size. The concept behind such fonts—and the Font Tailor program—has its roots in Donald Knuth's (1986) notion of a meta-font—a computer program to mathematically describe a font whose individual parameters can be adjusted, and from which an infinite variety of fonts may be generated. Font Tailor is a simple meta-font, whose only adjustment parameters are ones thought to affect legibility. Real-time interactive animation allows a user to continuously observe legibility changes as font parameters are manipulated. Thus, using sliders and controls analogous to the interface shown at the bottom of figure 1, visually impaired users can, while viewing text, make adjustments to produce a font that is most legible to them given their particular functional condition. This may be particularly important in eye diseases where functional condition can change from day to day, such as diabetic retinopathy and the exudative form of macular degeneration.

The parameters that can be adjusted by Font Tailor are cap height, stroke width, letter aspect ratio, serif size, x-height, inter-letter spacing, descent, leading and fixed vs. proportional spacing. Most of these are illustrated in figure 2. An important feature of the program is that users may build *their* most legible font into the operating system, by allowing the adjusted font to be saved as a TrueType font. Given the very frequent complaints people with mild and moderate visual impairments make about typography, we believe this ability to tailor text and conveniently install it for use within the operating system could be especially useful. Versions of this technology can also, of course, be built into other applications software or dedicated machines designed to vary text presentation mode.

The Font Tailor prototype software was written in Microsoft Visual C++ and accomplishes the central goals of the project concept, in that it renders text in real-time based on adjusted font parameter values, and is capable of saving the user's creations as TrueType font files. Font Tailor was developed solely for the experiments described here, and is not generally available.

Figure 1 is the opening screen from the Font Tailor prototype. The font displayed is the default one that is displayed when Font Tailor begins. The Latin-like words on the screen are from a paragraph often used by type and graphic designers when they want to assess the look of a text sample without being distracted by its content. For the same reason, we used this passage while participants were adjusting the font for best legibility (described below). The user can type in whatever text sample is desired into the text box on the dialogue box, or can read it in from a file. The user may also operate the sliders in the dialogue box or type values in their companion text boxes, to adjust font parameters.

When any parameter from the dialogue box is updated, the entire display is redrawn. For quicker display updating, only characters that are in the text sample box are generated. Note that the letters drawn in the main window of figure 1 are not actually outline fonts—they are merely rendered drawings of letters, that make use of similar information as an outline font. Font files are constructed and written only after the user requests them. The font glyphs we coded for this prototype are the
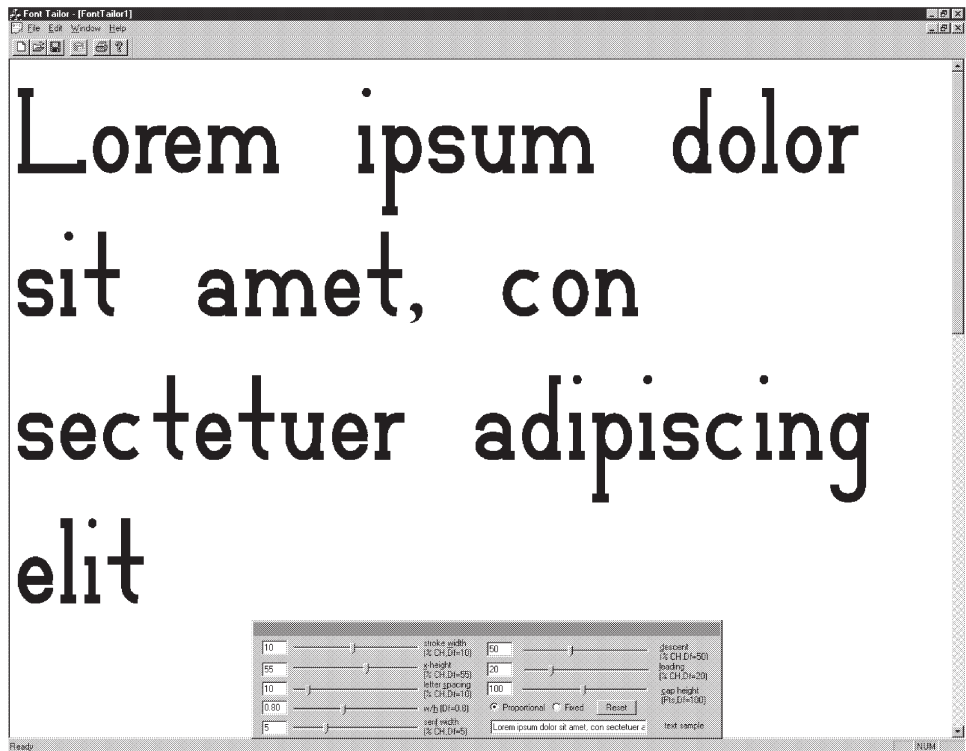
Figure 1. Font Tailor's main screen, showing its font adjustment dialogue box, which
contains slider controls, text boxes and buttons for font specification. Shown in the main
window is Font Tailor's default font.

upper and lower-case letters, and a few punctuation characters needed for our
reading experiments—roughly half the ASCII set.

An unanticipated benefit of having the Font Tailor prototype, unrelated to the
specific project, is that we now also have a handy tool to use in controlled
psychophysical studies of the effects of typography on legibility. Our previous work
with METAFONT had limited us to upper-case letters, most of which lack serifs,
descenders and other font characteristics. Now we have the ability to parametrically
vary a complete upper- and lower-case font. We are now using Font Tailor to
generate fonts for our laboratory experiments on legibility.

Besides developing proof-of-concept software, we wanted to test the idea that
tailoring fonts is a useful capability, i.e. that *different* font parameters will result in
maximum legibility for persons with *different* visual problems (quite literally
'different strokes for different folks'); and to compare legibility of tailored fonts with
de facto standard fonts using a reading acuity criterion of legibility, and within the
same group of participants.

We addressed the feasibility of the Font Tailor concept, by assessing the amount
of variability among participants in font parameter adjustment, the amount of
legibility enhancement that resulted from font customization, and performance using
customized fonts as compared to an existing *de facto* standard commercial font. We
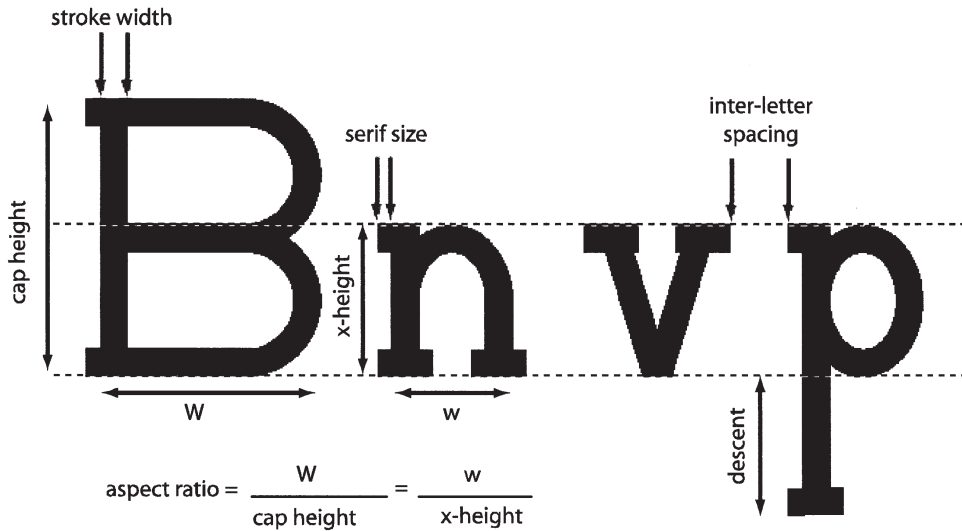used reading acuity as our legibility criterion, because it is easy to measure quickly,

Figure 2. Key font parameters. Cap height determines the overall size; point size, which is generally defined as the cap height + descent, was 1.5 * cap height for the fonts used in the study. In the Font Tailor program inter-letter spacing, stroke width, x-height, and serif size are expressed as a percentage of cap height. When aspect (width to height) ratio is 1, arcs used in letters with rounded features such as (o or n) are circular; additionally, the box enclosing all upper-case letters (excepting I) and many lower-case letters (e.g. x, o) is square. Aspect ratio shown is 0.8. Parameters that are adjustable within Font Tailor are shown in red.

and because we know of no instance in which legibility measured by this method consistently disagrees with that measured by other methods. Reading acuity is a trusted method that has a long history of use (see Tinker 1963), and is implicit in viewing distance metrics of legibility used, for example, for highway signage.

2. Methods

2.1. *Research participants*

Our participants were 40 individuals who had received recent services from Lighthouse International's low vision service, and were recruited first, by screening the Lighthouse Consumer Information database, and then by telephone. Typical of the low vision population, participants were predominantly older, with a mean age of 68.6 (median 73.5) years. Inclusion criteria were simple: the participant had to have presented at their low vision exam with a reading difficulty, had to have best-corrected acuity worse than normal by 0.3 log units (i.e. 20/40 or worse), and had to be willing to attend the test session. Characteristics of the sample are shown in table 1. It is important to appreciate that testing with an older, visually-impaired population who were recruited from a clinical service, required making some adjustments relative to a younger and healthier sample. It was simply not feasible to test over several sessions, nor for an extended period of time, nor with a large number of experimental trials. We made adjustments that would allow us to complete the study within a single experimental session.

A. Arditi

Table 1. Participant characteristics.

Participant	Age	Primary diagnosis	Log MAR	Snellen
BD	80	Maculopathy	0.72	20/105
SH	75	Maculopathy	1.14	20/276
SM	77	Maculopathy	0.60	20/80
LG	83	Maculopathy	1.10	20/252
RM	92	Maculopathy	0.92	20/166
CP	82	Maculopathy	1.00	20/200
IL	78	Maculopathy	1.00	20/200
MG	76	Maculopathy	1.00	20/200
RD	52	Maculopathy	0.90	20/159
BK	89	Maculopathy	0.72	20/105
PP	81	Maculopathy	0.82	20/132
DB2	78	Maculopathy	1.10	20/252
EG	50	Maculopathy	1.12	20/264
OL	32	Cataract	0.92	20/166
CD	80	Cataract	0.64	20/87
RD2	83	Cataract	0.84	20/138
MR	84	Cataract	0.80	20/126
HC	69	Glaucoma	0.50	20/63
RK	58	Glaucoma	0.80	20/126
MS3	84	Glaucoma	0.80	20/126
ED	75	Glaucoma	0.80	20/126
DB1	67	Glaucoma	0.82	20/132
HG	66	Glaucoma	1.34	20/438
MW	61	Glaucoma	1.20	20/317
MM	76	Diabetic retinopathy	0.70	20/100
EH1	64	Diabetic retinopathy	1.04	20/219
IR	72	Diabetic retinopathy	0.92	20/166
NR	77	Retinal vessel occlusion	1.00	20/200
CH	76	Macular edema	1.10	20/252
HL	70	Central vein occlusion	0.90	20/159
AS	63	Myopic maculopathy	1.12	20/264
SL	71	Degenerative myopia	1.50	20/632
AG	68	Degenerative myopia	1.00	20/200
OA	49	Foveal scar	1.24	20/348
WN	51	Retinal detachment	0.90	20/159
MS1	56	Corneal transplant	0.80	20/126
EH2	41	Multiple retinal surgeries	0.96	20/182
MS2	52	Uveitis	1.10	20/252
DG	75	Optic atrophy	0.68	20/96
JE	29	Achromatopsia	1.00	20/200

Log MAR acuity refers to the log of the minimum angle of resolution (MAR) and can be conveniently thought of as the log of the ratio of the smallest letter size that could be read by a participant to the smallest size that can be read by a person with normal vision. Thus a log MAR of 0 is normal vision; a log MAR of 1 indicates that the participant requires letters 10 times that required by a normally sighted observer. The Snellen fraction, a more common unit of visual function is the same ratio (but not logarithmically transformed), expressed with 20 in the numerator (because, historically, standard testing was conducted with a 20 ft viewing distance).

2.2. Stimuli

The font adjustment and reading acuity testing with customized fonts used the Font Tailor program, and a 19 inch display monitor centered at eye height (the participant was seated), viewed from a distance at which the default font (cap height 38 mm;

font size 162 point) could be read comfortably. The text on the display was made up of black letters (1.3 cd/m^2) on a white (115 cd/m^2) background. The experimenter manipulated the font controls, using the computer mouse and keyboard shortcuts.

There are four font parameters in Font Tailor that were not used in the feasibility experiments: cap height, descent, leading and fixed vs. proportional spacing. Cap height was not varied because it was used as the dependent (i.e. measurement) variable. We believed that descent and leading would have only a minimal impact on legibility and would complicate the data analysis. It has previously been shown that fixed vs. proportional spacing has a strong impact on legibility, but that is due to differences in average letter spacing (Arditi, Knoblauch and Grunwald 1990), which is an adjustable parameter in the experiment. All font parameters that were used in the experiment, except aspect ratio, were defined as a percentage of cap height – the height of an upper-case letter.

2.3. *Procedure*
At the test session, participants were told that we were evaluating the promise of an adjustable font technology for enhancing readability of text for people with vision-impairment. After reading or being read, and signing the informed consent form, each participant was introduced to the Font Tailor program and the idea that fonts could be varied parametrically. Then the following four measurements were made, in order.

2.4. *Font parameter adjustment*
Participants began the font adjustment procedure while viewing the default Font Tailor screen (see figure 1). First, participants were seated 30 inches from the monitor, at which the default Font Tailor font cap height subtended 2.85 deg arc. If letters were not comfortably legible at this distance, they were moved closer to the screen. All but four of the participants were tested at the 30 inch distance; one participant required a distance of 10 inches, and 8.51 deg cap height. Then baseline reading acuity for the default Font Tailor font was assessed using a modified method of adjustment, in which the experimenter gradually (through keystroke shortcuts for the parameter sliders) reduced or increased the font size until the participant reported that the letters could just be made out clearly enough to identify.

For each of the font parameters, text samples with text printed in large print on paper, using fonts that exemplify high and low values of the parameter to be tested were shown to the participants prior to adjustment, to insure that they fully understood how the parameter manipulation affected the font. After each example was shown, the participant then viewed the screen, and verbally guided the experimenter to manipulate the parameter by indicating 'up' or 'down', with the aim of maximizing the subjective legibility of the text sample on the screen.

For each parameter, when satisfied that the font was maximally legible, the experimenter then repeated the reading acuity measurement using this newly modified font, until the participant achieved the same subjective level of clarity that they had experienced with the default font at threshold. This was repeated for each of the font parameters tested. Parameters were tested in the same order each time: 1, letter spacing; 2, stroke width; 3, serif size; 4, x-height; 5, aspect ratio.

After the sequence was completed, the experimenter then rechecked each parameter insuring that the the participant was satisfied with the adjustment. The participant had the option of making changes to the font at this time. Since

participants sometimes altered their viewing distance slightly while making adjustments, the final viewing distance was measured once again, and recorded for reading acuity computations.

2.5. *Reading acuity with Times New Roman*

Next we measured reading acuity with TrueType Times New Roman, a popular font that exists on virtually all Windows computers and is distributed with the operating system, and as such is a *de facto* standard. This was done by asking the participant to walk (or roll their chairs) backwards from the monitor while viewing a sample of text set in Times New Roman, until it was, in their judgement, as readable as the final adjusted Font Tailor font. For this judgement, font size on the monitor was initially set to a nominal 18 point size, but if too small, was incremented in 18 point steps, until the participant could see the letters clearly at an easily measurable viewing distance. Viewing distances ranged from 7 to 40 inches; font sizes varied from 18 to 72 nominal points.

After the above measurements were made, participants' single letter visual acuities was measured with a traditional clinical chart, using letter-by-letter scoring of a Lighthouse/ETDRS chart transilluminated by a Lighthouse transilluminator.

3. Results and Discussion

3.1. *Font parameter adjustment*

Figures 3 and 4 contains box plots showing key features of the distributions of adjustments for the 40 participants. Figure 3 shows the box plots for all parameters that are expressed as a percentage of cap height, while figure 4 shows the same for aspect ratio, the one parameter that is in dimensionless units.

The most striking thing about these graphs is their variability. Participants varied widely in the font that produced the most legible text, and this diversity supports a basic premise of this project: that participants have different needs in terms of font characteristics. Of course, variability alone does not indicate useful diversity of adjustments. However, all participants' reading acuities improved with the adjusted font. These data suggest that it is unlikely that there is one most legible font that will meet the needs of all.

Nevertheless, we were interested in what the *average* font adjusted by our participants looked like, since there are many situations in which one might wish to use a (non-adjustable) font that will work well for many people with low vision. This average font is shown in figure 5, and it is interesting for two reasons: First, since letter spacing is expanded, it supports the idea that people with low vision perform better with increased letter spacing, a result that is corroborated by a large number of empirical studies (reviewed in Arditi 1996). Second, the large width-to-height aspect ratio suggests that horizontal magnification alone may increase font legibility for people with low vision.

How much did each parameter adjustment contribute to legibility enhancement? Figure 6 shows the mean enhancement of legibility (using the visual acuity criterion) gained for each of our adjustable font parameters. Manipulation of inter-letter spacing had the largest impact on legibility (almost 20% smaller characters could be read than with the default font spacing), which as noted above, corroborates earlier findings.

Manipulation of x-height and aspect ratio also resulted in substantial gains in legibility. Both of these variables magnify the font. Increasing x-height increases the
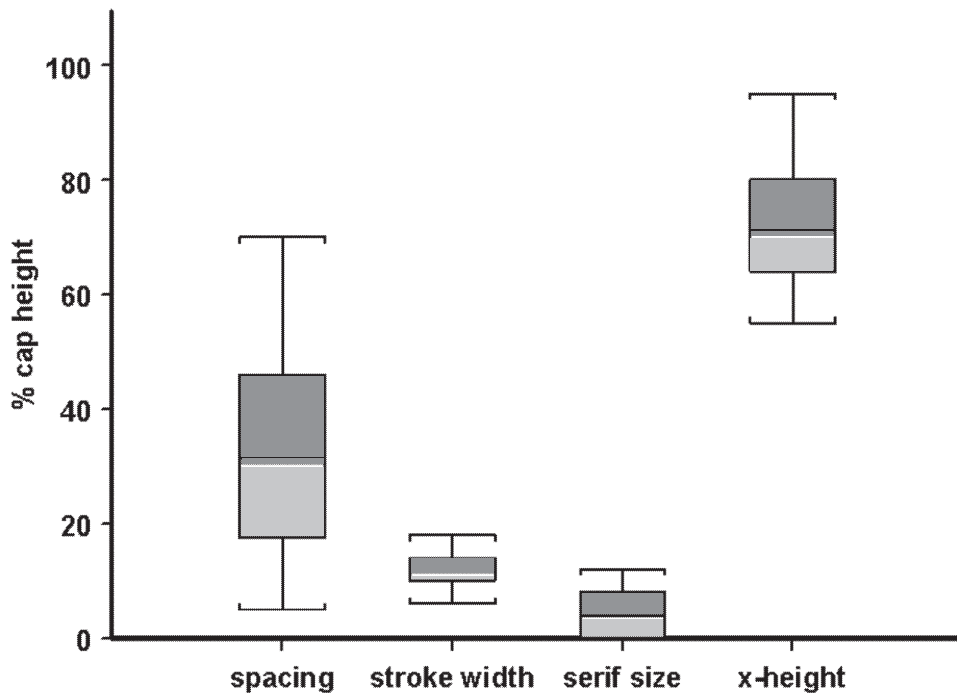
Figure 3. Box and whisker plots showing the distributions of all adjusted parameters whose value is expressed in % cap height, for the 40 participants. The extremes of the shaded boxes show the lower and upper quartiles of the distributions, while the white lines within the boxes denote the medians. The ranges of the distributions are also indicated by the lengths of the whiskers outside the box. For example, the distribution of adjusted letter spacings ranges between about 5 and 70% cap height, with 25% of the adjustments falling below 18.6, 50% falling below 30, and 75% falling below 44% cap height. The means are indicated by black lines within the interquartile boxes.

overall size of most lower-case letters, while increasing the aspect ratio increases only the horizontal extent of all letters (meridional magnification). Both these manipulations magnify without increasing the point size of the font, which, in digital typography is customarily defined as the sum of the cap height and the descent, i.e. the vertical space required to set successive lines of type with no intervening vertical space (leading). Increasing aspect ratio, however, significantly increases the amount of page 'real estate' that a given text sample takes up, and thus it may be more costly in page count and line count.

The smallest gain was seen for manipulation of serif size. This corroborates a finding from a separate experiment that we conducted to test the effect of serif size on legibility, which utilized fonts generated by Font Tailor. Results of this study (Arditi and Cho 2000), indicated that serifs provide a very modest legibility enhancement that can be wholly accounted for by the increased centre-to-centre letter spacing that arises from the addition of serifs at the base of many letters (e.g. m, n and i).

Perhaps the most significant finding from this experiment, however, is that the total legibility gain, from all adjustments, averaged 75%. Thus, while each
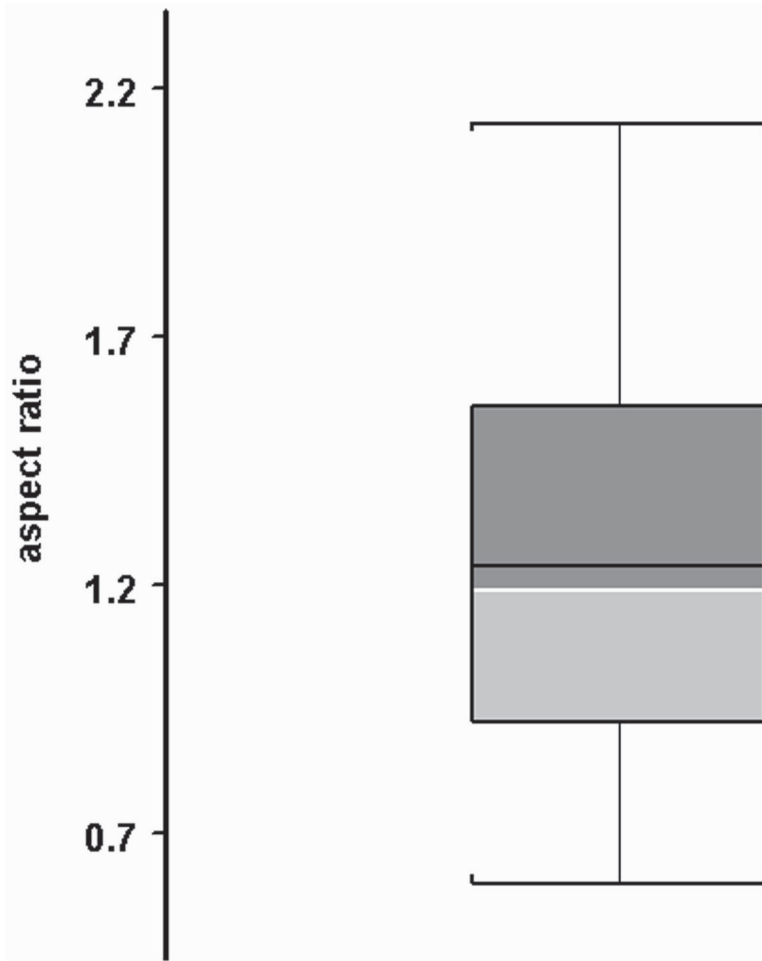
Figure 4. Box and whisker plot showing the distribution of adjusted aspect ratios for the 40 participants.

adjustment has a relatively modest enhancement effect, the compounded value of these enhancements is quite substantial.

3.2. *Reading acuity with Times New Roman*
Figure 7 shows threshold letter sizes in degrees for the adjusted Font Tailor font and Times New Roman. The regression line shown is a least trimmed squares line. The latter is a robust fit (i.e. relatively insensitive to outliers; Huber 1981), and has unity slope and a very small y-intercept. This graph shows that for a broad range of visual acuities, the adjusted font and Times New Roman are of almost identical legibility. The data do not indicate that the adjustable font yields better legibility than Times New Roman, but it is clear that even this first attempt at adjustable typography produced fonts that rival in legibility one whose design has, through a kind of typographic natural selection, evolved through many design generations, and is one of the most popular fonts in existence today. We are hopeful that as we develop

Figure 5.   The font that is the average (arithmetic mean) of all parameters adjusted by our 40 participants.
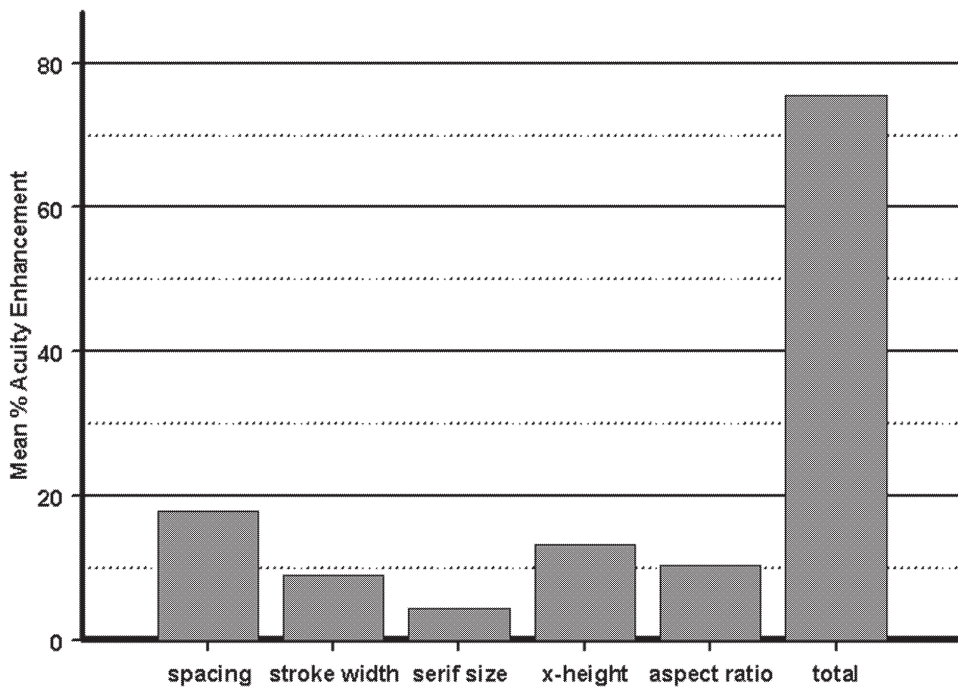

Figure 6.   Legibility (acuity) enhancement of each of the adjusted Font Tailor parameters. Each individual parameter adjustment contributed a small degree of enhanced legibility, but with adjustment of all parameters, a 75% enhancement was achieved.

better protocols and procedures for guiding our users through the adjustment process, we will be able to achieve even better legibility.
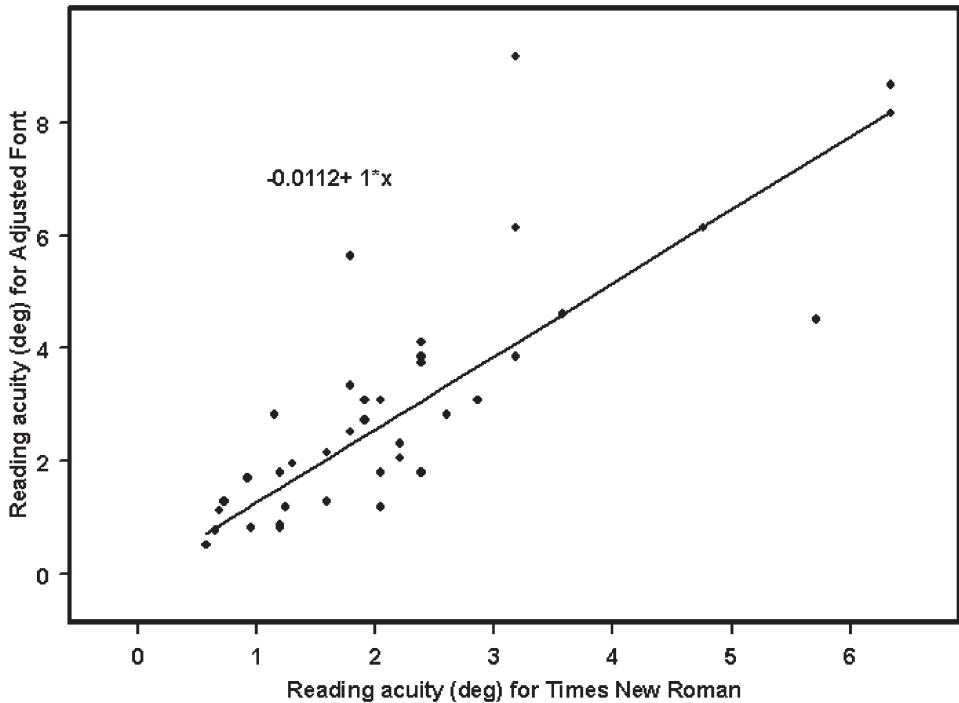
Figure 7.   Threshold letter size, in degrees, for the adjusted font vs. Times New Roman. The
        fitted line is a robust linear least trimmed squares line, along with corresponding
        regression equation.

It is important to stress that the user interface we have built into this prototype version of Font Tailor meets the needs of our feasibility tests, but is otherwise completely unsuitable for use by a person with a significant visual impairment. The text and controls are too small, and many important elements of the controls have insufficient contrast. Most people with low vision would have great difficulty operating the program in its current state for these reasons; a more intelligent interface would guide the user through a font customization protocol via voice output.

It is also important to note that Font Tailor is not intended to be, nor is, a font design tool for graphic professionals. There are many things that it cannot do. For example, it is currently capable of producing only 'slab' style serifs, even though hairline, wedge, bracketed, and pen nib serifs are also popular. It is incapable of producing fonts with strokes that vary in width (what the typographer often calls 'stroke contrast'). It does not produce slanted, italic, or cursive letters, nor letters with ornaments. The font designer has available many tools that are capable of producing such font characteristics, including Fontographer, Intellifont, Font Edit, and others. This program is equipped in spartan fashion with only font parameters thought to have an impact on legibility.

Finally, we note that nearly all of our participants expressed interest in Font Tailor, and based on their brief experience with the program, believed it would be a useful addition to their arsenal of reading aids.

4. Conclusion

The most significant limitation experienced by the large and growing number of older visually impaired individuals is reduced ability to read. This in turn reduces independence, productivity, privacy, and opportunities for intellectual stimulation. While many elders still shun computers and other electronic devices, the older generation is increasingly made up of individuals who are comfortable with, and indeed depend on computer displays for much of their reading (Morrell, 2002).

It has been proposed that allowing visually-impaired users to tailor typography to their own needs with a computer graphic tool, has the potential for enhancing text access, especially on computers. Initial testing of the tool produced mixed results. On one hand, it showed that visually-impaired users tend to produce a variety of very distinct fonts, and that the adjustment process resulted in greatly enhanced legibility. On the other hand, these early studies have not yet demonstrated that legibility may be enhanced relative to highly legible fonts such as Times New Roman, that have evolved over the long history of type.

Nevertheless, these initial results are promising, and suggest that adjustable type may find its way into the growing number of computer-based tools for enhancing visual performance for people with low vision.

References

AMERICAN FOUNDATION FOR THE BLIND 1989, *Prevalence estimates of blindness and low vision in the United States—Late 1980s* (Unpublished report prepared by Social Research Department).

AMERICAN PRINTING HOUSE FOR THE BLIND 2001, APHFont: A font for low vision. http://www.aph.org/products/aphont.html

ARDITI, A. 1996, Typography, print legibility and low vision, in B. Rosenthal and R. Cole (eds), *Remediation and Management of Low Vision* (St. Louis, MO: Mosby).

ARDITI, A., CAGENELLO, R. and JACOBS, B. 1995a, Letter stroke width, spacing, and legibility, in *Noninvasive Assessment of the Visual System Technical Digest* (Washington, DC: Optical Society of America).

ARDITI, A., CAGENELLO, R. and JACOBS, B. 1995b, Effects of aspect ratio and spacing on legibility of small letters, *Supplement to Investigative Ophthalmology and Visual Science*, **36,** 671.

ARDITI, A. and CHO, J. 2000, Do serifs enhance or diminish text legibility?, *Investigative Opthalmology and Visual Science*, **41(suppl.),** S437.

ARDITI, A., KNOBLAUCH, K. and GRUNWALD, I. 1990, Reading with fixed and variable character pitch, *Journal of the Optical Society of America*, **7,** 2011–2015.

ARDITI, A., LIU, L. and LYNN, W. 1997, Legibility of outline and solid fonts with wide and narrow spacing, in D. Yager (ed.), *Trends in Optics and Photonics* (Washington, DC, Optical Society of America).

BERGER, C. 1944a, Stroke-width, form and horizontal spacing of numerals as determinants of the threshold of recognition I, *Journal of Applied Psychology*, **28,** 208–231.

BERGER, C. 1944b, Stroke-width, form and horizontal spacing of numerals as determinants of the threshold of recognition II, *Journal of Applied Psychology*, **28,** 336–346.

BERGER, C. 1948, Experiments on the legibility of symbols of different width and height, *Acta Ophthalmologica*, **26,** 423–434.

FAYE, E. E. 1984, *Clinical low vision*, 2nd edn. (Toronto, Canada: Little, Brown and Co).

Ferris, F. L., Kassoff, A., Bresnick, G. H. and Bailey, I. L. 1982, New visual acuity charts for clinical research, *American Journal of Ophthalmology*, **94,** 92 – 96.

Huber, P. J. 1981, *Robust statistics* (New York: John Wiley and Sons).

Knuth, D. E. 1986, *The METAFont Book* (Boston: American Mathematical Society, Addison-Wesley).

Lighthouse International 1995, *The Lighthouse National Survey on Vision Loss: The experience, attitudes and knowledge of middle-aged and older Americans* (New York: The Lighthouse Inc).

Mansfield, J. S., Legge, G. E. and Bane, M. C. 1996, Psychophysics of reading: XV: Font effects in normal and low vision, *Investigative Ophthalmology and Visual Science*, **378,** 1492 – 1501.

Moriarty, S. E. and Scheiner, E. C. 1984, A study of close-set text type, *Journal of Applied Psychology*, **69,** 700 – 702.

Mclean, R. 1980, *Thames & Hudson Manual of Typography* (London: Thames and Hudson).

Morrell, R. W. (ed.) 2002, *Older adults, health information, and the world wide web* (Mahwah, NJ: Erlbaum).

National Advisory Eye Council 1983, *Vision Research: A National Plan 1983 – 1987,* Vol. 1, (NIH Publication No. 83-2469) (Washington, DC: US Government Printing Office).

Rubinstein, R. 1988, *Digital Typography: An introduction to type and composition for computer system design* (Boston, MA: Addison Wesley).

Silver, J., Gill, J., Sharville, C., Slater, J. and Martin, M. 2000, A new font for digital television subtitles. http://www.tiresias.org/fonts/designreportsf.htm

Soar, R. S. 1955, Height-width proportion and stroke width in numerical visibility, *Journal of Applied Psychology*, **39,** 43 – 46.

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

Whittaker, S., Rohrkaste, F. and Higgins, K. E. 1989, Optimum letter spacing for word recognition in central and eccentric fields, *Noninvasive Assessment of the Visual System, Technical Digest Series 7* (Washington, DC: Optical Society of America), 56 – 59.