Low Vision
A.C. Kooijman et al. (Eds.)
IOS Press, 1994

On the Relationship between Letter Acuity and Reading Acuity

Aries ARDITI
Vision Research Laboratory, The Lighthouse Research Institute
*800 Second Avenue, New York, NY 10017, USA**

Abstract. Despite the elemental relationship of letters to written words, letter acuity is well-known to be a poor predictor of several indices of reading performance. This is why direct measurement of reading acuity is necessary in prescription of effective reading aids in low vision rehabilitation.

This paper presents a) a general discussion of differences between reading and letter acuity stimuli, and cognitive demands in the two acuity tasks, that may account for the poor power of acuity for single letters to predict reading performance, and b) an outline of a sensor model of text processing that can account for text and optotype crowding phenomena. The model has a linear filtering stage consisting of an array of sensors localized in space and spatial frequency that produce parallel bandpass representations of the text stimulus, and a decision stage consisting of a letter template-matcher and an attentional mechanism that selects the bandpass representations on which to perform the match. It is suggested that crowding effects at the acuity limit occur because neighboring letters or contour elements effectively add noise that falls within the the receptive fields and pass bands of sensors processing the letter.

1. Introduction

Acuity refers to the smallest stimulus size at which a visual task may be successfully performed. Letter acuity, which is measured clinically with a Snellen chart, is usually used as a measure of the resolving capacity of the eye, whereas reading acuity, measured clinically using reading cards and ordinary reading materials, is more often used for functional diagnosis and prescription of reading aids to individuals with low vision. Both kinds of acuity involve identifying letter symbols, and at the smallest sizes, both seem to involve identifying them for the most part at the level of letter units, rather than word or phrase units. While whole word and phrase recognition may play some role in reading acuity, identification of individual letters is clearly necessary for reading and is a sufficient condition for at least slow reading. Because letter recognition is so important in both acuity tasks, it would seem that the two should be highly related. Because so many people with low vision must read by identifying one letter at a time at, or close to, their acuity limit, one would think that especially for these people, the two acuities should be strongly linked. But many studies have shown letter acuity not to be a good predictor of reading performance[1, 2, 3, 4, 5, 6], and most low vision clinicians accordingly measure reading acuity directly for prescription of reading

---

*After July 1, 1994, The Lighthouse Research Institute will be located at 111 East 59 Street, New York, NY 10022, USA.

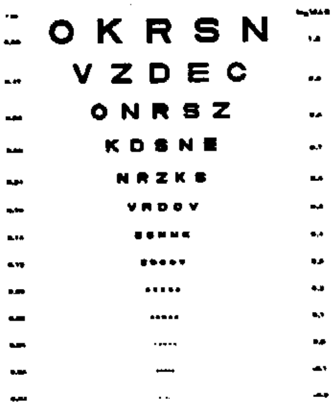
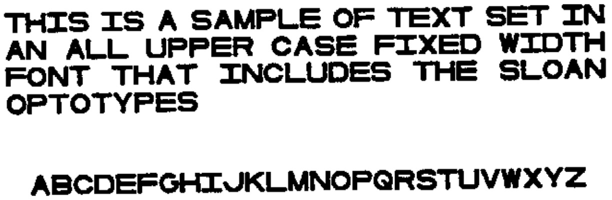


Figure 1: An acuity chart using Sloan letter optotypes.



THIS IS A SAMPLE OF TEXT SET IN
AN ALL UPPER CASE FIXED WIDTH
FONT THAT INCLUDES THE SLOAN
OPTOTYPES

ABCDEFGHIJKLMNOPQRSTUVWXYZ

Figure 2: Some text set in an optotype-like font that includes the Sloan optotypes, and whose non-Sloan letter forms emulate the Sloan design.

aids[6]. An understanding of the relationship between the two kinds of acuity can reduce clinical assessment time by allowing good prediction of reading function from conventional optotype acuity measurements; it can also contribute to our understanding of the factors that make text legible for both partially-sighted and normally sighted people.

2. Letter optotypes, letters, and words

In comparing Figure 1, an acuity chart, with nearly any sample of printed text such as the text of this paper, a number of important differences emerge:

size Optotype letter sizes and print text letter sizes are not directly comparable, although if one equates optotype height with upper-case letter height, print letters are generally smaller because of the greater prevalence of lower-case. Print letters, of course, vary widely in height between upper- and lower- case letters, and in letter width as well. Optotypes, on the other hand, are all the same size. Contrary to popular belief, the point size of a font only loosely specifies its size.

letter shapes Print fonts have more distinctive shapes and are thus more distinguishable from one another, at least in principle, whereas optotype letters are intentionally designed to look similar in all but their finest features. As can be seen in Figure 2 this uniformity tends to diminish their legibility relative to ordinary type.

contrast and illumination Optotype letters are almost always presented under good conditions of illumination and are printed in very high contrast. The same is generally not true of printed text.

isolation Optotype letters are usually presented in isolation, which enhances their legibility relative to the crowding of text characters on a printed line. Crowding is typically found

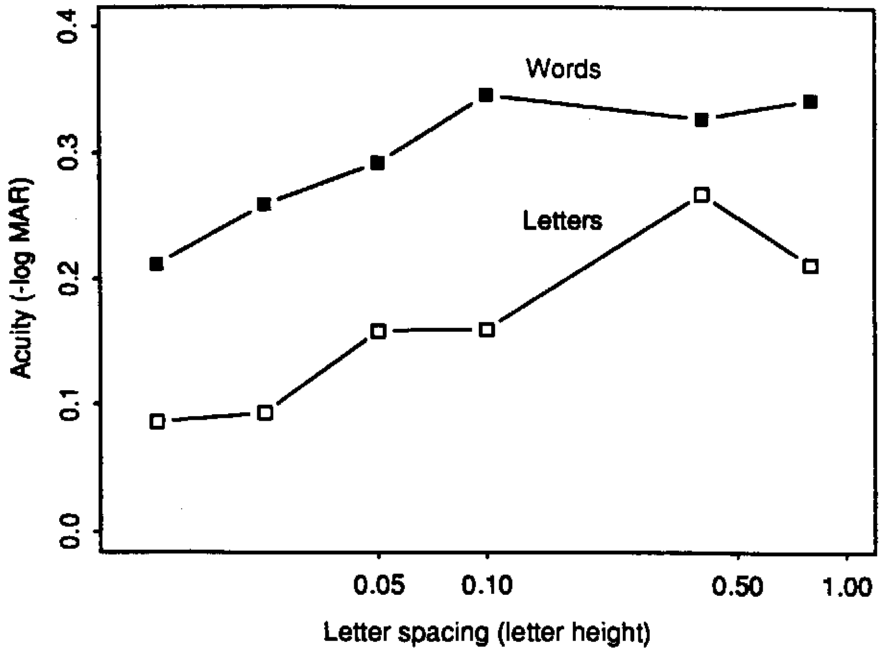


Figure 3: Acuity for 5-letter words vs. 5 random letters of displayed in the optotype-like font shown in Figure 2, as a function of lètter spacing.

to affect optotype acuity[7, 8, 9, 10, 11], but is also found with reading of ordinary text at the acuity limit[12]

cognitive factors There are many important differences between the two acuity tasks that can generally be called *cognitive factors*. First, ordinary text generally has meaning and produces mental associations whereas optotype letters are simply randomly chosen symbols. Second statistical properties of the stimuli are very different: with text, some letters are far more probable than others, and there are many frequently repeated sequences of letters. Finally, there are typically only ten optotypes on an acuity chart, whereas there are 52 upper- and lower-case letters and many more symbols in ordinary printed text.

Figure 3 shows how powerful such effects can be, even in what is typically thought of as a resolution task. The figure shows some typical acuity measurements (for one subject) Ron Cagenello and I made recently, using the optotype-like font shown in Figure 2. To remove word shape and length cues we used only 5-letter words, and compared acuity for these words to acuity for 5 randomly chosen letters. We removed context cues that can aid in word identification by using randomly chosen words, but obviously many cognitive cues remained. Since the words were the same length and made up of all upper-case letters, the subject was forced to perform the task letter-by-letter. We scored the tasks identically, giving credit for each correctly identified letter.

The resistance of meaningful units like words to image degradation seen in these data, have been known for nearly a century[13]. The data also show the effect of letter spacing, where at the smallest spacing, letters have only about 1% of their letter height between them; on the right side, space between the letters is 80% of the letter height. Acuity, of course, diminishes for very tightly spaced letters, by about 0.1 log minimum angle of resolution (MAR) unit, the equivalent of a line on many acuity charts. In these data, the superiority of words over letters here is about as strong as the superiority of widely spaced text over closely spaced text.

While we see that cognition is an important factor, it is one which we can do little about, in terms of ameliorating the effects of vision loss. Consequently, in the rest of the paper, we focus on stimulus factors, and in particular on the *typographic* stimulus factors that are concerned with the forms and layout of text.

3. Vision models and legibility

Typography is of special interest because of advances over the past twenty years in our understanding of how visual patterns are processed. In this time visual neuroscientists have developed many models of pattern discrimination (reviewed in [14, 15]) that are both highly predictive of human performance, *and* corroborated by physiological evidence at the level of single visually responsive neurons. Hopefully, such models can be applied to the problem of text legibility.

There is now a great deal of evidence from both psychophysical and physiological experiments, that the visual system processes patterns within size-tuned sensor channels, each of which is sensitive to a limited range of spatial frequencies. There are many different models of exactly how the sensors work, and what their filtering characteristics are in different parts of the visual field and at different levels of visual processing, but most contemporary models of pattern processing have some kind of sensors with limited spatial bandwidth.

From experiments conducted in several laboratories [16, 17, 18, 19] we know that the spatial bandwidth of a single sensor channel is sufficient for accurate recognition of letters. This means that at the acuity limit, the visual system uses only a single sensor channel for letter recognition: the channel tuned to the highest retinal spatial frequencies that can carry the lowest object (letter) spatial frequencies containing information sufficient to discriminate the retinally tiny letter forms. How can we use this information to assess the role of typographic factors in letter recognition?

3.1. Effects of typography on acuity

The top row of Figure 4 shows D's of varying stroke thicknesses. The second row shows the D's spatially filtered in much the same way as a single sensor channel might filter them at the acuity limit, although the filter profiles used for the sensor are somewhat simpler than those that would typically be used to model visual cortical neurons. The leftmost Sloan D clearly has the most contrast after being passed through this filter. So for thinner strokes than the Sloan, there is less contrast energy available in the neural image. Thus relative to their overall size, and to the extent that the sensor characteristics are described accurately, stroke thicknesses of Sloan D's are consistent with high legibility.

But while this shows that that the Sloan D is more salient to the small sensor representation with these characteristics than a D with a thinner stroke width and probably to D's used in ordinary typography, it says nothing about how well it might be discriminated from other letters—for that we need to know which levels of detail in the letter forms themselves carry information that can be effectively used to discriminate the letters.

Recently, David Parish and George Sperling [19] performed an experiment that showed persuasively that observers can use information at nearly any level of object detail with nearly equal efficiency to discriminate letters. What does this mean for legibility of text? Practically, it means that the legibility of text is unaffected by retinal size *until it gets so small as to approach the acuity limit.* At that point, where there is so little information available

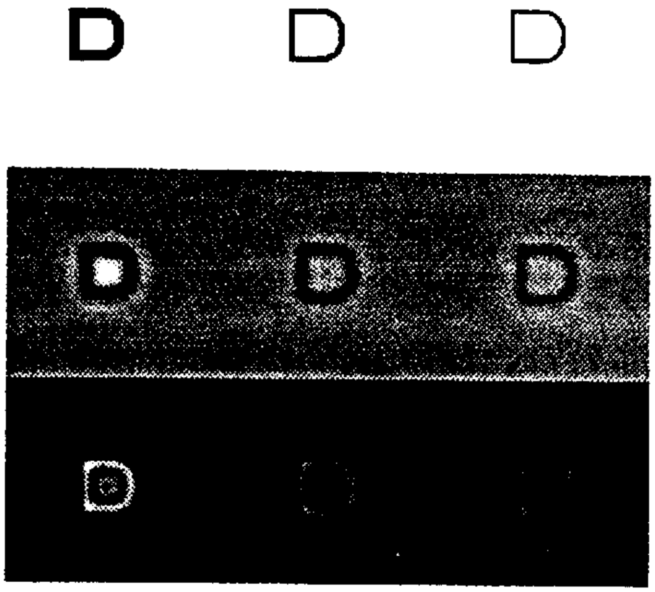


Figure 4: Top row: D's of varying stroke thickness. The leftmost is a Sloan D. Middle row: D's spatially filtered with a 1.25 octave-wide (at half power) two-dimensional difference of Gaussians bandpass filter centered at 1.5 c/letter. Bottom row: Squared filtered D images indicating (by pixel intensity) the contrast power in the images of the middle row.

in the retinal image that even a single sensor channel's capacity is compromised, legibility may decline rapidly, and it is at that point that differences in letter forms may have their most dramatic impact on legibility.

3.2 An explanation of crowding phenomena

We are developing a simple model of text processing that is similar to other contemporary models of letter recognition[20, 21, 19, 22], but have added a few new features that show how crowding phenomena may be responsible for the poor predictability of reading acuity from isolated acuity. The model is schematically shown in Figure 5, and has the following components:

- A filtering stage, with sensors localized in space and spatial frequency, producing parallel spatial representations of the input image, produced through a linear operation like cross-correlation.
- Template-matching performed within single sensor channels.
- An attentional mechanism that uses the lowest spatial frequency channel possible for template matching.

How is the model prone to crowding phenomena? At the acuity limit, the smallest sensors are large relative to the letter size. At this size, contrast energy from adjacent letters falls within the spatial profile of the sensors mediating the letter template match, as shown in Figure 6. This energy, which is uncorrelated with the letter being recognized, acts as a masking noise.

Thus to the model, the letter "D" embedded in the word "READING" in Figure 7(a) might just as easily be flanked by noise of similar character[1] such as that in Figure 7(b) as

---

[1] Binary noise made up of pixels that approximate the stroke width of the target letter probably match the letter fairly well in terms of spatial frequency content, but probably differ considerably in their orientation

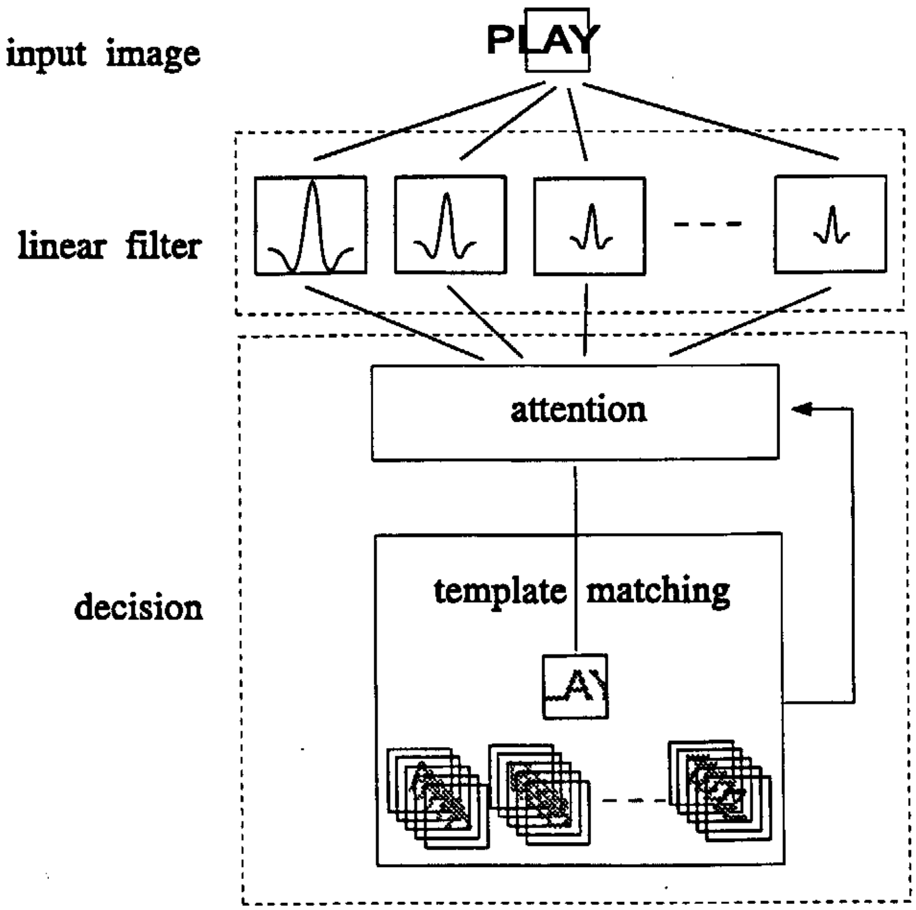


Figure 5: Schematic illustration of text processing model.

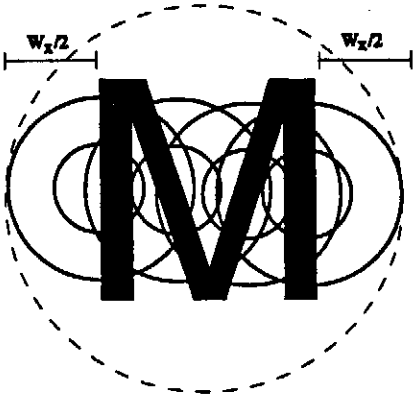


Figure 6: Schematic illustration of how the model predicts crowding effects. At the acuity limit, high *retinal* spatial frequency low *object* spatial frequency sensors mediating the letter recognition are broad enough spatially to receive contrast energy from neighboring letters.

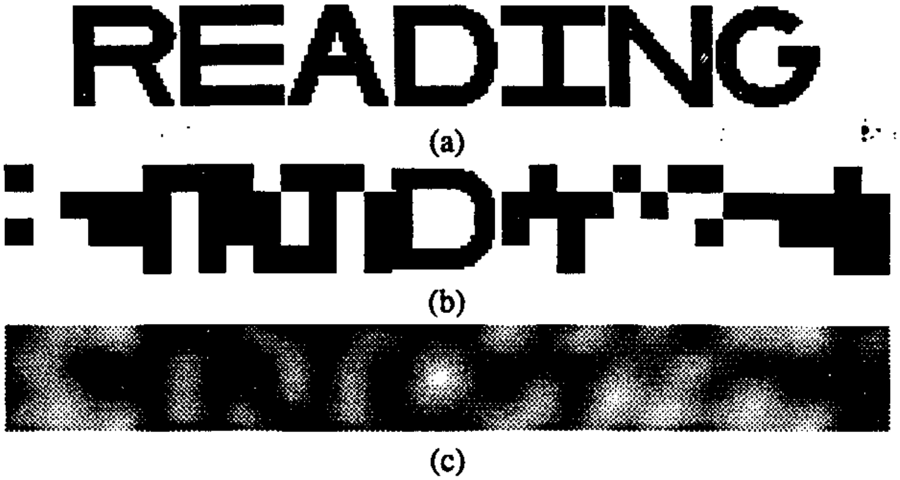


Figure 7: In template-matching of the letter 'D' in the word in (a), neighboring letters act as effective noise, mimicked in (b). Embedded in such noise, the letter is less visible to low spatial frequency sensor channels. (c) low-pass filtered image in (b). Filter used is Butterworth order 8, 1.5 c/letter cutoff.

by "REA" and "ING." When forced to identify characters with sensors corresponding to the lowest object spatial frequencies in the letter, as at the acuity limit, low spatial frequency information from such "noise" invades the region of the target letter being recognized, and makes it more difficult to identify (see Figure 7(c).

It is interesting to note, that with practice and feedback, and interfering image elements that are constant from trial to trial, contour interaction effects disappear, [23]. Under such circumstances, neighboring elements lose their noise-like character.

4. Summary

Despite the fact that letter symbols are identified in both tasks, the relationship between reading acuity and letter acuity is complex, being affected by many stimulus and cognitive factors. Typographic stimulus factors, which can affect legibility especially at the acuity limit, are amenable to computational modeling of vision. Crowding effects of close text spacing, in particular, are derivable from a simple sensor model of early visual processing.

Acknowledgements

Supported in part by NASA-Ames Cooperative Agreeement NCC2-541. I thank Ron Cagenello and Ken Knoblauch for many helpful discussions on this work.

References

[1] Brown, B. (1981). Reading performance in low vision patients: Relation to contrast and contrast sensitivity. *American Journal of Optometry and Physiological Optics*, 58/3:218–26.

[2] Goodrich, G. L., Mehr, E. B., Quillman, R. D., Shaw, H. K., and Wiley, J. K. (1977). Training and practice effects in performance with low vision aids: A preliminary study. *American Journal of Optometry and Physiological Optics*, 54/5:312–18.

[3] Faye, E. E. (1976). The role of eye pathology in low vision evaluation. *Journal of the American Optometric Association*, 47:1395–140.

[4] Legge, G. E., Rubin, G. S., Pelli, D. G., and Schleske, M. M. (1985). Psychophysics of reading - II. low vision. *Vision Research*, 25/2:253–66.

[5] Sloan, L. L. and Brown, D. J. (1963). Reading cards for selection of optical aids for the partially-sighted. *American Journal of Ophthalmology*, 55/6:1187–99.

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

[7] Anstis, S. M. (1974). A chart demonstrating variations in acuity with retinal position. *Vision Research*, 14:589–92.

[8] Flom, M., Heath, G. G., and Takahashi, E. (1963). Contour interaction and visual resolution: Contralateral effects. *Science*, 142:979–980.

[9] Loomis, J. M. (1978). Lateral masking in foveal and eccentric vision. *Vision Research*, 18:335–8.

[10] Skottun, B. C. and Freeman, R. D. (1983). Perceived size of letters depends on inter-letter spacing: A new visual illusion. *Vision Research*, 23:111–12.

[11] Stuart, J. A. and Burian, H. M. (1962). A study of separation difficulty: Its relationship to visual acuity in normal and amblyopic eyes. *American Journal of Ophthalmology*, 53:471–477.

[12] Arditi, A., Knoblauch, K., and Grunwald, I. (1990). Reading with fixed and variable character pitch. *Journal of the Optical Society of America A*, 7:2011-2015.

[13] Erdman, B. and Dodge, R. (1898). Psychologische untertsuchungen über das Lesen. Halle, M. Neimeyere. Cited by R. Woodworth and H. Schlosberg, *Experimental Psychology*. New York: Holt, 1958.

[14] Graham, N. (1989). *Visual pattern analyzers*. Oxford University Press, New York.

[15] Landy, M. S. and Movshon, J. A. (1991). *Computational models of visual processing*. MIT press, Cambridge, Massachussetts.

[16] Beckmann, P., Legge, G. E., and Luebker, A. (1991). Reading: Letters, words, and their spatial-frequency content. In *Society for Information Display International Symposium Digest of Technical Papers*, 22:106–108.

[17] Ginsburg, A. B. (1978). Visual information processing based on spatial filters constrained by biological data. Technical report, U.S. AFAMRL.

[18] Legge, G. E., Pelli, D. G., Rubin, G. S., and Schleske, M. M. (1985). Psychophysics of reading - I. Normal vision. *Vision Research*, 25/2:239–52.

[19] Parish, D. H. and Sperling, G. (1991). Object spatial frequencies, retinal spatial frequencies, noise, and the efficiency of letter discrimination. *Vision Research*, 31-7/8:1399–1415.

[20] Gervais, M. J., Harvey, L. O., and Roberts, J. O. (1984). Identification confusions among letters of the alphabet. *Journal of Experimental Psychology: Human Perception and Performance*, 10:655–66.

[21] Loomis, J. M. (1990). A model of character recognition and legibility. *Journal of Experimental Psychology: Human Perception and Performance*, 16/1:106–20.

[22] Watson, A. B. and Fitzhugh, A. E. (1989). Modelling character legibility. In *Society for Information Display International Symposium Digest of Technical Papers*, 20: 360–363.

[23] Manny, R. E., Fern, K. D., Loshin, D. S., and Martinez, A. T. (1988). The effects of practice on contour interaction. *Clinical Vision Sciences*, 3:59–67.