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PSYCHOPHYSICS OF READING—V. THE ROLE OF CONTRAST IN NORMAL VISION

GORDON E. LEGGE, GARY S. RUBIN* and ANDREW LUEBKER
Department of Psychology, University of Minnesota, 75 East River Rd, Minneapolis, MN 55455, U.S.A.

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Abstract—How does contrast affect reading rate? What is the role of contrast sensitivity? We measured reading rate as a function of the contrast and character size of text for subjects with normal vision. Reading rates were highest (about 350 words/min) for letters ranging in size from 0.25° to 2°. Within this range, reading was very tolerant to contrast reduction—for 1° letters, reading rate decreased by less than a factor of two for a tenfold reduction in contrast. The results were very similar for white-on-black and black-on-white text. Reading rate declined more rapidly for very small (<0.25°) and very large (>2°) letters. People with low vision usually require large characters to read, so high contrast is particularly important for them. Taking 35 words/min to be a threshold for reading, we constructed a contrast-sensitivity function (CSF) for reading. We were able to relate the shape of this CSF to the shape of sine-wave grating CSFs.

Reading   Psychophysics   Contrast   Low vision   Contrast sensitivity

INTRODUCTION

A major challenge faced by visual scientists is to apply basic knowledge to the understanding of everyday visual tasks. In our lab, we have been studying the visual requirements of reading with two major goals: to understand the role played by vision in this task, and to understand how visual disorders hinder reading.

In the first two papers of this series, we measured the minimum spatial-frequency bandwidth and field size for reading, as well as the effects of several other important stimulus variables (Legge *et al.*, 1985a; Legge *et al.*, 1985b). We found that text can be read rapidly when the letters have been filtered to a bandwidth of just one octave or when the field has been restricted to only four or five characters. Our results helped guide us in the development of a fiberscope low-vision reading aid (Pelli *et al.*, 1985).

What role does contrast play in reading? In recent years, there have been many studies of contrast processing in vision, but most have been confined to the measurement of thresholds for simple patterns like sine-wave gratings. Methods for studying suprathreshold contrast processing include matching (Georgeson and Sullivan, 1975), magnitude estimation (Cannon, 1979; Gottesman *et al.*, 1981), and masking (Wilson, 1980; Legge and Foley, 1980; Legge, 1981). These studies have suggested models of suprathreshold contrast coding in vision. The role played by contrast in everyday tasks, however, has been largely neglected. No one has thoroughly studied how contrast affects reading performance. This issue is of particular importance because it is known from clinical experience that many people with low vision cannot read unless text has very high contrast. In this paper, we explore the role of contrast in reading by subjects with normal vision. In a subsequent paper, we will deal with the effects of contrast on low-vision reading.

There are several definitions of contrast. We will use the Michelson definition

$$C = (L_{max} - L_{min})/(L_{max} + L_{min})$$

Where L_{max} and L_{min} are the maximum and minimum luminances. For text, L_{min} will usually refer to the dark letters and L_{max} to the white background. Michelson contrast ranges from 0 to 1.0. Figure 1 illustrates words printed at four contrast levels. Several studies to be cited below use other definitions of contrast, but all values given in this paper have been converted to Michelson contrast.

*Present address: Wilmer Ophthalmological Institute, The Johns Hopkins University School of Medicine, Baltimore, MD 21205, U.S.A.

Tinker and Paterson (1931) compared reading speeds for 10 combinations of colored inks and colored papers as well as black ink on white paper. They found that reading was faster for black-on-white text than for any of their other color combinations. They suggested that luminance contrast is a more important determinant of reading speed than is color.

Luckiesh and Moss (1938) measured reading rates for texts composed of black ink on ten different papers. The papers ranged from white with reflectance of 0.85 to red with reflectance of 0.38. If the black ink had a reflectance of 0.1 (Luckiesh and Moss do not give a value), corresponding contrasts would range from 0.59 (red) to 0.78 (white). Although fastest reading was found for the black-on-white text, there was less than 7% difference in mean rates across all conditions. These findings suggest that reading rate depends only weakly on contrast, at least over a narrow range of high contrasts.

There have been a few studies of the effects of contrast on letter and word recognition. Although these tasks differ from reading, they are related to it and may give clues to its stimulus dependence. Letter or word recognition is easier to measure than reading performance and is more likely to be suitable for clinical tests.

Howell and Kraft (1960) used speed and accuracy of response to evaluate legibility of alphanumeric symbols. They varied the blur, size and contrast of the symbols. Contrast ranged only from 0.86 to 0.95. Their analyses indicated a significant, but small, effect of contrast as well as an interaction between contrast and symbol size.

Ginsburg (1978) measured contrast thresholds for the detection and identification of letters on different lines of a Snellen chart, i.e. for letters of different sizes. Letters ranged in size from 0.8° (6/60 line) to 0.07° (6/5 line). Ginsburg found greater sensitivity for the larger letters, thereby demonstrating a character-size effect. He also found that substantially more contrast was required for identification than for detection of the smaller letters. This he interpreted in terms of properties of the contrast-sensitivity function for sine-wave gratings and the spatial-frequency bandwidth requirements for letter identification.

As part of this paper, we will report contrast-sensitivity measurements for letter identification for characters ranging in size from 0.13° to 24°. Large characters are of particular importance in low vision.

Van Nes and Jacobs (1981) studied the effect of contrast on recognition accuracy for tachistoscopically presented single letters or three-letter Dutch words. The letters subtended 0.25° and were presented for 100 msec. Contrasts ranged from 0.031 to 0.82. They found that recognition accuracy did not decline much for contrasts down to about 0.12 but decreased rapidly for lower contrasts.

This rather sketchy literature suggests that reading depends only weakly on contrast for text of medium to high contrasts. Taking character and word-recognition studies into account, we might expect a stronger dependence at lower contrasts. A major aim of this study was to document the dependence of reading speed on contrast over a wide range of contrasts and character sizes.

Contrast polarity is one aspect of reading that has been studied in some detail. It designates whether text is presented as black letters on a white background or vice versa. It has been known for some time that many low-vision observers prefer white-on-black text (Sloan, 1977). Legge *et al.* (1985b) demonstrated that low-vision subjects with cloudy ocular media read faster with white-on-black text. This effect is probably due to abnormal light scatter in the eye. There have been several reports of small advantages in normal reading performance for black-on-white text, especially for small letters. For a review, see Tinker (1963, Chap. 9). However, Legge *et al.* (1985a) found no systematic effect of contrast polarity in their study of the reading performance of subjects with normal vision. They examined effects of contrast polarity for characters ranging in size from 0.06° to 12°. Recent interest in contrast polarity centers on alternative designs for video-display terminals. Bauer and Cavonius (1980) found slightly lower error rates for character recognition and detection-of-discrepancy tasks for observers who worked with black-on-white compared with white-on-black displays. In a related study, Cavonius and colleagues measured performance on a task that required subjects to identify digits on a screen and then type them. When the contrast of the digits was very low, about 0.05, error rates were significantly higher for white-on-black than for black-on-white characters, but for high-contrast characters there was no significant difference (C. R. Cavonius, personal communication). This raises the possibility that a contrast polarity effect may be found for low-contrast

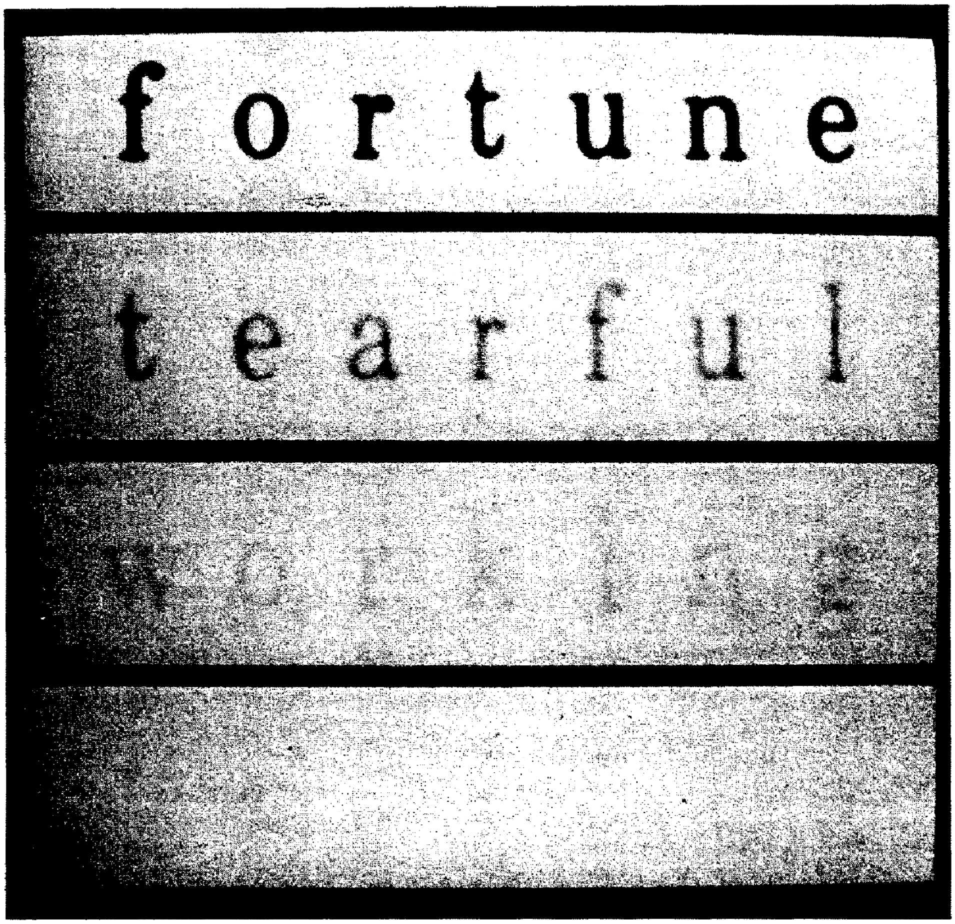

Fig. 1. Examples of words printed with different contrasts—"fortune" 0.90, "working" 0.30, "tearful" 0.10, and "visible" 0.03. These values do not take into account errors of photographic reproduction. In this paper, contrast is defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} and L_{min} are the luminances associated with letters and their backgrounds.

reading even when it is not evident at high contrasts. We address this question experimentally in this paper.

In our psychophysical procedure, subjects are asked to read aloud lines of text that drift across the face of a T.V. monitor. The drift rate is increased until the subject begins to make mistakes. Reading rate, in words/min, is computed after correction for errors. We use this method to find the maximum reading rate for the conditions under study. This procedure has the advantages of allowing for easy experimental control of stimulus parameters and straightforward measurement of reading performance. Moreover, the reading of drifting text is similar to much low-vision reading. Low-vision subjects typically scan text across the screen of a closed-circuit TV magnifier or through the field of a high-power optical magnifier. Our procedure has two major disadvantages; it relies on *oral* reading rather than the more common *silent* reading, and it uses *drifting* text rather than the more usual *static* text. In previous studies, we have shown that reading rate varies with character size and wavelength in the same fashion for drifting and static text and for silent and oral reading (Legge *et al.*, 1985a; Legge and Rubin, 1986). In this paper, we report on a control experiment in which we compared the effects of contrast on the reading of static and drifting text.

A major difference in the reading of drifting and static text is the pattern of eye movements, but there is a striking functional similarity between the two. Eye movement recordings in our lab (Legge *et al.*, 1985a) and by Buettner *et al.* (1985) show that for drifting text, the eyes fixate on a letter, track it across the screen through a distance of four or five character spaces, and then saccade back to pick up a new letter. The resulting sequence of retinal images is like that found for static text; there is a series of foveal fixations on letters, separated by saccades spanning a few letter spaces. The equivalence of eye-movement patterns suggests that the spatiotemporal characteristics of retinal images during reading are very similar for drifting and static text.

Can our knowledge of spatiotemporal contrast sensitivity (Robson, 1966; Kelly, 1972, 1979) allow us to predict the minimum contrast requirements of reading? The mean fixation duration for reading is about 250 msec, but the variation in fixation times is quite large and depends on the individual and characteristics of the text (Rayner and McConkie, 1976). Reading may therefore be described as having a broadband temporal signal peaking near 4 Hz. What about the spatial-frequency spectrum of reading? Previous studies have shown that the most critical spatial information for letter identification or reading lies between $1/x$ and $2/x$ c/deg, where x is the center-to-center character spacing (Ginsburg, 1978; Legge *et al.*, 1985a). We will ask whether the spatiotemporal characteristics of reading can be used to predict the form of a threshold-contrast function for reading, that is, the lowest contrast for which some criterion reading speed can be maintained, measured as a function of character size.

METHODS

Apparatus

The display was a Conrac Model SNA 17/Y monochrome monitor with P4 phosphor and 20 MHz bandwidth. Text drifted, one line at a time, from right to left across the screen. The text was stored as ASCII code in the memory of an LSI-11/23 computer. Rather than using the low-resolution symbols supplied by a character generator, we created our own character set, consisting of upper and lower-case letters, digits and punctuation. Each character was stored as a 32×36 (pixel) $\times$ 8 bit (grey level) image. The characters were originally digitized from dry transfer letters (Zipatone Century Schoolbook) using an RCA TC-1005/01 high-resolution black-and-white video camera. The images were passed via DMA transfer to a Grinnell GMR274 frame buffer having a resolution of 512×512 pixels. Drifting was accomplished using the pan control of the frame buffer. The vertical blanking signal from the frame buffer was detected by a Schmitt trigger on the computer's programmable clock. The Schmitt trigger's signal was used to update the pan control for each field (60 Hz update rate).

As the text was panned across the screen, the software periodically read new characters into the frame buffer's memory and deleted old characters from memory. With this system, it was possible to achieve drift rates up to 60 characters/sec (about 720 words/min).

Text was usually presented as black letters on a white background (luminance 300 cd/m^2). Contrast was controlled by a video bandwidth programmable attenuator built from mercury-wetted reed relays (Foresight Products, Syracuse, New York). The attenuator increased the luminance of the dark part of the field and left the luminance of the bright areas constant. In some experiments, white-on-black text was used. In this case, the video signal from the frame buffer was inverted with the aid of the frame buffer's look-up table. Contrast was still controlled by increasing the luminance of the dark parts of the field, this time with the bright letters remaining constant.

The luminance of the Conrac display was measured with a UDT 80-X Optometer and was a nonlinear function of input voltage. This nonlinearity was taken into account when computing contrast attenuations. The nonlinearity introduced small, contrast-dependent changes in the luminance profiles of the edges of the letters. These distortions are small compared with the distortion (blur) which we have previously shown to have no effect on reading speed (Legge *et al.*, 1985a).

A line of text was composed of 80 characters (average word length = 4.1 letters). Text was selected from materials designed to test reading ability and ranged in difficulty from Grade 4 to secondary school level. In all cases, care was taken to ensure that the difficulty of the text did not exceed the reading level of the observer. For more details, see Legge *et al.* (1985a).

The T.V. screen was masked to an aperture 25 cm wide by 5 cm high through which the line of text drifted. The zoom control of the frame buffer was set so that 8 or 16 character spaces filled the 25 cm wide aperture. Previous studies (Legge *et al.*, 1985a, b) have shown that a window width of five character spaces or more permits maximum reading rates for high contrast text. The angular size of characters was varied by changing viewing distance and zoom, taking care to refract subjects appropriately. Character size is defined as the center-to-center spacing and ranged from 0.13° to 12°.

Procedure

Room lights were extinguished during reading trials. Prior to a trial, the first letter of the line of text was visible at the right margin of the screen. After a warning signal, the experimenter pressed a button that initiated the sweep of a line of text across the screen. The sweep terminated when the last character of the line disappeared at the left margin. The observer read the text aloud and the experimenter counted the number of errors. *Reading rate* in words/min is equal to the drift rate in words/minute multiplied by the proportion of words correctly read. Legge *et al.* (1985a) showed that there is a very sharp transition from perfect reading to ineffective reading as drift rate increases. As a typical example, their subject KS read text drifting at 230 words/min with 100% accuracy (reading rate = 230 words/min), but text drifting at 300 words/min) with only 50% accuracy (reading rate = 150 words/min. Consequently, plots of reading rate vs drift rate have narrow peaks, and the peak reading rate occurs for a drift rate for which the subject makes a small proportion of errors. At faster drift rates, the proportion of errors rises rapidly and reading rate drops. At lower drift rates, reading is error free but, perforce, reading rate is suboptimal. It is quite easy to find the peak reading rate. The experimenter adjusts the drift rate until the observer makes a nonzero but small proportion of errors. Because the transition from errorless to error-prone reading is so sudden, a bracketing process quickly locates the critical drift rate. Final adjustments in drift rate may be smaller than 5%. Once the critical drift rate is located, a single measurement of reading speed is based on performance on two lines of text drifting at that rate. This is the method we used to measure reading rate. The data points in the figures are geometric means of two such measurements taken at different times.

In a typical experimental session, reading rates were obtained from one observer for a single character size. A session began with the highest contrast, followed by measurements with decreasing contrast. If reading rate took a precipitous drop with one step, an intermediate contrast condition was run. A typical session took about one hour. Several sessions were required to complete measurements for all character sizes.

In a control experiment, two subjects read static text (eleven 40-character lines) that appeared on the T.V. screen. This text was printed on cards and imaged by the T.V. camera. The character width was 0.5°. Reading rates were computed by timing the subjects as they read silently through the text as rapidly as they could without skimming. (We attempted to make similar measurements for 6° characters but the large head movements associated with the near viewing distance made the data uninformative.)

We also measured contrast thresholds for the identification of letters. Ten letters, Sloan optotypes, were digitized on a 32 × 32 grid using the video camera. Character size was varied by changing the subject's viewing distance and/or the frame buffer's zoom. The screen was masked to a square aperture measuring two character widths on a side. Contrast threshold was measured for a given character size using a 10-alternative forced-choice procedure. A letter was turned on abruptly and presented steadily to the subject who was required to name one of the ten letters. If six or more letters were correctly identified in a series of eight, contrast was reduced 2 dB. Contrast threshold is defined as the last contrast at which a subject correctly identified six or more of the eight letters.

Observers

Five subjects participated in the research. All had corrected acuities of 20/20 or better. All had adequate practice to ensure that performance was asymptotic. Viewing was binocular and with natural pupils. Subjects wore lenses to correct for refractive errors or viewing distance.

RESULTS AND DISCUSSION

The panels of Fig. 2 show reading rate in words/min as a function of contrast for three character sizes and two subjects. Solid symbols refer to black-on-white text and open symbols to white-on-black text. Each point is the mean of two measurements. Standard errors were typically less than 5%, except at the lowest reading rates (<40 words/min) where they ranged up to 20%.

First notice that for K.D., the open and solid symbols cluster together. This means that contrast polarity has no systematic effect on her reading speed at any contrast. In panels 2E and 2F, M.K. appears to show a contrast-polarity effect, but of inconsistent direction. These data do not provide evidence for a systematic advantage of either contrast polarity at low or high contrast.

Panels 2B and 2E show the data of two subjects for text composed of characters subtending 1° (a little more than twice the size of ordinary newsprint.) At the maximum contrast of 0.96, both subjects had reading rates close to 300 words/min. As contrast was reduced from its maximum value, reading rate first declined very slowly. For a contrast of 0.10, reading rates for the two subjects were still nearly 200 words/min. For contrast reduction below 0.10, reading rates declined much more rapidly. For

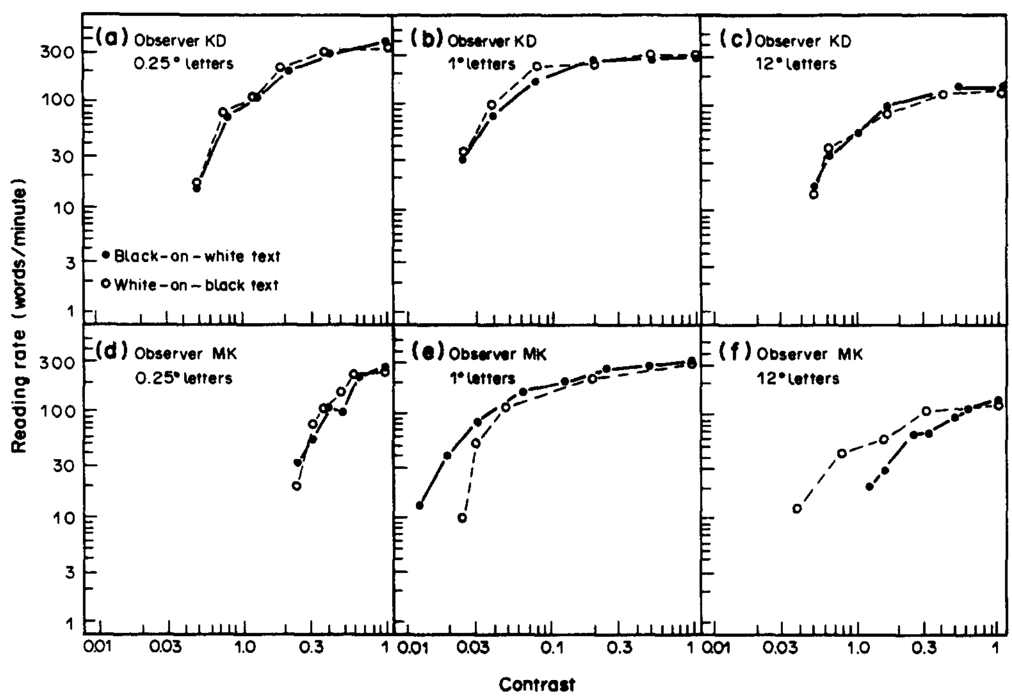

Fig. 2. Reading rate as a function of contrast for three character widths. Data are shown for observer K.D. in panels A, B and C, and for M.K. in panels D, E and F. Solid symbols refer to dark letters on a lighter background and open symbols to light letters on a darker background. Observers read aloud lines of text that drifted across the face of the T.V. monitor. The ordinate represents the fastest reading rate that could be achieved, errors having been taken into account. The definition of contrast is given in the text and in the legend to Fig. 1.

a contrast near 0.02, both read black-on-white text at about 30 words/min.

Panels 2(A) and 2(D) show comparable data for characters subtending 0.25° (= 15′ = 20/60 letters). For these smaller characters, contrast plays a much more critical role. Reading rate at maximum contrast was again close to 300 words/min, but a one-log-unit reduction of contrast had substantial effects for both subjects. K.D.'s rate dropped by about a factor of four while M.K. was unable to read at a contrast of 0.10.

Panels 2(C) and 2(F) show comparable data for 12° letters. These enormous letters would span about 8 cm at a reading distance of 40 cm. This time, reading rates at maximum contrast are lower, about 150 words/min. At a contrast of 0.10, both subjects read at about 50 words/min.

The data of Fig. 2 indicate that character size interacts with contrast in their effect on reading. This point is illustrated in Fig. 3 where reading rate is plotted as a function of character width for observer K.D. with contrast as a parameter. Results are shown for four contrasts—0.96, 0.30, 0.10 and 0.03. For a range of moderate character widths and medium to high contrasts, the curves cluster together. Reading rate is little affected by character size over a one-log-unit range from about 0.2° to 2° and by contrast over a one-log-unit range from about 1.0 to 0.10. This means that normal vision is remarkably tolerant to changes in both character size and contrast. Tolerance to contrast reduction has also been demonstrated in face recognition (Rubin and Siegel, 1984), mobility (Pelli and Serio, 1984) and shopping (Pelli and Applegate, 1985).

Reading rates become more dependent on contrast when character width is either very small or very large; the curves in Fig. 3 diverge. Because subjects with normal vision demonstrate a greater dependence on contrast for large letters, there is *a priori* reason to expect that contrast may play a more critical role for people with low vision who require large characters to read. Legge *et al.* (1985b) showed that many

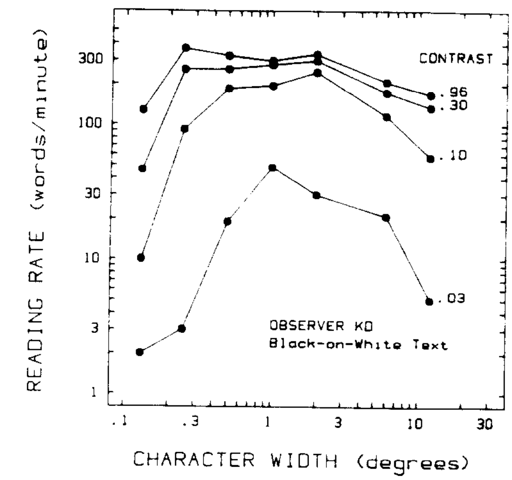

Fig. 3. Reading rate as a function of character width for four contrasts. The data have been taken from graphs like those in Fig. 2. The contrasts correspond to those shown in Fig. 1. Data are for black letters on a white background.

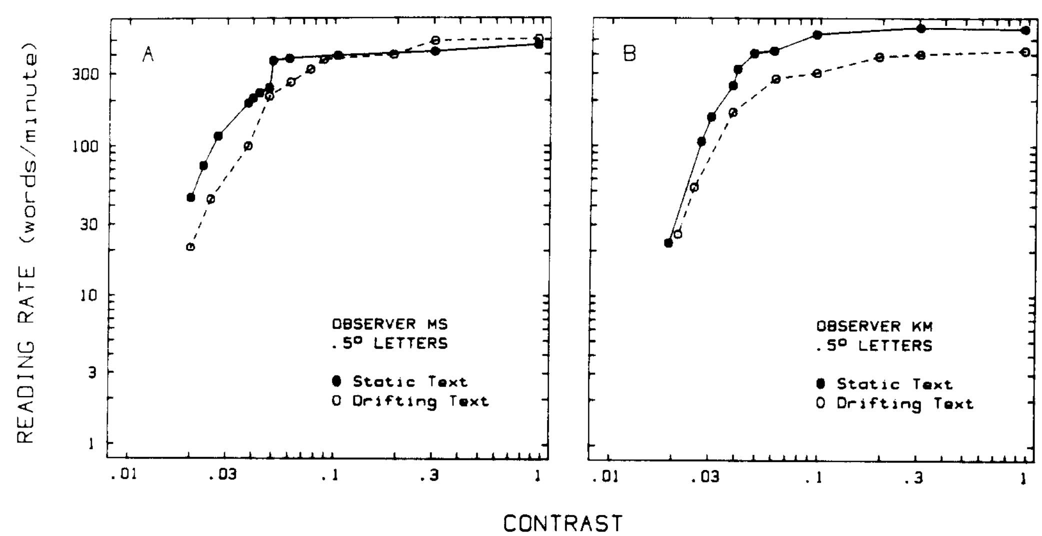

Fig. 4. Comparison of reading rates for static and drifting text. Reading rate is plotted as a function of contrast for static text read silently (solid symbols) and drifting text read aloud (open symbols). The character width was 0.5°. Black-on-white text was used. Panels (A) and (B) show data for observers M.S. and K. M. respectively.

people with low vision require character sizes of 3° or more to achieve their maximum reading speeds.

In our experiments, subjects were asked to read aloud lines of text that drifted across the screen. This task differs in several ways from ordinary reading. For comparison, we conducted an experiment in which observers K.M. and M.S. read static text silently (see Method). The panels of Fig. 4 compare silent reading of static text with oral reading of drifting text. Data are shown for 0.50° characters. Although K.M.'s overall rates were a little higher for static text, the curves have very similar shapes. These results, together with those mentioned in the Introduction, encourage us to believe that much of what we learn from our studies with drifting text will generalize to ordinary reading.

Can the shapes of the curves in Figs 2, 3 and 4 be related to basic psychophysical findings? We will address this question in two parts. First, we will ask whether the dependence of reading rate on contrast can be related to models of contrast coding. Then we will ask whether measurements of spatiotemporal contrast sensitivity can help us to understand the character-width dependence of reading performance.

Models of suprathreshold contrast coding typically contain a nonlinear compressive relationship between internal response and stimulus contrast (Carlson and Cohen, 1978; Legge and Foley, 1980; Wilson, 1980; Burton, 1981; Legge, 1984). The Legge and Foley model was developed to account for contrast masking and contrast-discrimination data. In contrast discrimination, an observer is required to indicate which of a pair of otherwise identical patterns has the higher contrast. The smallest contrast difference that can be discriminated is the contrast-increment threshold. For many conditions, the increment threshold rises as a power function of target contrast, with a typical exponent of 0.6 (Legge, 1981). Furthermore, contrast-discrimination functions (increment threshold vs target contrast) tend to be shape invariant; functions obtained with different targets tend to superimpose when contrast is normalized by threshold contrast. According to the Legge and Foley model, there exists a nonlinear relationship between internal response R and stimulus contrast C of the form

$$R = (aC^{2.4})/(C^2 + b^2)$$

where a and b are constants that depend upon properties of a linear filter and intrinsic noise. For suprathreshold conditions—$C \gg b$—the relation reduces to

$$R \simeq aC^{0.4}.$$

This compressive relation indicates that internal response increases ever more slowly with C and accounts for the growth of the contrast-increment threshold. Suppose that reading rate is proportional to internal response R. The dependence of reading rate on contrast should then mimic the form of the nonlinear relationship between R and C. Two predictions follow: (1) functions of reading rate vs contrast for different character sizes should superimpose when contrast is normalized by an appropriate threshold value; and (2) these curves should have the form of the nonlinear transformation proposed by Legge and Foley.

Figure 5 shows data for observer K.D. for character widths of 0.25, 1 and 6 deg. The horizontal axis shows normalized contrast. It was computed by dividing the actual contrast of the letters by the threshold contrast for letter recognition. (Contrast thresholds for reading and letter recognition will be described below. We could have normalized by the threshold for reading rather than the threshold for letter recognition but, for the sets of data in Fig. 5, these two types of thresholds differ by a nearly constant value of four so the only effect would be to scale the numbering on the X-axis.) Accordingly, a normalized contrast of 1.0 refers to the contrast threshold for letter recognition. The three sets of data superimpose up to a nor-

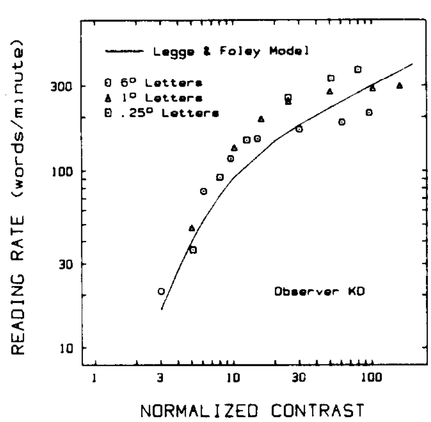

Fig. 5. Relating the contrast dependence of reading to the Legge and Foley model of contrast coding. Reading rate is plotted as a function of contrast after normalization by the contrast threshold for recognizing letters of the appropriate size. Data for three character sizes are shown for observer K.D. The solid curve has the form of the compressive nonlinearity proposed by Legge and Foley (1980) to describe suprathreshold contrast coding.

malized contrast of about 10 at which point the 6° data drop below the others. The remaining two sets of data rise together to a normalized contrast of about 25 whereupon the 1° data drop below the 0.25° data. In a corresponding plot for observer M.K. (not included), the 1° and 6° data superimpose over their entire range, but the 0.25° data rise more steeply than the others above a normalized contrast of 10. These findings indicate that curves of reading rate vs normalized contrast have a common shape at low contrasts but idiosyncratic differences in steepness at high contrast. The solid curve through the data has the form of the Legge and Foley nonlinear transformation. Its vertical position is arbitrary since we have no means, *a priori*, of establishing the constant of proportionality relating reading rate to internal response. The solid curve conforms qualitatively to the reading data. For both, there is a steep rise at low contrast and a roll-off at high contrast. Quantitatively, the solid curve rises with shallower slope at low contrast and steeper slope at high contrast. Overall, the two predictions from prevailing models of contrast coding correctly account for major qualitative features of the contrast dependence of reading. However, quantitative discrepancies, particularly at high contrast, remain to be explained.

Interpretation of our data in terms of internal response functions has a curious twist. As the data show, normal reading is quite tolerant to contrast reduction. This would normally be regarded as a property of considerable functional value. Yet, this tolerance may actually be a consequence of the compressive, or even saturating, coding of suprathreshold contrast by the visual system.

In the preceding paragraphs, we have provided a sensory interpretation of limitations on reading rate. Alternatively, reading rate may be limited by cognitive factors. This would almost certainly be the case if skimming or other methods of "speed reading" were permitted. In our paradigm, cognitive demands are reduced. It is possible, however, that the peak rates of about 350 words/min, obtained with medium character widths, might be due to some cognitive ceiling. It is unlikely that cognitive factors can account for the lower maximum rates achieved with very small or very large character widths.

We now turn to the influence of character width and the construction of a *contrast sensitivity function for reading*. In Fig. 6, the lower horizontal scale gives the "fundamental spatial frequency" corresponding to the character width shown on the upper scale. The fundamental frequency is the reciprocal of the center-to-center character spacing.* We define the *threshold for reading* as the contrast at which a rate of 35 words/min can be achieved. This is about 10% of the maximum rate. A lower criterion would be inconvenient because the measurements are more difficult and variable. In any case, the shapes of the resulting curves do not appear to be much affected by modest changes of the criterion around the value chosen. In Fig. 6, contrast threshold is shown on the right vertical scale and its reciprocal, contrast sensitivity, on the left vertical scale. Contrast sensitivity functions are shown for observers K.D. and M.K. The highest sensitivity of

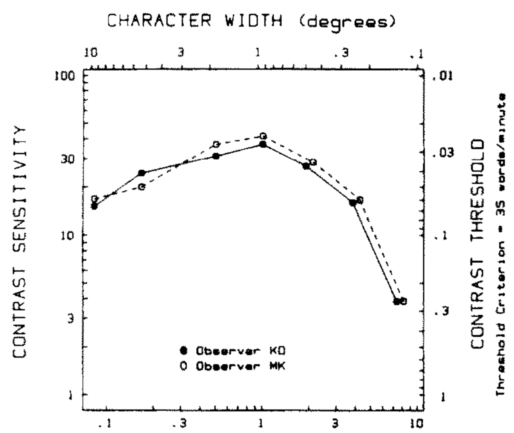

Fig. 6. Contrast sensitivity functions for reading. The contrast threshold for reading is defined to be the contrast required to read 35 words/min. Contrast sensitivity is the reciprocal of threshold contrast. Values of threshold contrast in this figure have been interpolated from curves like those shown in Fig. 2. The fundamental spatial frequency is equal to the reciprocal of the character width (i.e. the reciprocal of the center-to-center character spacing). CSFs are shown for observers K.D. and M.K.

*The concept of the "fundamental spatial frequency" of a letter may be understood as follows. Suppose that we have a line consisting of repetitions of the same letter, e.g. ". . .OOOOOOO . . .". This pattern is periodic in the horizontal direction. Its Fourier series representation would have a fundamental frequency equal to the reciprocal of the period of repetition, that is, the center-to-center spacing. If all but one of the letters is stripped away, we are left with an aperiodic pattern. Its Fourier transform is continuous, but the critical information distinguishing one letter shape from another resides in spatial frequencies above the original fundamental frequency. It is therefore convenient to retain the notion of fundamental frequency, even though the patterns are nonperiodic.

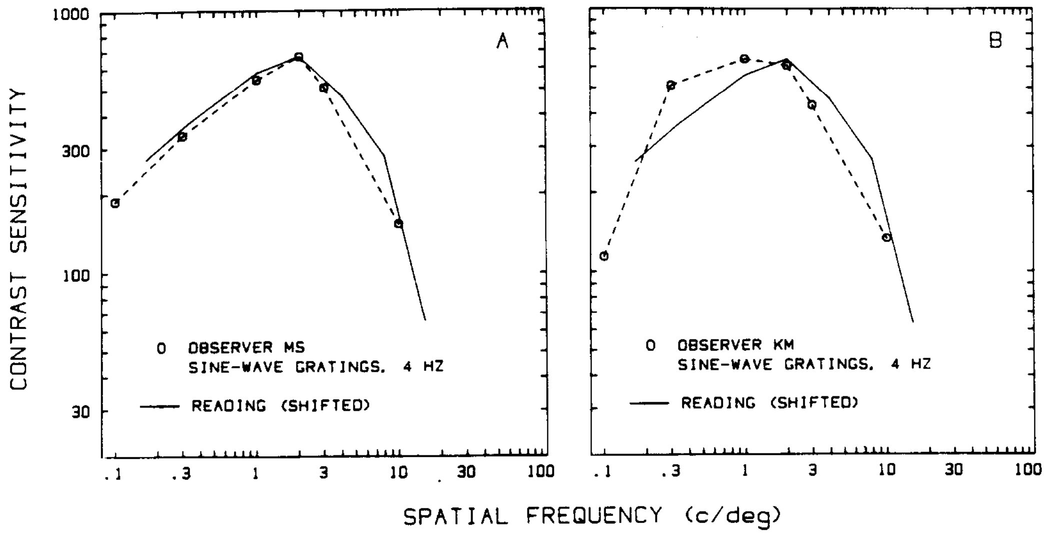

Fig. 7. Comparison of CSFs for reading and for grating detection. The data points show contrast sensitivity functions for the detection of sine-wave gratings with 4 Hz sinusoidal flicker. Spatial frequency was varied by changing viewing distance so that all the stimuli had six cycles. The data are means of two threshold estimates, each derived from a forced-choice staircase. The solid curve in each panel is the mean reading CSF from Fig. 6, based on the data of observers K.D. and M.K. The reading CSF has been shifted vertically so that its peak value is equal to that of the grating CSF and shifted rightward by a factor of two for reasons described in the text. The data points in panels A and B are for subjects M.S. and K.M. respectively.

about 50 (corresponding to a lowest threshold of about 0.02) occurs for characters subtending 1°. Sensitivities decline slowly for low frequencies (large characters) and more rapidly for high frequencies (small characters).

The CSF for reading is qualitatively similar in shape to the more conventional CSF for sine-wave gratings. For comparison, we measured sine-wave CSFs for similar conditions. We used a spatial two-alternative forced-choice procedure in which a vertical grating appeared on either the left or right side of a Joyce Electronics CRT display (mean luminance = 340 cd/m^2). The QUEST staircase procedure (Watson and Pelli, 1983) was used to estimate the observer's threshold (criterion = 75% correct). Because we varied viewing distance to change character size in our reading experiments, we varied viewing distance to change spatial frequency for the grating CSF. As a result, the grating stimuli contained six cycles at every spatial frequency. As described in the Introduction, the retinal stimulus in reading has a broad temporal spectrum with a dominant frequency near 4 Hz. We therefore modulated our grating stimuli with 4 Hz sinusoidal flicker.

The data points in Fig. 7(A) and (B) show the sine-wave CSFs for observers M.S. and K.M. The solid curves show an average reading CSF from Fig. 6, but shifted as follows. Since the threshold criteria for reading and sine-wave detection are quite different, the relative vertical position of the two CSFs is not informative. The reading curve has therefore been shifted vertically in Fig. 7 so that its peak sensivitivity matches those of the grating CSFs. The reading curve has been given a horizontal shift as well. Legge *et al.* (1985a) determined that reading requires a bandwidth of one octave in spatial frequency, extending upward from the fundamental frequency of the characters. For example, for characters with center-to-center spacing of 1°, the fundamental frequency is 1 c/deg, and the required bandwidth extends from 1 to 2 c/deg. The information in this band permits one letter to be distinguished from another. It is therefore appropriate to compare the contrast sensitivities of text composed of letters with fundamental frequencies of 1 c/deg with 2 c/deg gratings. A similar argument has been made for the discrimination between sine- and square-wave gratings at threshold (Campbell and Robson, 1968) and for the identification of individual letters (Ginsburg, 1978). In Fig. 7(A) and (B) the solid curve has been shifted rightward by a factor of two relative to its position in Fig. 6. The fit of the shifted reading curve to M.S.'s sine-wave CSF in

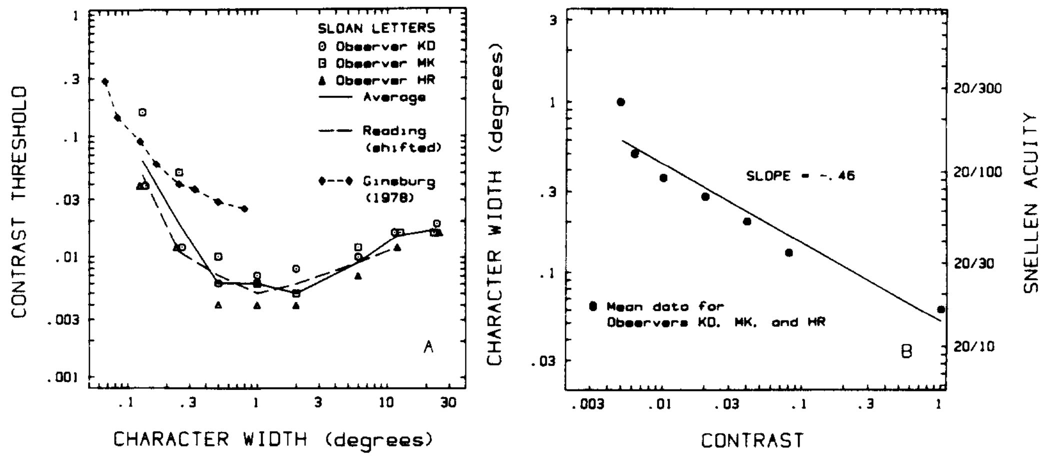

Fig. 8. Contrast thresholds for letters. (A) Contrast thresholds are plotted as a function of character width for three observers. The stimuli were Sloan optotypes and were black letters on a white background. The solid curve connects average values. Mean contrast thresholds for reading have been replotted from Fig. 6 and are shifted vertically to optimize the fit to the letter-recognition data. Contrast thresholds for letter recognition have been replotted from Ginsburg (1978) for comparison. (B) The average data for our three observers have been replotted from panel (A) as the letter size (vertical axis) associated with a given contrast (horizontal axis) at threshold. The right vertical scale gives letter size in Snellen notation. The data point with Snellen value of 20/15 at unit contrast was not measured in the experiment, but represents the average acuity of our subjects measured on a Snellen chart. The best-fitting straight line in these log–log coordinates has a slope of −0.46 indicating that letter acuity has nearly an inverse square-root dependence on contrast.

Fig. 7(A) is very good. The match to K.M.'s data, Fig. 7(B), is not as good, but is still quite close. These findings suggest that the character-width effects in reading are closely linked to the spatiotemporal contrast sensitivity of vision.

Finally, we measured contrast thresholds for the recognition of individual letters. Figure 8(A) shows contrast threshold as a function of letter size for three subjects. The solid curve gives the average. The curve with long dashes is the average contrast threshold for reading. Since the threshold criteria for reading and letter recognition are incommensurate, the reading curve has been shifted vertically so that its peak matches the curve for letter recognition. The two curves overlap suggesting that character size plays a similar role in reading and letter recognition. We argued above for the importance of 4 Hz contrast sensitivity in reading. In the letter-recognition experiment, the stimulus was turned on abruptly and had a broad temporal spectrum. The overlap of the two curves in Fig. 8(A) may be interpreted as suggesting that 4 Hz components in the temporal spectra of the stimuli played a dominant role in the letter-recognition task.

Our letter-recognition data extend the work of Ginsburg (1978) to large character sizes. His data are shown in Fig. 8(A) for comparison. Given the variation in thresholds of our observers, the agreement is reasonably good, except for character widths near 1° where Ginsburg's sensitivities are substantially lower than ours. This difference might be due to the lower luminance used by Ginsburg (68 compared with 300 cd/m^2), to the use of lines of letters on a Snellen chart rather than individual letters or to practice.

There is a second way of looking at the letter-recognition data: as acuity vs contrast. The data of Fig. 8(A) may be viewed as specifying the smallest resolvable character sizes for given values of contrast. Figure 8(B) shows averages of the small-character data (1° and less) from Fig. 8(A) with the horizontal and vertical axes interchanged. The data are shown as equivalent Snellen acuity (right ordinate) or letter size (left ordinate) vs contrast. We have added a point depicting an acuity of 20/15 for a contrast of 1.0. The data reveal a relatively weak dependence of acuity on contrast. The best fitting straight line with slope −0.46 in log–log coordinates gives a fair fit. This means that acuity is approximately proportional to the square root of contrast. Processes that attenuate contrast will have relatively weak effects on acuity. Glare is one example. Glare is usually thought to act by scattering light into a retinal image, thereby reducing image contrast. Contrast sensitivity, which more directly reflects contrast attenuation, should be more effective in revealing glare effects than acuity.

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REFERENCES

Bauer D. and Covonius C. R. (1980) Improving the legibility of video display units through contrast reversal. In *Ergonomic Aspects of Video Display Terminals* (Edited by Grandjean E. and Vigliani E.), pp. 137–142. Taylor & Francis, London.

Buettner M., Krischer C. and Meissen R. (1985) Characterization of gliding text as a reading stimulus. *Bull. Psychon. Soc.* **23**, 479–482.

Burton G. J. (1981) Contrast discrimination by the human visual system. *Biol. Cybernet.* **40**, 27–38.

Campbell F. W. and Robson J. G. (1968) Application of Fourier analysis to the visibility of gratings. *J. Physiol., London.* **197**, 551–566.

Cannon M. Y. Jr (1979) Contrast sensation: a linear function of stimulus contrast. *Vision Res.* **19**, 1045–1052.

Carlson C. and Cohen R. (1978) A nonlinear spatial frequency signal detection model for the human visual system. *J. opt. Soc. Am.* **68**, 1379.

Georgeson M. A. and Sullivan G. D. (1975) Contrast constancy: deblurring in human vision by spatial frequency channels. *J. Physiol., Lond.* **252**, 627–656.

Ginsburg A. P. (1978) *Visual Information Processing Based on Spatial Filters Constrained by Biological Data*. Vols I and II, Ph.D. thesis, Cambridge Univ., in Rep. AMRL-TR-78-129, Wright Patterson AFB, Ohio.

Gottesman J., Rubin G. S. and Legge G. E. (1981) A power law for perceived contrast in human vision. *Vision Res.* **21**, 791–799.

Howell W. and Kraft C. (1960) *Size, Blur, and Contrast as Variables Affecting the Legibility of Alphanumeric Symbols on Radar-type Displays*. WADC Tech. Rep. 59–536, Wright-Patterson AFB, Ohio.

Kelly D. H. (1972) Adaptation effects on spatio-temporal sine-wave thresholds. *Vision Res.* **12**, 89–101.

Kelly D. H. (1979) Motion and vision. II. Stabilized spatio-temporal threshold surface. *J. opt. Soc. Am.* **69**, 1340–1350.

Legge G. E. (1981) A power law for contrast discrimination. *Vision Res.* **21**, 457–467.

Legge G. E. (1984) Binocular contrast summation—II. Quadratic summation. *Vision Res.* **24**, 385–394.

Legge G. E. and Foley J. M. (1980) Contrast masking in human vision. *J. opt. Soc. Am.* **70**, 1458–1471.

Legge G. E. and Rubin G. S. (1986) Psychophysics of reading. IV. Wavelength effects in normal and low vision. *J. opt. Soc. Am.* **A3**, 40–51.

Legge G. E., Pelli D. G., Rubin G. S. and Schleske M. M. (1985a) Psychophysics of reading. I. Normal vision. *Vision Res.* **25**, 239–252.

Legge G. E., Rubin G. S., Pelli D. G. and Schleske M. M. (1985b) Psychophysics of reading. II. Low vision. *Vision Res.* **25**, 253–266.

Luckiesh M. and Moss F. K. (1938) Visibility and readability of print on white and tinted papers. *Sight-Saving Rev.* **8**, 123–134.

Pelli D. G. and Applegate L. C. (1965) The visual requirements of shopping. *J. opt. Soc. Am.* **A2**, 89.

Pelli D. G., Legge G. E. and Schleske M. M. (1985) Psychophysics of reading. III. A fiberscope low-vision reading aid. *Invest. Ophthal. visual Sci.* **26**, 751–763.

Pelli D. G. and Serio J. A. (1984) The visual requirements of mobility. *Invest. Ophthal. visual Sci., Suppl.* **25**, 72.

Rayner K. and McConkie G. (1976) What guides a reader's eye movements? *Vision Res.* **16**, 829–837.

Robson J. G. (1966) Spatial and temporal contrast sensitivity functions of the visual system. *J. opt. Soc. Am.* **56**, 1141–1142.

Rubin G. S. and Siegel K. (1984) Recognition of low-pass filtered faces and letters. *Invest. Ophthal. visual Sci., Suppl.* **25**, 71.

Sloan L. L. (1977) *Reading Aids for the Partially Sighted: A Systematic Classification and Procedure for Prescribing*. Williams & Wilkins, Baltimore, Md.

Tinker M. A. (1963) *Legibility of Print*. Iowa State Univ. Press, Ames, Iowa.

Tinker M. A. and Paterson D. G. (1931) Studies of typographical factors influencing speed of reading. VII. Variations in color of print and background. *J. appl. Psychol.* **15**, 471–479.

Van Nes F. L. and Jacobs J. C. (1981) The effects of contrast on letter and word recognition. *IPO Ann. Prog. Rep.* **16**, 72–80.

Watson A. B. and Pelli D. G. (1983) Quest: A Bayesian adaptive psychometric method. *Percept. Psychophys.* **33**, 113–120.

Wilson H. R. (1980) A transducer function for threshold and suprathreshold spatial vision. *Biol. Cybernet.* **38**, 171–178.