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PSYCHOPHYSICS OF READING. VI—THE ROLE OF CONTRAST IN LOW VISION

GARY S. RUBIN[1] and GORDON E. LEGGE[2]

[1]Wilmer Ophthalmological Institute, The Johns Hopkins University School of Medicine, Baltimore, MD 21205 and [2]Department of Psychology, University of Minnesota, Minneapolis, MN 55455, U.S.A.

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Abstract—The effect of contrast on reading performance was measured in 19 low-vision observers with a wide range of visual disorders and degrees of vision loss. The observers read text composed of 6 deg letters, ranging in contrast from 0.96 down to contrast threshold for reading. Reading performance was characterized by two parameters: *peak reading rate* is the reading rate at maximum contrast, and *critical contrast* is the contrast at which reading rate drops to half its maximum value. Peak reading rates were lower in observers with central field loss than in observers with intact central vision. In 16 of 19 cases, critical contrasts were higher for low-vision observers than for normal observers (averaging 3.9 times higher), indicating a decreased tolerance to contrast reduction. Values of critical contrast were closely linked to contrast sensitivity for letters ($r = 0.87$), but did not vary systematically with type of vision loss. Five observers read white-on-black text faster than black-on-white at both high and low contrasts. Four of the five had cloudy ocular media. We attribute this contrast polarity effect to abnormal light scatter in eyes with cloudy media. We examined the hypothesis that our low-vision observers' deviation from normal performance could be characterized (1) by a contrast scaling factor representing an attenuation of effective contrast and (2) that this scale factor could be identified with reduced contrast sensitivity. Such a description provided a good account for subjects with cloudy ocular media, where contrast attenuation results from intraocular light scatter. It provided a first order, but incomplete account for subjects with field loss where contrast attenuation is related to contrast sensitivity losses due to neural factors.

Low vision   Reading   Psychophysics   Contrast   Contrast sensitivity

INTRODUCTION

In recent years, the contrast dimension has received increased attention in studies of vision, but no one has thoroughly studied its role in low-vision reading. We are interested in contrast for two main reasons: (1) Clinical wisdom suggests that some low-vision patients are more debilitated by reduced contrast than others. Conventional low-vision reading magnifiers are incapable of enhancing contrast but some electronic aids, like the closed-circuit TV magnifier, have contrast enhancement circuitry. In addition, image processing techniques, like gray-scale histogram flattening, have the effect of enhancing contrast. It is important to determine how contrast affects low-vision performance in tasks like reading, and to identify those people with low vision who might benefit from contrast enhancement. (2) Most people with low vision have reduced contrast sensitivity. It is important to determine how this might affect their reading performance, and how it relates to the dependence of reading performance on contrast.

There are two aspects of contrast which are important to low-vision readers, contrast magnitude and contrast polarity (the distinction between bright text on a dark background and the reverse). This study is primarily concerned with contrast magnitude, although we did evaluate reading performance using both black-on-white and white-on-black text.

Legge *et al.* (1987) studied the effect of contrast magnitude on reading of normal observers. They found that reading speed was tolerant to substantial contrast reduction. For text composed of 1 deg letters* (about 2.5 times the size of ordinary newsprint) contrast had to be reduced to 0.06 in order for reading speed to drop to half its maximum value. For decreases in contrast below 0.06, reading speed dropped much more rapidly. We will refer to the contrast which produces half the maximum reading rate as the *critical contrast*.

Legge *et al.* (1987) found that the critical contrasts were higher for character sizes larger or smaller than 1 deg. For 12 deg characters,

*Throughout this paper letter size is defined as the center-to-center letter spacing.

the critical contrast was 0.17, and for 0.25 deg characters the critical contrast was 0.33. Since people with low vision often require very large character sizes—often 6 deg or more—we would expect higher contrast to be necessary for fast low-vision reading.

In a study of word recognition, Brown (1981) reported that observers with central field defects due to age-related maculopathy (ARM) required greater magnification and more time to recognize words than observers with cataracts. But high contrast was more critical for the cataract subjects. Reducing contrast from 0.8 to 0.45 resulted in a 75% increase in word recognition time for cataract observers, but only a 47% increase for ARM observers.

Our previous work (Legge *et al.*, 1985b) suggests that two factors are of primary importance in limiting reading speed for high contrast text: cloudiness of the ocular media, and loss of central vision. Since the major effect of cloudy media is a reduction in retinal image contrast due to light scatter, we expect these observers to behave like normal observers reading lower contrast text.

Observers with central field loss must rely on peripheral vision in order to read. There is evidence that peripheral vision is normal in some disorders that lead to central vision loss (Sunness *et al.*, 1985). These disorders include ARM, histoplasmosis, and other diseases which result in focal lesions. Other disorders which can cause central vision loss, such as cone dystrophy and optic neuropathy, are known to affect peripheral vision as well. To the extent that peripheral vision is unaffected, we may try to predict reading performance based on what we know about the properties of normal peripheral vision.

Basic psychophysical studies of contrast detection and discrimination suggest that contrast coding is qualitatively similar in central and peripheral vision. If targets are increased in size according to M-scaling, contrast thresholds remain invariant (Virsu and Rovamo, 1979). Legge and Kersten (1987) found that contrast discrimination functions for 2 c/deg Gaussian-windowed grating patches have the same shape from 0 to 20 deg eccentricity, and differ only by a scale factor proportional to local contrast sensitivity. This scaling, although neural in origin, is equivalent to an attenuation of retinal image contrast. If this contrast scaling principle also applies to reading, then subjects with central field loss (and intact peripheral vision) might also perform like normal subjects reading low contrast text.

This simple picture, however, is unlikely to be the whole story. Legge *et al.* (1985b) found differences between subjects with central loss and those with residual central vision that could not be traced to simple scaling laws. More likely, a complete picture will include consideration of several factors such as lateral masking in peripheral vision (Bouma, 1973) and impairments in eye-movement control (Whittaker *et al.*, 1986). We do not know how these factors interact with contrast reduction, but as a starting point, we can examine the hypothesis that subjects with central loss will show a reading dependence on contrast that has the same form as for normal subjects, when differences in contrast sensitivity are taken into account.

The loss of peripheral vision will reduce the number of letters simultaneously visible. As we have previously shown (Legge *et al.*, 1985a, b), at least four or five letters must be visible for optimal reading of scanned text. But provided that the intact central field is large enough to accommodate four to five letters, we would expect peripheral loss to have no special effect on the contrast requirements for reading. However, peripheral field loss may also be accompanied by a reduction in central visual function. Contrast sensitivity may be reduced in glaucoma (Atkin *et al.*, 1979), retinitis pigmentosa (Hyvarinen *et al.*, 1981), and other diseases which primarily affect peripheral vision. Although there are no data on superthreshold contrast coding in these disorders we may assume, for simplicity, that the contrast response is scaled down. Therefore subjects with peripheral field loss and reduced contrast sensitivity should also perform like normal, except for contrast attenuation.

For each group of low-vision observers we are lead to the same prediction: the dependence of reading on contrast should have the same form as for normal observers if scaled appropriately for contrast attenuation. We refer to this as the *contrast attenuation hypothesis*. A direct measure of the contrast scaling factor is the contrast threshold for isolated letters. We also measured contrast sensitivity functions (CSFs) for sine-wave gratings to determine whether some property of the CSF predicts reading performance.

Traditional assessment of visual function has relied heavily on measures of visual acuity. We have found that near acuity measured with

Sloan *M* cards (Sloan and Brown, 1963) is a good predictor of optimal character size in reading (Legge *et al.*, 1985b). However neither near acuity nor distance acuity is a good predictor of maximum reading speed (Legge *et al.*, 1985b). Brown (1981) examined the relationship between low-vision word recognition speed, acuity, and contrast sensitivity. He found that contrast sensitivity measured with Arden Plates was a better predictor of recognition speed than visual acuity. In the present study, we compare near acuity, distance acuity, and contrast sensitivity measures, as predictors of the effects of contrast on reading speed.

The effect of contrast polarity on normal reading has been widely studied (for a review see Legge *et al.*, 1987). The major finding is that there is little difference in reading speed for white-on-black vs black-on-white text over a wide range of character sizes, from 0.06 to 12 deg (Legge *et al.*, 1985a) or as a function of contrast magnitude (Legge *et al.*, 1987). However, it has long been known in clinical practice that some low-vision observers read better with "reverse contrast" text, that is, white letters on a black background (see e.g. Sloan, 1977). This question was studied by Legge *et al.* (1985b) who found that low-vision observers with cloudy ocular media read up to 50% faster with reversed-contrast text. In the study reported here we extended this work by measuring the effects of contrast polarity across a wide range stimulus contrasts.

The contrast polarity effect is probably due to abnormal light scatter in eyes with cloudy media. Light is scattered by media opacities to produce a veiling luminance that reduces retinal-image contrast. Photometric measurements indicate that in a page of black print on a white background, more than 80% of the page is high-reflectance white and a source of light scatter. Less than 20% of the page's surface is covered with black ink. In the opposite contrast polarity, these proportions are switched. This asymmetry may explain why people with cloudy media read white-on-black text faster. Legge *et al.* (1986) proposed that the contrast-reduction factor due to light scatter can be estimated by measuring contrast thresholds. They analysed in detail the performance of one subject with severe corneal vascularization. His contrast thresholds for the identification of 6 deg letters were elevated by factors of 16.9 for black-on-white letters and 12.1 for white-on-black letters above thresholds for subjects with normal vision. Legge *et al.* were able to account for the quantitative differences in this subject's reading performance with the two contrast polarities by assuming that he behaved normally except for contrast attenuation by unequal amounts in the two cases.

Gardner (1985) studied contrast polarity effects in 18 low-vision children. None were reported to have cloudy media, but nine were albinos who might be subject to light-scattering effects through the poorly pigmented iris. There was no difference in letter recognition scores for white-on-black vs black-on-white letters across the group as a whole. However, the data were not analyzed separately for the albino subjects, so it is not possible to determine whether they showed a contrast-polarity effect.

METHOD

This paper is concerned primarily with the effects of contrast on reading speed. In addition we measured contrast thresholds for letter recognition, contrast sensitivity functions for sine-wave gratings, and near and distance acuities of our low-vision observers. All tests except near acuities were conducted in a darkened room.

Reading speed measurements

A detailed description of the apparatus and procedures used to measure reading speed as a function of contrast has been given previously (Legge *et al.*, 1987). Briefly, text was displayed on a high-resolution monochrome monitor (Conrac SNA 17/Y) with P4 phosphor. The maximum luminance of the display was 300 cd/m^2. The monitor was driven by a Grinnell Systems GMR 274 frame buffer, used in conjunction with an LSI-11/23 laboratory computer. The frame buffer had a resolution of 512 × 512 pixels and 256 grey levels. An alphabet of upper and lower case letters was digitized with an RCA TC-1005/01 high resolution monochrome TV camera, and stored on computer disk. The letter font was a typical typesetting font with serifs (Zip-a-Tone Century Schoolbook). Under computer control, a line of text drifted smoothly at a constant rate across the TV monitor. Scan rates up to 60 characters/sec could be obtained. Text was selected from materials designed to test reading ability and ranged in difficulty from Grade 4 to secondary school levels.

Contrast polarity (white letters on a black background or black-on-white) was changed by inverting the frame buffer's look-up tables. Text contrast was defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$. Contrast was controlled with a video bandwidth, programmable 12-bit attenuator (Foresight Products, Syracuse, NY). The attenuator increased the luminance of the dark parts of the field and left the luminance of the bright areas constant. Thus, for black-on-white text, the luminance of the black letters increased as contrast was reduced, while for white-on-black text the luminance of the black background increased as contrast was reduced.

The luminance of the video display was a nonlinear function of output grey level (as measured with a UDT 80X Opto-Meter). This nonlinearity was taken into account for all contrast calculations. The nonlinearity introduced small contrast-dependent distortions in the luminance profiles of the letters. These distortions are small compared with the distortion (blur) that we have previously shown to have no effect on reading speed (Legge *et al.*, 1985a).

The TV screen was masked to an aperture 25 cm wide by 5 cm high. Eight letter spaces, each measuring 3.2 cm from center to center, were visible through this aperture. Our previous research (Legge *et al.*, 1985a, b) has shown that a field of four to five characters is sufficient for optimal reading of scanned text by normal and low-vision observers.

The observer was seated 30 cm from the TV screen. At this viewing distance the letters subtended 6 deg (center-to-center letter spacing). Previous research (Legge *et al.*, 1985b) has shown that the optimal character size varies widely across low-vision readers, but that reading rates obtained with 6 deg characters are highly correlated with reading rates for characters of optimal size.

At the beginning of a reading trial, the first letter of an 80-character line of text was visible at the right edge of the screen. The experimenter gave a warning signal, then pressed a button which caused the text to drift from right to left across the screen, in a single continuous line. The observer read the text aloud. The experimenter adjusted the drift rate between trials until a speed was found for which the observer made one or two errors per line of text. *Reading rate* was computed for each line of text as the number of words read correctly per minute. We used the geometric mean of at least two reading rates as our dependent measure.

Reading speed was measured first for text of the highest contrast (0.96), then in decreasing steps of 0.2 log unit. If reading rate was found to drop sharply with the decrease in contrast, an additional measurement was made at an intermediate contrast level. An entire contrast series was measured with black-on-white text, followed by a series for white-on-black text.

Although our reading measurements were made with drifting text read aloud, control experiments with normal subjects using static text and silent reading (Legge *et al.*, 1985a, 1986, 1987) have shown that reading rate varies with character size, wavelength, and contrast in the same fashion for both methods of presentation. Moreover, the reading of drifting text is similar to low vision reading when text is scanned through the field of a high-power optical magnifier or closed-circuit TV magnifier.

Contrast thresholds for letters

Ten uppercase letters, Sloan optotypes, were digitized. The video attenuator and look-up table were used to control contrast, as in the reading experiment. The TV screen was masked to a square 15 by 15 cm aperture. Black letters, measuring 6.2 by 6.2 cm, were presented one at a time in the center of the bright aperture. Maximum luminance was reduced to 100 cd/m^2, by means of a polarizing filter placed over the display. The lower luminance was used so that it would correspond to luminance levels used in visual acuity and contrast sensitivity tests, and recommended as the standard for visual acuity testing (Working Group 39, 1980).

Contrast thresholds for 6 deg letters were measured at a viewing distance of 60 cm. Beginning with the highest contrast (0.96) a single letter was presented and remained on the screen until the subject responded. Eight letters were presented at the same contrast, and if six or more were correctly identified, the contrast was reduced 0.1 log unit. The subject could elect to skip a contrast level if he or she found the letters very easy to identify. Contrast threshold was defined as the lowest contrast at which a subject correctly identified at least six of the eight letters.

Contrast sensitivity functions

CSFs were measured with a Joyce Electronics CRT (P31 phosphor) driven by a 12-bit digital to analog converter. Stationary vertical sine-wave gratings were synthesized by an LSI-11/23 computer and contrast was controlled with a 12-bit programmable dB attenuator. The mean

Table 1. Subject characteristics

Subject	Age	Brief diagnosis	Distance acuity*	Near acuity**	Central loss	Peripheral loss	Cloudy media
A	45	Cone dystrophy	0.13	3.0	X		
B	45	Macular degeneration	0.40	1.5	X		
C	28	Ocular histoplasmosis	0.25	5.0	X		
D	39	Optic neuropathy	0.03	14.0	X		
E	24	Optic nerve atrophy	0.13	2.5	X		
F	72	Age-related maculopthy	0.17	2.5	X		
G	71	Age-related maculopathy	0.40	7.0	X		
H	21	Retinitis pigmentosa	0.33	1.5		X	
I	19	Optic nerve atrophy	0.04	10.0		X	
J	47	Diabetic retinopathy	0.17	2.5		X	
K	27	Retinitis pigmentosa	0.08	5.0		X	
L	34	Optic nerve hypoplasia	0.17	3.0		X	
M	47	Diabetic retinopathy	0.50	1.0		X	X
N	47	Diabetic retinopathy	0.10	4.0		X	X
O	26	Congenital cataracts	0.13	2.0			X
P	23	Congenital cataract	0.08	2.5			X
Q	35	Corneal vascularization	0.02	20.0			X
R	35	Congenital cataract (aphakia)	0.17	2.0			X
S	35	Congenital cataract (aphakia)	0.03	7.0			X

*Distance acuity is specified in decimal notation. The corresponding Snellen acuity has the same decimal value (e.g. 0.2 is equivalent to 20/100 Snellen. **Near acuity is given as the size of the smallest print (in *M* units, where a 1M letter subtends 1 min at 1 m) that could be read at 40 cm viewing distance.

luminance of the CRT was 300 cd/m^2, which was reduced to 100 cd/m^2 by means of a large polarizing filter.

CSFs were measured with a spatial two-alternative forced-choice procedure. The screen was divided into left and right halves by a 1 cm translucent divider. At the viewing distance of 1 m, each half field subtended 8.6 wide by 12.9 deg high. Vertical sinewave gratings were presented on either the left or right side of the display. The gratings were presented in cosine phase with the center of the half field. They were ramped on gradually to minimize transient temporal cues and remained on until the subject responded. The subject's task was to indicate on which side of the screen the grating appeared by pressing one of two buttons. Tones indicated whether the answer was correct or incorrect. The QUEST procedure (Watson and Pelli, 1983) was used to estimate the observer's threshold (criterion = 75% correct). Contrast thresholds were measured over a range of spatial frequencies from 0.1 to 6 c/deg. At the lowest spatial frequency, slightly less than one full cycle of the grating fit into the half field. Thus at 0.1 c/deg the observer saw a single bright bar flanked by two dark bars. Two thresholds were measured at each spatial frequency. It took about 40 min to measure an entire CSF.

Visual acuity measurements

Distance visual acuity was measured with a Good-Lite 10-foot Sloan chart that was illuminated with a slide projector to 100 cd/m^2. Acuity was measured at 10 feet if the subject could identify the largest letters on the chart at that distance. Otherwise it was measured at 5 or 2.5 feet, as necessary. Subjects were asked to read down the chart until they were unable to read any letters on a line. The experimenter indicated the current line on the chart for those subjects who had particular difficulty maintaining fixation. Acuity was determined by the last line for which at least 75% of the letters were correctly identified.

Near acuity was measured with Sloan *M* cards (Sloan and Brown, 1963) under ordinary room illumination (approximately 405 lx). The test was performed at 40 cm for letter sizes up to 10 M (a 1 M letter subtends 5 min at 1 m) and 20 cm for letter sizes from 10 to 20 M. The subject was instructed to read the card aloud, and near acuity was defined as the smallest letter size the subject could read, however slowly.

Subjects

Data are reported for 19 eyes of 17 low-vision subjects. The characteristics of the observers are given in Table 1. Two subjects were tested twice.

The first, designated N and J, was tested 1 month before and 12 months after focal laser photocoagulation for diabetic retinopathy. The second, designated R and S, had sufficiently different vision in the two eyes to merit separate study.

A brief report was obtained from each patient's ophthalmologist. The diagnosis, field and media classifications were based on those reports. If there was not sufficient information to classify a visual field, we evaluated the central 60 deg (all field measurements refer to diameter, not radius) with a tangent screen. There were seven eyes with cloudy ocular media, mostly due to cataract, and 12 eyes with clear media. Five eyes were classified as "intact field" meaning that there were no dense scotomas in the central 60 deg. Seven eyes were classified as "central field loss" defined as a dense scotoma within the central 10 deg, and possibly in peripheral regions as well. The remaining seven eyes were classified as "peripheral field loss" defined as one or more dense scotomas confined to areas outside the central 10 deg. The majority of our subjects were under 40 years of age. The distribution of ages in our group is different from the population of low-vision subjects in which more than 50% are over the age of 65.

Consent was obtained from each observer after the nature of the experimental procedures had been explained. Since all of our subjects participated in several 2-hr sessions, they had to be highly motivated. The subject's acuities were measured first, followed by contrast sensitivity functions, reading performance, and contrast thresholds for individual letters. Tests were conducted binocularly except for two subjects. P had normal vision in one eye, so this eye was occluded. Both eyes of one subject were tested separately (R and S), as described above. The remaining subjects had one eye that was significantly better than the other; although tested binocularly, their performance was determined by the better eye. Special care was taken to refract each subject for the test distances used.

RESULTS AND DISCUSSION

We are going to look at the reading data in two ways. First we will examine the form of curves relating low-vision reading rate to contrast. We will characterize these curves by two parameters, peak reading rate and critical contrast. Then we will evaluate the contrast attenuation hypothesis, which attempts to relate the effects of contrast on low-vision reading performance to normal reading performance.

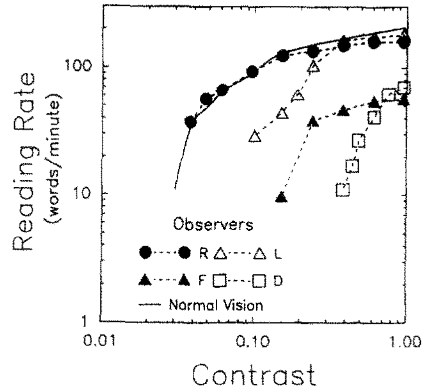

Fig. 1. Reading rate is plotted as a function of contrast for four low-vision observers. Observer designations correspond to entries in Table 1. The solid line represents average data for three normal observers. The standard deviation for normal subjects was about the size of the data points.

The effect of contrast on low-vision reading rate

Figure 1 shows reading data for four observers with low vision. Reading rate is plotted as a function of letter contrast for black-on-white text composed of 6 deg letters. For comparison, the solid curve is average data for three observers with normal vision. Variability among normal observers was quite low. The average standard deviation was about $\pm 15\%$, about the size of the data points. The normal data were discussed in detail in a previous paper (Legge *et al.*, 1987). Note that the normal observers read about 200 words/min at the highest contrast (0.96). As contrast is reduced, reading rate declines slowly at first, then more rapidly with further contrast reduction. Reading rate has dropped to one-half its maximum value at a contrast of 0.09. We refer to this point on the curve as the *critical contrast*. This critical contrast indicates that normal observers can tolerate substantial contrast reduction. More than a 20-fold reduction in contrast is required to reduce reading rate by a factor of two.

It is of practical and theoretical significance to discover how well low-vision observers can read with high contrast, and how tolerant they are to contrast reduction. We will use *peak reading rate* and *critical contrast* as indices of low-vision reading performance.

Observer R is a 35-yr old female with congenital cataract and surgical aphakia. Despite the removal of her cataract, her physician's report indicated cloudy ocular media. R's data (Fig. 1, filled circles), are similar to those of normal subjects for 6 deg letters. Her peak reading rate is 159 words/min (compared to 204 words/min for normal observers) and her critical contrast is 0.08. Note that observer R achieved near normal reading speeds for these large letters despite a visual acuity of 0.17 (Snellen equivalent = 20/120).

Observer L is a 34-yr old female with optic nerve hypoplasia. Her media are clear but her visual field is constricted to a 7 deg central island in her better eye. Although her physician's report indicated no central field involvement, her acuity is reduced to 0.17 (20/120). L's data (open triangles), are near normal at high contrast (peak reading rate = 181 words/min) but her reading speed dropped more rapidly than normal when contrast was reduced (critical contrast = 0.23).

Observer F is a 72-yr old female with ARM. She has a 20 deg scotoma which includes the fovea, with a perimacular 7 by 10 deg island of preserved vision at 5 deg eccentricity, in the better eye. Her visual acuity is 0.17 (20/120). F's reading rates (filled triangles), are depressed at the highest contrast (peak reading = 57 words/min), and her reading speed declined more rapidly than normal with reduced contrast (critical contrast = 0.22).

Observer D is a 39-yr old male with optic neuropathy. He has a dense cecocentral scotoma and a visual acuity of 0.033 (20/600) in the better eye. D's reading rates (open squares) are depressed at high contrast (peak reading rate = 70 words/min) and decline very rapidly with even a slight reduction in contrast (critical contrast = 0.66).

Data for all 19 observers are shown in Fig. 2. Peak reading rate is plotted on the ordinate and critical contrast on the abscissa. Each subject is represented by a single point, with the letter corresponding to subject designations in Table 1. The asterisk represents average values for three normal observers. Filled symbols designate subjects with cloudy media. The symbol shape indicates whether the subject has intact fields (triangle), central field loss (circle), or peripheral loss (diamond). Note that there are no observers with clear media and intact fields or cloudy media and central field loss in our study.

The correlation between log peak reading rate and log critical contrast was −0.65. Observers who read slower at high contrast, showed a faster decline in reading rate with reduced contrast. For a two-fold reduction in peak reading rate there was a four-fold reduction in critical contrast.

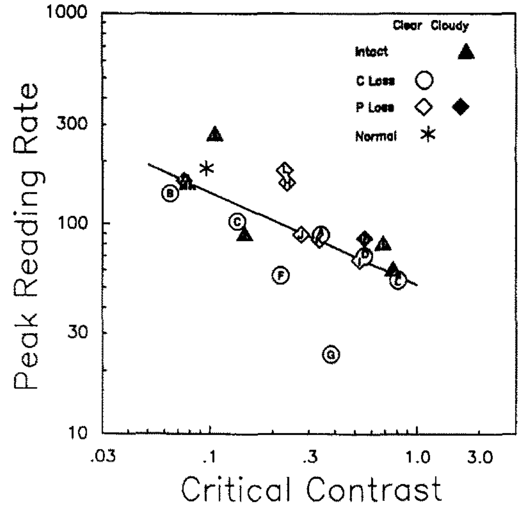

Fig. 2. Each low-vision observer's reading rate at maximum contrast (peak reading rate) is plotted vs the contrast at which reading rate has dropped to 50% of maximum (critical contrast). The letter inside each symbol corresponds to the observer designation in Table 1. A regression line is fit to the data and the correlation coefficient is −0.65.

There were no significant differences in critical contrasts due to types of vision loss (e.g. clear vs cloudy media, or central vs peripheral field loss). For comparison, we also computed critical contrasts for Brown's word recognition data (Brown, 1981, Figs 1 and 2). As in the present study, critical contrasts did not differ significantly between cataract and ARM subjects.

Consistent with our previous data (Legge *et al.*, 1985b) and those of Brown (1981), observers with central field loss had lower peak reading rates than observers with intact central fields (112 words/min ± 24% for intact central field vs 68 words/min ± 14% for central field loss, $P < 0.05$). However the difference is smaller than previously reported. This is probably due to the fact that the previous studies compared reading rates for characters of optimal size, whereas the present study used characters of a fixed size. As Legge *et al.* (1985b) showed, observers with central field loss tend to read best with characters that subtend at least 6 deg, while observers with intact central fields tend to read better with characters smaller than 6 deg. Thus the 6 deg characters used in this study will tend to favor observers with central loss, and minimize differences between the two groups.

It would be of clinical value to be able to predict peak reading rate and critical contrast from more basic clinical measures. We per-

Table 2. Reading and contrast sensitivity data

Subject	Peak reading rate	Critical contrast	Reading rate attenuation	Contrast attenuation	Peak sensitivity	Peak frequency (c/deg)	Cutoff frequency (c/deg)	Letter threshold
A	89	0.341	2.0	4.5	79.3	0.9	8.3	0.031
B	140	0.064	1.4	0.8	266.0	2.5	24.1	0.016
C	103	0.135	2.0	1.8	150.0	0.9	14.4	0.016
D	70	0.555	1.0	13.2	75.0	0.9	4.3	0.050
E	54	0.809	0.7	23.9	41.3	0.9	8.0	0.251
F	57	0.218	3.1	3.2	59.5	2.5	9.8	0.031
G	24	0.382	8.3	3.9	118.0	0.9	13.9	0.025
H	158	0.234	1.1	3.2	39.7	0.9	11.0	0.063
I	67	0.529	1.8	9.2	12.6	0.3	5.1	0.126
J	89	0.273	2.3	3.3	79.3	0.9	11.9	0.039
K	84	0.335	2.0	5.2	74.8	0.9	7.5	0.100
L	181	0.227	1.1	2.6	244.0	0.9	8.9	0.019
M	161	0.075	1.2	1.1	211.0	1.5	26.1	0.012
N	85	0.557	2.2	6.0	63.0	0.9	9.7	0.039
O	272	0.106	0.8	1.1	82.4	0.3	8.1	0.013
P	81	0.685	0.7	17.0	12.0	0.3	3.7	0.125
Q	61	0.763	0.7	20.8	16.8	0.1	1.1	0.158
R	159	0.078	1.3	0.8	282.0	0.9	12.0	0.007
S	90	0.147	2.3	1.4	141.0	0.9	9.7	0.010

formed a multiple regression analysis to evaluate the predictive value of the following clinical measures: near and distance visual acuity, contrast sensitivity for 6 deg letters and contrast sensitivity functions for sinewave gratings, state of the ocular media and visual fields. There are many different measures that can be extracted from the CSF. We have previously shown (Pelli *et al.*, 1986) that in our sample of low-vision observers, most of the between-subject variance in CSF data can be accounted for by only two parameters—peak contrast sensitivity, and cutoff frequency. In addition to these, we also included contrast sensitivity at each spatial frequency tested, and the frequency at the peak of the CSF. With the exception of contrast sensitivity at each spatial frequency, all of these measures are listed for each observer in Table 2. The analysis was done on the logarithms of the two dependent measures (peak reading rate and critical contrast) and all numeric variables. Cutoff was estimated for each observer by extrapolating from the highest two frequencies tested. The extrapolation was done on linear frequency and log contrast coordinates since Campbell and Robson (1968) have shown that the normal CSF for sinewave gratings decreases exponentially above the peak frequency. Multiple regression analyses were performed with SYSTAT on an IBM-AT computer. Further details of the multiple regression procedure are given in Legge *et al.* (1985b).

Table 3 lists the best predictors of critical contrast and peak reading rate. The best predictor of critical contrast is contrast threshold for 6 deg letters, which accounts for 76% of the variance. Peak contrast sensitivity was almost as good a predictor (59% of variance accounted for), which is not surprising since these two measures of contrast sensitivity are highly correlated ($r = 0.84$). With the addition of near acuity, the model accounts for 83% of the variance. No other predictor significantly improves the fit of the regression model.

There was not a strong correlation between any of the variables and peak reading rate. The best single predictor was contrast sensitivity at 0.3 c/deg which only accounted for 37% of the variance. By adding near acuity and cutoff frequency we could account for 66% of the variance but several other combinations of variables were nearly as good.

Table 3. Multiple regression analysis of critical contrast and peak reading rate

Critical contrast Predictor(s)	Multiple r	Multiple r^2*	Peak reading rate Predictor(s)	Multiple r	Multiple r^2
Letter threshold	0.87	0.76	CS 0.3 c/deg**	0.61	0.37
Letter threshold + near acuity	0.91	0.83	CS 0.3 c/deg + near acuity	0.72	0.52
			CS 0.3 c/deg + near acuity + cutoff	0.81	0.66

*Proportion of variance accounted for. **Contrast sensitivity at 0.3 c/deg.

We previously reported (Legge *et al.*, 1985b) that central field loss and clarity of the ocular media were good predictors of peak reading rate and accounted for more of the variance than clinical measures such as visual acuity. In the present study, media and fields were not good predictors of peak reading rate. However in the earlier study peak reading rate was measured with each observer's *optimal* character size. Reading rate declined as character size departed from the optimal size. Since optimal character size was highly correlated with near acuity we would expect an indirect correlation between near acuity and reading rate when characters of a *fixed* size are used, as in the present study. Alexander *et al.* (1986) measured reading rate for a fixed character size in patients with macular disease. She, too, found that acuity was a good predictor of reading rate.

The results of Legge *et al.* (1985a) and Ginsburg (1978) suggest that information sufficient for fast reading is contained within a one-octave wide band of spatial frequencies extending upward from the fundamental frequency of the letters. Parish and Sperling (1987) have found that normal observers are more efficient at extracting information about letter identity from this band than from other octave-wide bands. It is natural to suppose that low-vision reading performance may be related to a subject's contrast sensitivity within this "critical band". The fundamental frequency of letters is the reciprocal of the center-to-center letter spacing.* For 6 deg letters this is 0.17 c/deg, so the critical bandwidth extends from 0.17 to 0.34 c/deg. We have found that both peak reading rate and critical contrast were more highly correlated with contrast sensitivity at 0.3 c/deg ($r = 0.61$ for peak reading rate and -0.74 for critical contrast) than at other spatial frequencies.

Brown's (1981) study of word recognition used letters of various sizes, depending on each subject's preferred magnification. Yet he found that contrast sensitivities over the range of 0.2–0.4 c/deg were good predictors of recognition speed for low contrast words, regardless of size. This suggests that performance may be governed by sensitivity in a retina-based band of spatial frequencies (approx. 0.2–0.4 c/deg), rather than in a band locked to the fundamental of the letters. For this hypothesis to produce different results from the "critical band" hypothesis, it must be assumed that sensitivities in the different spatial frequency bands are independent (uncorrelated).

Pelli *et al.* (1986) have argued that low-vision contrast sensitivities are highly correlated across spatial frequencies, and that just two parameters are sufficient to characterize the CSF. This does not necessarily conflict with (independent) channel models. First, it has sometimes been argued that at low spatial frequencies (those most important for low-vision reading of large letters), simple detection is better described by a single-channel model (see e.g. Legge, 1978; Campbell *et al.*, 1981). Secondly, whatever the nature of the pathology in low vision, it will usually be channel nonselective, and hence depress sensitivity across a wide range of spatial frequencies.

If sensitivities were perfectly correlated across spatial frequencies, we would not be able to distinguish between the two hypotheses. One consequence would be that the correlation between peak reading rate and contrast sensitivity across different spatial frequencies would be constant, regardless of character size. Figure 3 plots the correlation between reading rate and contrast sensitivity as a function of spatial frequency, for three character sizes—1.5, 6 and 24 deg. The correlations for all letter sizes peak at 0.1 or 0.3 c/deg, contrary to the critical band

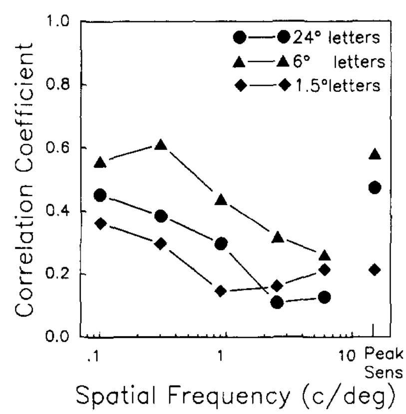

Fig. 3. The correlation between reading rate and contrast sensitivity at the indicated spatial frequency is plotted for text of three sizes. The symbols at the far right indicate the correlation between reading rate and peak contrast sensitivity.

*A line of text consisting of repetitions of the same letter has a fundamental frequency equal to the reciprocal of the period of repetition. Since an individual letter is an aperiodic pattern, its Fournier transform is continuous. Nevertheless, the critical information distinguishing one letter from another is contained in spatial frequencies above the original fundamental frequency. Therefore it is convenient to retain the notion of fundamental frequency, even though real text is nonperiodic.

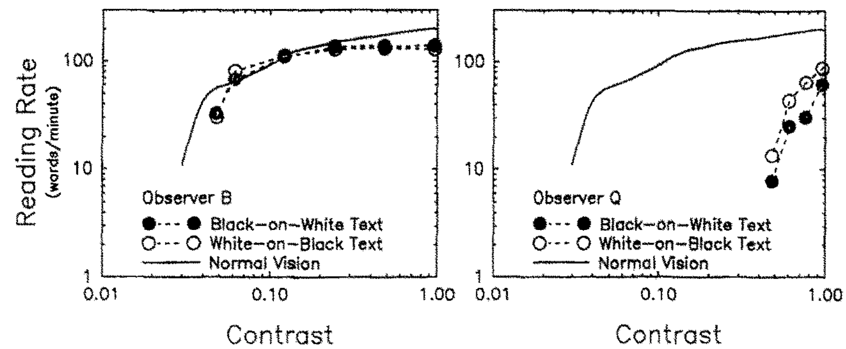

Fig. 4. Reading rate functions are plotted for two low-vision observers. Each panel contains data for both black-on-white and white-on-black text, as well as average data for normal observers (either contrast polarity). The observer on the left shows no consistent contrast polarity effect. The observer on the right reads better with reversed-contrast text.

hypothesis. There is no evidence that the peak in the correlation function shifts systematically with character sizes. While the peak does not shift, the functions become flatter as the critical band departs from 0.2 to 0.4 c/deg. This suggests that the critical band plays some role in determining reading performance.

The correlation of reading rate with peak contrast sensitivity (plotted at the far right) is almost as high as the correlation at any particular spatial frequency. This means that general shifts in contrast sensitivity among low-vision subjects have greater effects on reading performance than the relatively small changes in sensitivity in different bands.

Up to this point, we have examined data for conventional black-on-white text only. We also measured reading rates for white-on-black text. Figure 4 shows reading rate functions for both contrast polarities for two observers. A single curve represents average data for three normal observers because there were no consistent contrast polarity differences. In the left panel, data are shown for observer B who has central field loss due to macular degeneration, but clear media. Her data show no consistent effect of contrast polarity. Peak reading rates differ by only 4% for the two polarities, with black-on-white reading being slightly faster than white-on-black (140 words/min compared to 131 words/min). But her critical contrast is 10% higher for black-on-white text (0.064 compared to 0.058 for white-on-black). Observer Q, on the right, has intact fields, but cloudy media due to corneal vascularization, secondary to Stevens–Johnson syndrome. His data show a consistent contrast polarity effect. He reads 44% faster with white-on-black text (88 words/min compared to 61 words/min for black-on-white), and his critical contrast is 26% lower for white-on-black text (0.61 compared to 0.76 for black-on-white).

We have attributed this contrast polarity effect to abnormal light scatter in eyes with cloudy ocular media (Legge *et al.*, 1985a; Legge *et al.*, 1987). If this explanation is correct, then we would expect the effect to occur only in observers with cloudy media. Of the seven observers with cloudy media, four read faster with white-on-black text (i.e. higher peak reading rate and lower critical contrast). The remaining three showed no consistent contrast polarity effect. Of the 12 observers with clear media, one read faster with white-on-black text and one read faster with black-on-white text. The remaining 10 showed no consistent contrast polarity effect. The contrast polarity effects were not large. Peak reading rates and critical contrasts for the two contrast polarities differed by no more than 50% for observers showing a consistent polarity effect.

Evaluation of the contrast attenuation hypothesis

In the Introduction we proposed that low-vision curves of reading rate vs contrast will coincide with normal curves when scaled for contrast attenuation. The *contrast attenuation factor* would be given by the ratio of the low-vision subject's contrast sensitivity for 6 deg letters to the normal contrast sensitivity for 6 deg letters, and would appear as a horizontal shift in plots of reading rate vs contrast.

Factors besides optical contrast attenuation or reduction of contrast sensitivity may also act to reduce reading speed. This is likely to be the case in subjects with central-field loss. There-

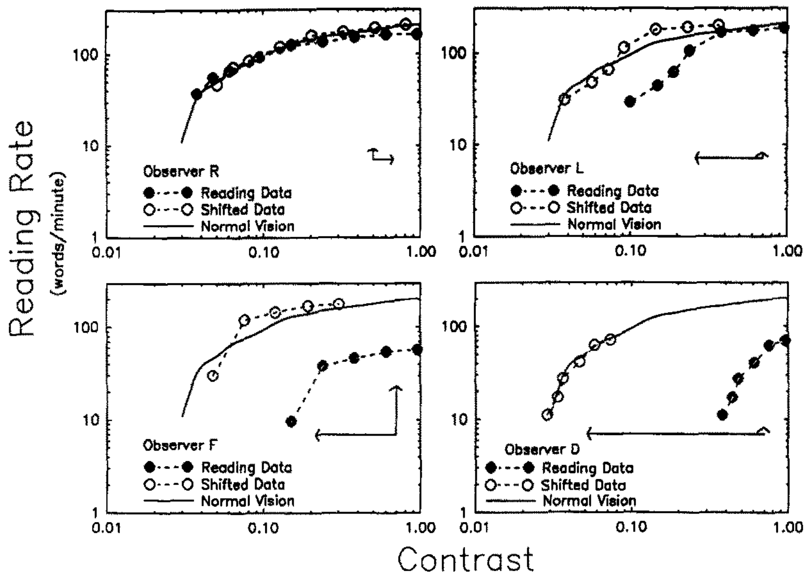

Fig. 5. Reading rate functions are shown for the same four observers whose data appear in Fig. 1. Each panel graphs reading vs contrast (reading data) and the same data shifted horizontally and vertically so that it overlaps the normal curve (shifted data). The horizontal and vertical arrows in each panel represent the contrast and reading rate shifts required for each observer.

fore, low-vision plots of reading rate vs contrast may also require vertical scaling if they are to be brought into coincidence with normal curves. We term this the *reading attenuation factor*; it represents the factor by which reading speed is reduced, after effects of contrast attenuation have been taken into account.

We evaluated this hypothesis by shifting each subject's curve of reading rate vs contrast (as in Fig. 1) horizontally and vertically until we obtained the best overlap with the normal function. A horizontal shift corresponds to a contrast attenuation factor, and a vertical shift corresponds to a reading attenuation factor. We used an iterative search to obtain the best fit in log–log coordinates, according to a least squares criterion. The fits were generally quite good, with rms errors less than 0.2 log units. Figure 5 shows shifted (open circles) and unshifted (filled circles) reading rate functions for the four observers in Fig. 1. The horizontal and vertical lines in the bottom right of each panel indicate how much shift was required in the x and y directions.

Three of the four observers in Fig. 5 required a vertical shift upward, indicating a reading rate attenuation compared to normal observers. Reading rate attenuation factors ranged from 1.1 for observer L to 3.1 for observer F. Except for observer R, whose data had to be shifted to the right, each observer in Fig. 5 required a larger contrast attenuation factor than reading rate attenuation factor. Contrast attenuation factors ranged from 0.8 for observer R to 13.2 for observer D. Contrast attenuation and reading rate attenuation factors are listed for each observer in Table 2.

We compared each subject's contrast attenuation factor for reading with his or her contrast attenuation factor for letter identification (i.e. ratio of contrast sensitivity for 6 deg letters to normal contrast sensitivity for 6 deg letters). Figure 6 is a scatterplot relating the contrast attenuation factor for reading with the contrast attenuation factor for letter identification, both on log scales. The dashed line indicates where the data would fall if the two contrast attenuation factors were equivalent, and the solid line is a regression line fit to the data. The two contrast attenuation factors are highly correlated ($r = 0.92$). This indicates that the dependence of reading on contrast can be predicted from a simple measurement of contrast thresholds for letters.

Figure 7 plots the contrast attenuation factor vs the reading rate attenuation factor for each observer. Filled symbols designate observers with cloudy media, and symbol shape indicates the type of visual field loss, if any. Letters inside each symbol correspond to subject designations in Table 1.

Two observers were tested twice. One was

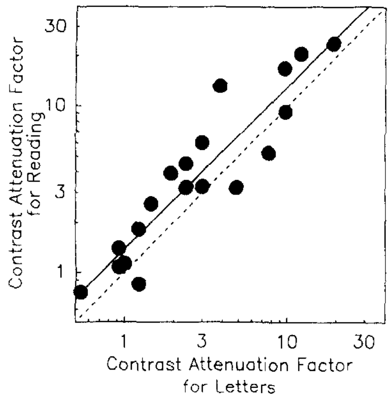

Fig. 6. The contrast attenuation factor for reading is the amount of contrast shift required for the low vision data to overlap normal data. This factor is plotted vs the contrast attenuation factor for letters, which is the ratio of low-vision contrast threshold for letters to normal threshold. The dashed line indicates where the data would fall if the two factors were in perfect agreement. The solid curve is the actual regression line fit to the data. The data are displaced upward, indicating that the ratio of letter thresholds underestimates the contrast attenuation factor for reading.

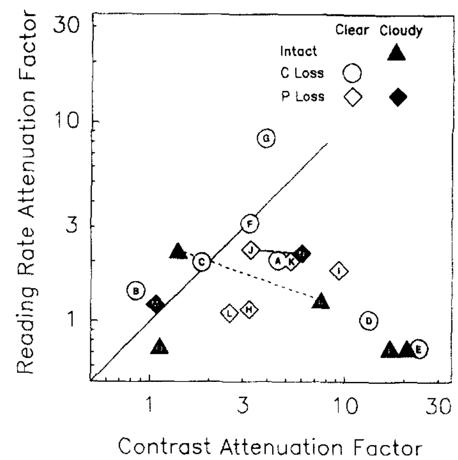

Fig. 7. Reading rate and contrast attenuation factors are shown for 19 low-vision observers. The two factors represent shifts that must be applied to the low-vision reading data so that they most closely overlap the normal data. The letter inside each symbol corresponds to observer designation in Table 1. The dashed and dotted lines connect data points obtained on separate occasions from the same observer.

tested before and after laser treatment for diabetic retinopathy. His data are connected by the solid line in Fig. 7. According to the physicians' reports, this observer had peripheral field loss both before and after treatment, but his ocular media were cloudy before treatment, and clear after treatment. Note that the only change in his data is a reduction in the contrast attenuation factor, indicating less contrast attenuation after treatment.

The other observer's two eyes were tested separately. Both had cloudy media despite surgical aphakia following congenital cataracts. Data for the two eyes are connected by a dashed line. The magnitude of the contrast attenuation and reading rate attenuation factors were both greater for the left eye, which also had significantly worse acuity (0.031 or 20/640 compared to 0.17 or 20/120).

Most subjects lie to the right of the diagonal line, indicating greater contrast attenuation than reading rate attenuation. In fact, most of the subjects with cloudy media had reading rate attenuation factors near 1 (and the average reading rate attenuation factor did not differ significantly from 1, $P > 0.4$). For these subjects, it appears that reading speed is limited primarily by contrast attenuation. Several subjects with central field loss had reading rate attenuation factors that were substantially greater than 1 (and the average reading rate attenuation factor was marginally different from 1, $P < 0.07$). Thus, as expected, changes in effective contrast alone cannot account for the abnormalities in their reading performance. But the contrast attenuation factor was, on average, 6.7 times greater than the reading rate attenuation factor. This indicates that changes in effective contrast, due to optical scattering or nonoptical reductions in contrast sensitivity, play a significant role in limiting low-vision reading performance.

SUMMARY

The dependence of reading rate on contrast seems, at first, to vary widely across low-vision observers. For text composed of large (6 deg) letters, some low-vision subjects are as tolerant to contrast reduction as normal subjects. Their reading rates do not drop to half maximum values (the "critical contrast") until contrast has been reduced to about 0.1–0.2. Others are more sensitive to even a slight reduction in contrast, with critical contrasts as high as 0.8. The degree of sensitivity is not determined by the eye disease that caused the vision loss, nor by the type of vision loss (cloudy media, central or peripheral field loss). But it appears to be highly predictable from measures of sensitivity for letters.

So it is gratifying, from both theoretical and practical standpoints that contrast effects on low-vision reading are closely related to contrast sensitivities of low-vision observers. The practical implication is that we can easily determine which low-vision observers will benefit most from contrast-enhancing low-vision aids, and conversely, which observers will suffer most under poor contrast conditions. It appears that an overall reduction in an observer's contrast sensitivity has a greater effect on reading performance than small depressions in sensitivity at particular spatial frequencies. Therefore, we need not administer elaborate psychophysical tests of contrast sensitivity, but simply measure peak contrast sensitivity. Pelli *et al.* (1988) have developed a chart for such a purpose, that is as quick and easy to use as an ordinary acuity test.

The main result of theoretical interest is that many of the low-vision subjects studied here can be described as "contrast attenuators". The effect of contrast on reading is the same for them as for normal observers if contrast is scaled appropriately (i.e. according to contrast sensitivity). The contrast attenuation may result from optical factors, such as intraocular scatter in eyes with cloudy media, or from a reduction in effective contrast in eyes with field loss.

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