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PSYCHOPHYSICS OF READING—II. LOW VISION

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Abstract—Very little is known about the effects of visual impairment on reading. We used psychophysical methods to study reading by 16 low-vision observers. Reading rates were measured for text scanned across the face of a TV monitor while varying parameters that are likely to be important in low vision: angular character size, number of characters in the field, number of dots composing each character, contrast polarity (white-on-black vs black-on-white text), and character spacing. Despite diverse pathologies and degrees of vision loss in our sample, several major generalizations emerged. There is a wide variation in peak reading rates among low-vision observers, but 64% of the variance can be accounted for by two major distinctions: intact central fields vs central-field loss and cloudy vs clear ocular media. Peak reading rates for observers with central-field loss were very low (median 25 words/minute), while peak reading rates for observers with intact central fields were at least 90 words/minute (median 130 words/minute). Most low-vision readers require magnification to obtain characters of optimal size. Sloan *M* acuity was a better predictor of optimal character size than Snellen acuity, accounting for 72% of the variance. Low-vision reading is similar to normal reading in several respects. For example, both show the same dependence on the number of characters in the field. Our results provide estimates of the best reading performance to be expected from low-vision observers with characteristic forms of vision loss, and the stimulus parameters necessary for optimal performance. These results will be useful in the development of clinical tests of low vision, and in the design of low-vision reading aids.

Low vision Reading Psychophysics Acuity Visual field Contrast

INTRODUCTION

Low vision offers a challenge to visual science. As yet, our knowledge of vision is insufficient to predict the effects of visual impairment. Common clinical measures of visual capacity, like Snellen acuity, have proven to be poor predictors of performance on everyday tasks such as reading, face recognition, and mobility. There are two major gaps in our knowledge. We don't know how to characterize the visual limitations of a low-vision subject, and we don't know what role vision plays in everyday tasks.

Although definitions of low vision abound (Faye, 1976), we will define *low vision* as the inability to read a newspaper, with best spectacle correction, at a normal reading distance (40 cm). The National Society to Prevent Blindness (1977) has estimated that about 2 million people in the U.S.A fall into this category. Since the prevalence of low vision is greatest among the elderly, the number is growing as American longevity increases.

For most people with low vision, the inability to read normally is a serious handicap. A major purpose of our research is to discover how visual disorders of various kinds limit reading performance. In the first paper of this series (Legge *et al.*, 1985), we showed how normal reading performance is influenced by factors that are likely to be important in low vision. In the present paper, we will report the results of extensive reading measurements on a group of low-vision observers having a broad range of pathologies. In the third paper of this series (Pelli *et al.*, 1985), we will describe a new reading aid whose design is based on the results presented here.

Low vision encompasses a great variety of pathologies. Defects in the eye's optics, the retina, or other parts of the visual system can result in low vision. Our interest is in reading and low vision, not diagnosis. Therefore we worked with a diverse group of observers, hoping to discover general factors that affect reading. We have found two principal factors that affect low-vision reading: (1) whether the central visual fields are intact, and (2) whether the ocular media are clear.

We have adopted a testing procedure in which observers read aloud individual lines of text that are scanned across the face of a TV monitor. The scanning rate is increased until the observer begins to make errors. We compute reading rate, in words/minute, from the number of words correctly read. Reading rate can be measured as a function of any stimulus or observer variable. This procedure has three advantages. First, it allows for easy experimental control of stimulus parameters and for straightforward measurement of reading performance. Second, the reading of scanned text is similar to the way many low-vision people read when they manually scan text through the field of a high-power optical magnifier or across the screen of a closed-circuit TV magnifier. Third, our method helps

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isolate visual limitations from motor limitations. Motor limitations occur when low-vision readers have trouble scanning a magnifier across a line of text, finding a new line, or maintaining text at a critical focal distance from a strong positive spectacle lens (reading addition). Goodrich *et al.* (1977) have shown that many hours of practice are often necessary to achieve best performance with a new reading aid. Undoubtedly, much of the time is taken in acquiring appropriate motor skills. Our method bypasses the motor problems so that reading performance is primarily determined by visual factors. A disadvantage of our method is that oral reading of single lines of text differs from silent reading of continuous text. This issue is addressed by Legge *et al.* (1985) and is taken up briefly, later in this paper. A procedure similar to ours has been used by Krischer and Meissen (1978; 1983) to study low-vision reading.

In this paper, we report the effects on low-vision reading of character size, character spacing, number of characters simultaneously present in the field, sample density, and contrast polarity. In the following paragraphs, we briefly review the significance of these variables for low vision and our reasons for studying them.

Character size

Magnification is usually critical for low-vision reading. A variety of magnifying techniques exist (Sloan, 1977), but all are aimed at increasing character size on the retina. It is therefore essential to understand how reading rate depends on angular character size. Legge *et al.* (1985) found that for normal observers, the relationship between reading rate and character size has a broad maximum for characters subtending 0.3° (18′) to 2°. Reading rates drop rapidly for characters smaller than 0.3° and slowly for characters larger than 2°. (A 20/20 Snellen letter subtends 5′.)

Do low-vision observers also read best for a restricted range of character sizes? Does low-vision reading performance converge with normal performance for large character sizes? Bouma *et al.* (1982) compared oral reading rates for observers with "high acuity" (greater than 0.8) and "low acuity" (0.1–0.3) for character sizes ranging from about 0.3–2.8°. Even for the largest character sizes, the low-acuity group read more slowly than the high-acuity group.

Field loss might be expected to interact with character size. Clinical experience suggests that observers with central-field defects would benefit from high magnification (see, e.g. Faye, 1976, Chapter 18). But observers with small islands of central vision might achieve optimal reading performance for characters of some intermediate size.

We examined these questions by measuring reading rates for character sizes ranging from 24° to the observer's acuity limit.

Contrast polarity

Contrast is undoubtedly an important parameter in low-vision reading (Brown, 1981). A detailed report on this topic will appear in a later paper. Here we deal only with contrast polarity, that is, white-on-black vs black-on-white text. It is known that some low-vision observers prefer white-on-black print (Sloan, 1977). In many cases, this preference is probably related to abnormal light scatter in eyes with cloudy ocular media. If so, observers with clear media should not exhibit such a preference. To test this prediction and to assess the magnitude of the contrast-polarity effect, we made many of our measurements with both contrast polarities.

Some electronic reading aids are capable of contrast reversal, but they tend to be expensive. It is therefore important to identify those low-vision patients who might benefit from contrast reversal in reading. We asked whether a simple comparison of black-on-white and white-on-black acuities would identify which low-vision observers would read better with white-on-black text.

Sample density

The amount of information available to the low-vision observer is usually less than that available to the normal observer. Information may be lost due to field defect, reduced spatial frequency content (blur), or reduced contrast. The amount of information required to perform a visual task will determine whether the losses experienced by the low-vision observer impair performance of the task. We restricted the amount of visual information in two ways: by matrix sampling, and by limiting the "window" size, i.e. the number of characters in the field.

We have been particularly interested in *matrix displays*. Matrix displays depict visual information, such as pictures or text, by reproducing an array of samples from the original image. Examples of matrix sampling are shown in Fig. 1 of the accompanying paper (Legge *et al.*, 1985). Low-resolution matrix displays may be useful as components of new, low-vision reading aids. The cost of such aids is closely related to the resolution of the display. It is therefore important to know the minimum number of samples/character that is required for effective reading. The results given below indicate that sample densities of only about 13 × 13 samples/character are sufficient for low-vision reading.

Window size

Some observers with severe field loss must rely on small patches of spared retina to read. Only a few characters at a time may fit within the spared region. Even observers with intact fields may often have to cope with reduced "windows" because aids that achieve high magnification do so at the expense of field size as measured in character spaces. It is therefore important to know how reading performance depends on the number of characters simultaneously present in the field. Legge *et al.* (1985) found that for the reading of scanned text, normal observers require fields of only four characters to achieve optimal performance. Usable reading rates were achieved with windows as small as one character space. These values are encouraging for low-vision reading. They suggest that successful reading may be possible with small windows. We examined this issue in detail by measuring reading rates as a function of window size for our group of low-vision observers.

Character spacing

In the course of our experiments, several of our low-vision subjects commented that they thought they would read better if the characters were more widely spaced. These comments suggested to us that a "crowding phenomenon" might be acting to depress reading performance in some cases. The crowding phenomenon (Burian, 1969) is most familiar from its effects in amblyopia. Youngson (1975) compared Snellen acuities for optotypes presented singly or in rows to the normal and amblyopic eyes of 30 children. There was very little difference for normal eyes. For amblyopic eyes, the character size at the acuity limit was, on average, 3.6 times smaller for the single optotypes. It has been shown that lateral-interference effects among adjacent letters reduce letter recognition in normal parafoveal vision (Bouma, 1970, 1973; Loomis, 1978; Skottun and Freeman, 1983). Is crowding a problem in low-vision reading? To answer this question, we measured reading rates as a function of character spacing for two normal and four low-vision subjects.

Reading rate and acuity

Snellen acuities are notoriously poor predictors of low-vision performance on everyday tasks such as reading and mobility. For example, Goodrich *et al.* (1977) measured reading speed as a function of practice over a 10-day period for patients learning to use either a conventional reading aid or a closed-circuit TV magnifier. They also measured near and far letter acuities. With the exception of a weak correlation between near acuity and reading speed on day one for the "TV group," none of the correlations was statistically significant. However, it should be noted that Krischer and Meissen (1983) state that the reading rates of their low-vision subjects showed a "partial dependence" on their opto-kinetic nystagmus measure of acuity, but they do not give correlation coefficients.

There are several reasons why Snellen acuity fails to be a good predictor of reading performance. Nonvisual factors such as motivation or motor coordination may often limit reading ability. Apart from these, Snellen acuity involves the recognition of single letters, a visual task that differs in important ways from reading. As an alternative, Sloan (1977) has developed a test of near acuity, which she named "*M* acuity", in which patients read lines of text printed on cards. Sloan and Brown (1963) have shown that this *M* acuity is only loosely correlated with Snellen acuity, and that *M* acuity is a better guide to the prescription of reading aids. Another factor contributing to the poor predictive power of Snellen acuity is the heterogeneity of low-vision conditions. An observer with a small paracentral island of vision may have reasonably good Snellen acuity but severely impaired reading. A patient with an intact field but very low acuity due to cloudy ocular media may read quite well given sufficient magnification. In order to examine the relation between acuity and reading rate, we measured Snellen acuities and Sloan *M* acuities for our subjects.

METHOD

Apparatus

Apparatus and procedures are described in more detail in the first paper of this series (Legge *et al.*, 1985). The display was a Visualtek Model MV-2 Miniviewer closed-circuit TV system. The screen was masked to an aperture 25 cm wide by 7 cm high through which a single line of text was scanned in each reading trial. Text appeared as white letters on a black background or black letters on a white background. In both cases, contrast exceeded 94%, and the white parts of the field had a luminance of about 300 cd/m^2. (The illumination at the subject's cornea was about 3 lx at a viewing distance of 1 m.)

In most experiments, magnification was set so that 10 character spaces filled the 25 cm screen width. The angular subtense of the characters was controlled by varying the viewing distance, taking care to refract observers appropriately where necessary. *Character size* means the center-to-center spacing of the characters, when printed with normal spacing. In the "window" experiment, portions of the screen were occluded to limit the number of letters simultaneously present. In the "spacing" experiment, text was printed with either normal spacing (2.5 cm center-to-center distance between adjacent letters on the screen), one and one-half times normal spacing, or twice normal spacing.

To create a matrix display, a black opaque acetate sheet with a regular array of transparent holes was placed over the TV screen. The sample density associated with the matrix display is designated $N \times N$ samples/character, indicating that the array consisted of N holes horizonally by N holes vertically per nominal character size (usually 2.5 cm).

Procedure

Prior to experiments with a low-vision observer, a brief clinical history was obtained. In most cases, reports from ophthalmologists were also available. Snellen acuity was measured. Near acuity was obtained with Sloan *M* reading cards (Sloan and Brown, 1963). The *M* cards consist of short sentences in high-contrast (93%) black print on a white background of luminance $190\ \mathrm{cd\ m^{-2}}$. The card with the smallest print is labelled 1 M, because the height of the lower-case letters subtends $5'$ at 1 m. The other cards contain print scaled in integer multiples of this basic size. *M* acuity is determined by the card having the finest print that can be read without errors, even if very slowly, at a viewing distance of 40 cm (except for 14 M and greater, viewed at 20 cm). An observer who can just read the 1 M card at 40 cm is said to have an acuity of 1 M. We also measured near acuities with photographically produced "reversed-contrast" *M* cards. These cards were identical to the *M* cards except that they consisted of high-contrast (92%) white letters on a black background.

Following the *M*-card measurements, reading trials were conducted. The room lights were turned off and all sources of glare illumination were blocked from the observer. The trial began with the first letter, of a line of text, stationary and 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 observer read the line of text aloud. The number of words correctly read was divided by the scan period to give the *reading rate* in words/minute. A single reading measurement was based on performance on two lines of text scanned at the same rate.

Two procedures were used to collect the reading rate data. The first used a method of constant stimuli. Reading rates were measured for a set of scanning rates that spanned a range from perfect reading (100% correct) to ineffective reading. The second method used an adjustment procedure. The experimenter adjusted the scanning rate until one was found for which the observer made a small number of errors.

In a typical experimental session, reading rates were obtained from one observer while one stimulus parameter was varied, e.g. reading rate as a function of sample density. A typical session took about one hour. However, several of our low-vision observers tired quickly, and several read very slowly. Accordingly, some returned for as many as 15 sessions on separate days to complete all measurements.

Observers

We studied the reading performance of 16 low-vision observers. Consent was obtained from each observer after the nature of the experimental procedures had been fully explained. Table 1 presents characteristics of the subject group. A brief report was obtained from each observer's ophthalmologist. The ocular media have been classified as "cloudy" if the report mentioned corneal scarring, cataract, or vitreous debris. Otherwise they are classified as "clear." Visual fields have been classified into one of three categories. "Intact" refers to an absence of absolute scotomas. "Central loss" indicates absolute scotomas covering all or part of the central 5° (diameter) of the visual field, and possibly scotomas in peripheral regions as well. "Peripheral loss" indicates that there are one or more absolute scotomas confined to non-central areas of the visual field.

Measurements were usually made binocularly with natural pupils. For two observers, reading was sufficiently different in the two eyes to merit separate measurement. These measurements were conducted monocularly, and are shown as H/I, and P/Q in Table 1. Both eyes of observers D, E, G, and L had the same characteristics. These characteristics are shown in Table 1. The remaining observers had large differences in the conditions of the two eyes, with their "better" eye determining their reading per-

Table 1. Characteristics of the low vision subjects

Subject	Age	Diagnosis	Ocular media*	Visual field†
A	27	Retinal detachment	Clear	Peripheral loss
B	35	Occipital infarcts	Clear	Peripheral loss
C	18	Optic nerve atrophy	Clear	Peripheral loss
D	27	Optic nerve atrophy	Clear	Peripheral loss
E	26	Cataract surgical aphakia	Cloudy	Peripheral loss
F	55	Progressive myopia	Cloudy	Peripheral loss
G	26	Congenital cataract surgical aphakia	Cloudy	Intact
H	31	Congenital cataract surgical aphakia	Cloudy	Intact
I	31	Congenital cataract surgical aphakia	Cloudy	Intact
J	34	Corneal vascularization	Cloudy	Intact
K	20	Cataract	Cloudy	Intact
L	26	Diabetic retinopathy	Cloudy	Central loss
M	14	Retinitis pigmentosa	Clear	Central loss
N	25	Optic nerve atrophy	Clear	Central loss
O	25	Ocular histoplasmosis	Clear	Central loss
P	28	Macular degeneration	Clear	Central loss
Q	28	Macular degeneration	Clear	Central loss
R	76	Macular degeneration	Clear	Central loss

*The ocular media are classified as cloudy if the ophthalmologist's report indicates the presence of corneal scarring, cataract, or vitreous debris.

†Peripheral loss refers to absolute scotomas that are confined to non-central regions of the visual field. Central loss refers to absolute scotomas located in the central 5° (diameter) of the visual field, and possibly in peripheral regions as well.

formance. The characteristics of this eye are given in Table 1. Appropriate refractive corrections were provided in all cases. Special care was taken to refract aphakic subjects for each viewing distance.

In this study, our aim was to strike a balance between comprehensive individual measurements, and measurements across a range of low-vision pathologies and degrees of visual deficit. Many of our observers were students, under 30 years of age, and therefore our age distribution differs from that of the low vision population as whole. Only one of our observers (L) was diagnosed as having senile macular degeneration—one of the most common causes of low vision among the elderly. Nevertheless, we expect that many of our results apply to senile macular degeneration because the results appear to transcend specific pathologies.

Our observers were highly motivated. We are quite certain that their reading performance was limited by visual factors, not motivational factors. In all cases, the observers were given enough practice with the reading paradigm to ensure that their performance was stable. We determined that practice effects were negligible by comparing reading rates collected in the first session with those collected in later sessions for several observers. In no case did reading rates increase by more than about 30% for a given set of stimulus conditions.

RESULTS AND DISCUSSION

Our strategy has been to evaluate low-vision reading performance in comparison with data from normal observers. Legge *et al.* (1985) have reported comparable results from normal observers in detail. In most cases, there was very little individual variation among normal observers. Usually, their results could be summarized by single smooth curves. These curves are used in several of the figures in this paper for comparison with data from low-vision observers.

Scanning rate and reading rate

For both normal and low-vision observers, there is a very sharp transition from nearly perfect reading to ineffective reading as scanning rate increases.

In Fig. 1(a) solid symbols represent data for a normal observer, and the open symbols represent data for low-vision observers. Letters next to symbols for the low-vision observers refer to subject designation in Table 1. The horizontal axis is scanning rate in words/minute, representing the rate at which text was scanned across the screen. The vertical axis is the percentage of scanned words correctly read aloud. For all cases shown in the figure, the observers were reading 6° characters.

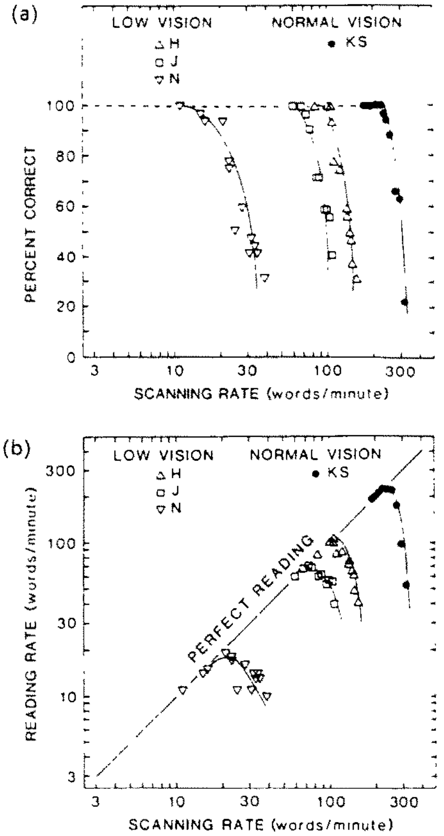

Fig. 1. Reading accuracy as a function of scanning rate. (a) Percentage of words correctly read is plotted as a function of scanning rate for one normal observer (solid symbols) and three low-vision observers (open symbols). Data are shown for 6° letters with a sample density of 22 × 22 samples/character. The horizontal solid line at 100% correct represents perfect reading. (b) The data in panel (a) have been replotted as reading rate vs scanning rate. Reading rate is the product of scanning rate and proportion correct. The diagonal solid line represents perfect reading.

In Fig. 1(a), the sharp transition from perfect to ineffective reading shown by the normal observer is also exhibited by low-vision observers H and J. They differ from the normal observer only because the transition points occur for lower scanning rates. For each, the transition from 100% to 50% occurs for only a 30% increase in scanning rate. The corresponding function for observer *N* is a little shallower and more jagged, but still shows a fairly rapid transition. In general, all of our low-vision observers showed such sharp transitions, but the points of transition varied widely.

From a practical point of view, it is important to realize that a low-vision observer who is unable to read at one scanning rate may read very well at only a slightly lower scanning rate. For instance, J was unable to read when text was scanned at 100 words/minute, but read perfectly when text was scanned at 70 words/minute.

In Fig. 1(b), the data of Fig. 1(a) have been transformed to *reading rate* as a function of scanning rate. Reading rate, in words/minute, is the product of scanning rate and proportion correct. It is a measure of reading performance that represents the rate at which words are correctly read. The peaked nature of the functions in Fig. 1(b) indicates that there is a narrow range of scanning rates for which reading is

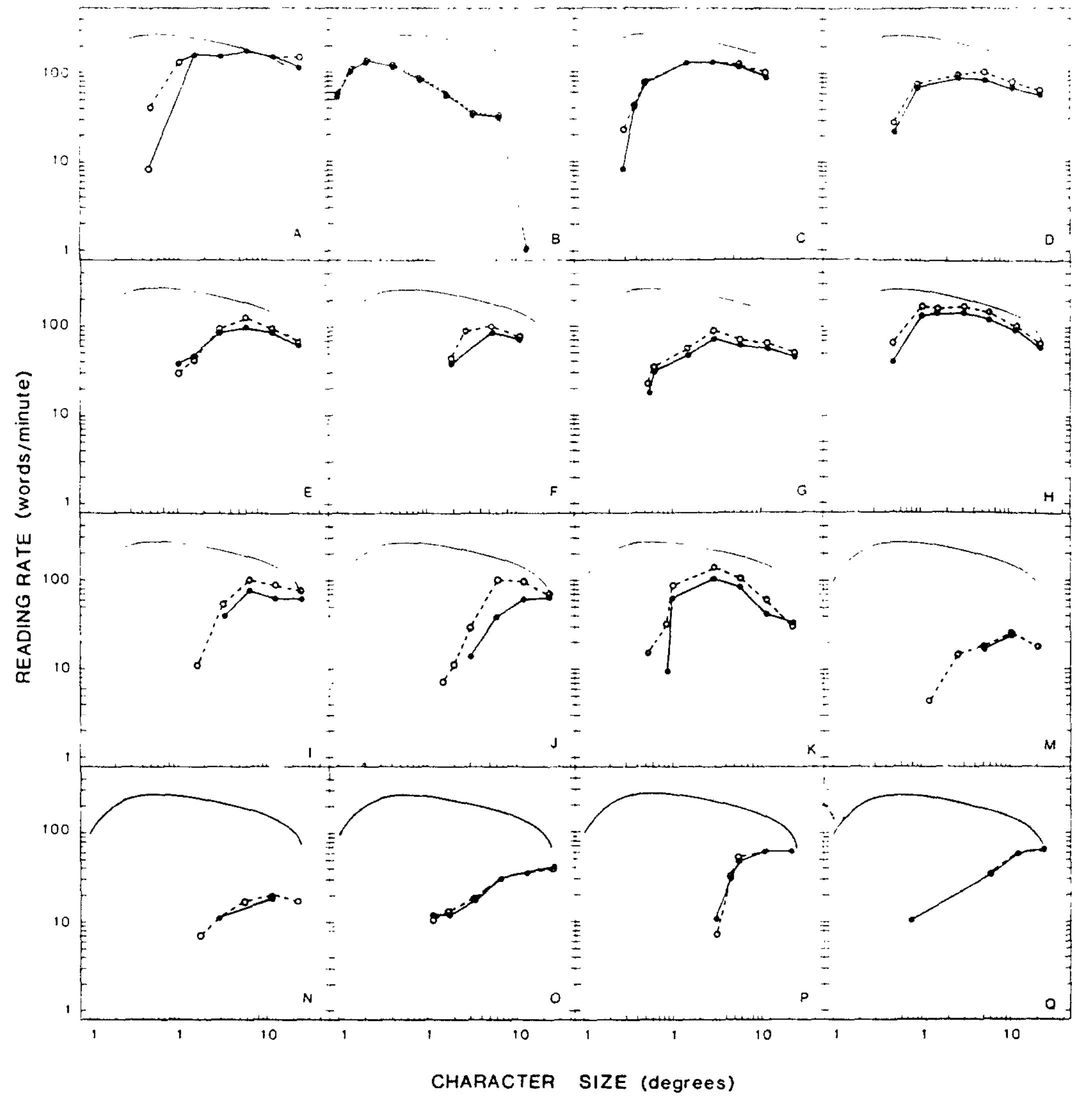

Fig. 2. Effects of character size on reading rate. Reading rate is plotted as a function of character size. Each panel shows data for one low-vision observer. Data are shown for black-on-white text (solid symbols) and white-on-black text (open symbols). The solid curve in each panel represents average data from a group of four observers with normal vision.

optimal, for a specific observer and a given set of conditions. In our study of reading by observers with normal vision (Legge *et al.*, 1985), we discovered that the maximal reading rates, represented by the peaks of functions like those in Fig. 1(b), provide good indices of performance for the conditions in question. We have used this measure in most of our experiments. It isn't necessary to measure entire functions like those of Fig. 1(b) to obtain the maximal reading rate. Instead, the experimenter adjusts the scanning rate until the observer makes a nonzero, but low, proportion of errors. This procedure quickly locates the scanning rate corresponding to the maximal reading rate.

In Fig. 1(b), the diagonal line with slope 1 represents perfect reading, that is, reading rate is equal to scanning rate. For very low scanning rates, all observers performed perfectly. As scanning rate is increased, points are reached at which low-vision observers can no longer read perfectly, and their data drop below the diagonal. Eventually, a scanning rate is reached at which the normal observer can no longer read perfectly, and the data fall below the diagonal.

Effects of character size and contrast polarity on reading rate

The panels of Fig. 2 show reading rate as a function of character size for most of our low-vision observers. Data for observers L and R are not shown because their reading performance was so limited that appropriate curves could not be constructed. Data are shown for 16 eyes, including both right and left eyes of two observers, panels H/I and P/Q.

Data for both white-on-black (open symbols) and black-on-white (solid symbols) text are shown. The solid curve that appears at the top of each panel represents the average performance of a group of four normal observers (Legge *et al.*, 1985). For normal observers, there was very little difference between black-on-white and white-on-black text.

The 16 panels of low-vision data can be classified and discussed in terms of two dichotomies: *intact central fields* vs *central-field loss*, and *clear* vs *cloudy ocular media*.

For observers with *intact central fields* (A–K), the shapes of the curves are similar to those of normal observers in that they exhibit a peak at some intermediate character size with a decline in performance for both larger and smaller characters. The peak usually occurs at character sizes of 3° or 6°. At a normal reading distance of about 40 cm, 8-point newsprint subtends about 0.4°, so these observers certainly require magnification to read a newspaper at optimal rates.

Observer B provides an interesting exception to this pattern of results. Following a sporting accident in which he sustained damage to the cerebral cortex, all vision was lost except for bilateral wedge-shaped fields that include about 5° (diameter) of central vision. His Snellen acuity is 20/15, but he is considerably handicapped in mobility. His reading-rate curve exhibits a peak of 134 words/minute at the very narrow character size of 0.2°. The curve shows a sharp decline for large character sizes. B is one of the few low-vision observers for whom minification may be better than magnification.

Although the peak reading rates achieved by this group of low-vision observers are usually less than normal, they are quite impressive and of great functional significance. Observer A, who suffers from peripheral field loss, actually reads faster than normals do for letters subtending 24°. Observer J's Snellen acuity is 20/960 and he is unable to count fingers beyond two or three feet. Yet, for white-on-black letters subtending 6°, he has a reading rate of about 100 words/minute. Even very modest visual capacities may be of great functional value in specific cases.

For observers with *central-field loss* (panels M–Q) the curves are less peaked than normal, and tend to rise to a maximum at 12–24° character size. Generally speaking, these observers would benefit from ever-increasing magnification, at least up to character sizes of 24°. It should be noted that 24° letters are enormous–this page is 25° wide at a normal 40 cm reading distance.

The peak reading rates for these observers are low. None exceeds 70 words/minute. However, for the largest character size tested (24°), three observers (O, P, and Q) have reading rates that are comparable to those of normal observers.

The difference between observers with intact central fields and those with central-field loss is shown more clearly by the scatter diagram in Fig. 3.

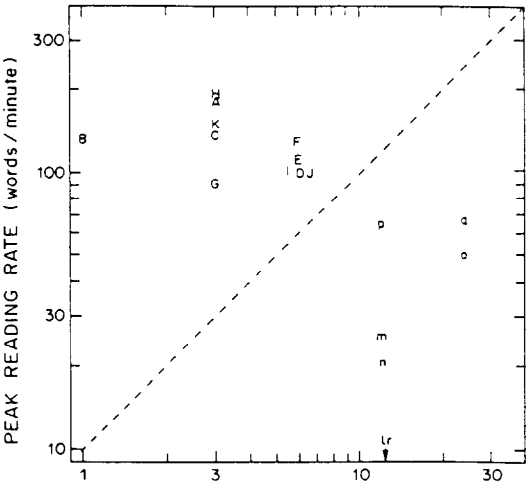

Fig. 3. Relation of peak reading rate to optimal character size. Each observer's peak reading rate is plotted at the character size for which it occurred. The data are for white-on-black text. Each letter represents one low-vision observer. Eyes A–K, which have intact central fields, are plotted as upper case letters. Eyes l-r, which have central-field loss, are plotted as lower case letters.

Here we have plotted each observer's *peak reading rate* against the character size for which it occurred, the *optimal character size*. Each letter refers to a low-vision observer listed in Table 1. Upper case letters (A–K) designate observers with intact central fields, and lower case letters (l – r) designate observers with central-field loss. A normal observer (not shown) would have a peak reading rate of about 250 words/minute at about 0.4° (Legge *et al.*, 1985). The symbols form two clusters. In the upper left quadrant is a cluster of subjects with peak reading rates ranging from 90 to 160 words/minute (median 130 words/minute) at character sizes of 6° or smaller. All of these subjects have intact central fields. In the lower right quadrant is a cluster with peak reading rates ranging from 0 to 68 words/minute (median 25 words/minute) at character sizes of 12° and 24°. All of the subjects in this cluster have central-field loss.

The clustering of subjects in Fig. 3 shows that the single most important factor in low-vision reading is whether or not the central fields are intact.

Now consider the second dichotomy: cloudy vs clear ocular media.

The observers with *cloudy media* (Fig. 2, panels E–K) read better when white letters appear on a black background than vice versa. The magnitude of the effect varies across the range of legible character sizes, but peak reading rates for white-on-black text are 10–50% greater than peak rates for black-on-white text.

The observers with *clear media* (Fig. 2, panels A–D and M–Q) show little difference in reading rate for the two contrast conditions, except for letters near their acuity limits (leftmost points in the panels of Fig. 2).

We computed the ratio of peak reading rates for white-on-black text and black-on-white text for each

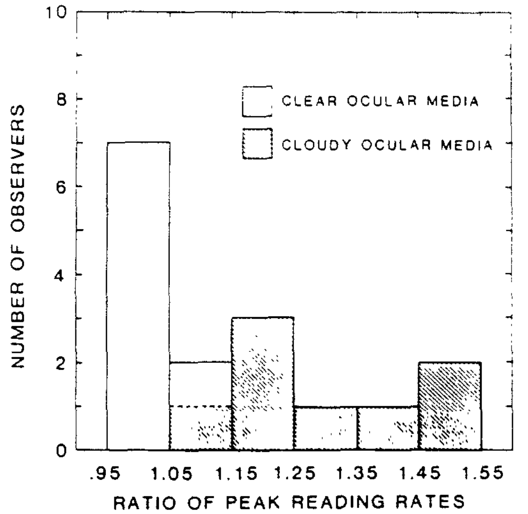

Fig. 4. Effect of contrast polarity on peak reading rate. The ratio of white-on-black to black-on-white peak reading rates was computed for each observer. The height of each bar shows the number of observers with reading rate ratios in the range indicated along the abscissa. Open bars designate observers with clear ocular media. Shaded bars designate observers with cloudy media.

observer. A histogram of the ratios is shown in Fig. 4. Open bars designate observers with clear ocular media. Shaded bars represent observers with cloudy media. Ratios greater than 1.0 indicate that performance is better with white-on-black than black-on-white text. Observers with clear media had ratios near 1.0 (0.97–1.11) while observers with cloudy media had ratios greater than 1.0 (1.10–1.52).

The effect of contrast polarity is not evident in the data of normal observers (Legge *et al.*, 1985). It is probably related to contrast reduction resulting from light scatter within the ocular media. Light scatter will reduce the Michelson contrast of black-on-white text substantially, while having less effect on the Michelson contrast of white-on-black text.*

Prediction of peak reading rate and optimal character size

For clinical practice it would be helpful to know each subject's peak reading rate and optimal character size. The optimal character size determines optimal magnification. The peak reading rate will be important in confirming that the prescribed aid is performing as well as it should. Direct determination of each of these quantities requires a long series of measurements. However, for our sample, 6° characters lie at or near the peak of the reading rate curves in Fig. 2. And, in practice, reading rates for 6° characters are highly correlated with peak reading rates (correlation coefficient = 0.96). Thus, measurement of reading rates under this one condition might provide a good estimate of peak performance.

We also asked whether peak reading rate and optimal character size could be predicted from more common clinical measures, i.e. acuity and state of media and fields. We measured two forms of acuity: Snellen acuity and Sloan *M* acuity. *M* acuities were measured with the regular Sloan *M* cards that have black letters on white backgrounds, and with "contrast-reversed" *M* cards that have white letters on black backgrounds. Table 2 lists these acuities.

We did a multiple regression analysis using *M* acuities (normal and reversed-contrast), Snellen acuity, state of the media, and state of the central field as predictors of optimal character size and peak reading rate for black-on-white text. To do the analysis, we took the logarithms of all numeric variables in Table 2 except reading rate ratio and *M* acuity ratio. We assigned values of 0 or 1 to the nonnumeric variables: 0 = clear ocular media and 1 = cloudy media, 0 = intact central field and 1 = central-field loss. Subjects L and R were excluded from the analysis because their data are incomplete. (Their reading rates were less than 10 words/minute and their Snellen acuities were unmeasurable.) Multiple regressions were performed to determine which predictors contributed significantly toward explaining the variance (Snedecor and Cochran, 1967). Correlation coefficients and proportion of variance accounted for are listed in Table 3. (The *proportion of variance accounted for* is the square of the correlation coefficient.)

The *best predictors* of optimal black-on-white character size are white-on-black *M* acuity and black-on-white *M* acuity, accounting for 76% and 72% of the variance, respectively. Snellen acuity accounts for only 53% of the variance. Adding a second variable to the regression model does not significantly increase the variance accounted for. The regression equations are

$$\log S = -0.06 + 1.31 \log M_{w/b}$$

and

$$\log S = -0.02 + 1.18 \log M_{b/w}$$

where S is the predicted optimal character size in degrees, $M_{w/b}$ is the white-on-black M acuity, and $M_{b/w}$ is the black-on-white M acuity.

The *best predictor* of peak reading rate is state of the central field, which accounts for 59% of the variance. For fixed state of the central field, the best predictor of peak reading rate is state of the ocular media, accounting for an additional 5% of the variance. The regression equation is

$$\log R = 2.12 - 0.53f - 0.14m$$

where R is the predicted reading rate in words/minute, $f = 0$ if the central field is intact and $f = 1$ if there is central field loss, and $m = 0$ if the ocular media are clear and $m = 1$ if they are cloudy.

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*The effect of contrast polarity may be greater in everyday situations than under our laboratory conditions. This is because we blocked all light reaching the eye except from the line of text being read. Informal testing of subject J showed that the effects are greater if the vertical extent of the window is increased. Presumably, this is because more light enters the eye and is scattered, the effect being greater for black-on-white text.

Table 2. Peak reading rate, optimal character size, and acuities for low vision subjects

Subject	Peak reading rate (words/minute) (w/b)	Peak reading rate (words/minute) (b/w)	Reading rate ratio	Optimal character size (degrees) (w/b)	Optimal character size (degrees) (b/w)	M acuity (w/b)	M acuity (b/w)	M acuity ratio	Snellen acuity	Cloudy media	Central loss
A	180	180	1.00	3	3	2.5	2.5	1.00	20/200		
B	132	134	0.99	0.2	0.2	1	1	1.00	20/15		
C	135	136	0.99	3	3	1.5	1.5	1.00	20/50		
D	100	90	1.11	6	3	2	2	1.00	20/120		
E	130	100	1.30	6	6	4	4	1.00	20/200	×	
F	110	100	1.10	6	6	5	5	1.00	20/320	×	
G	90	74	1.22	3	3	3	4	1.33	20/120	×	
H	190	160	1.19	3	3	2	2	1.00	20/120	×	
I	101	87	1.16	6	6	7	8	1.14	20/640	×	
J	100	66	1.52	6	24	14	20	1.43	20/960	×	
K	144	105	1.37	3	3	2	2.5	1.25	20/240	×	
L	6	3	—	12	12	40	40	1.00	—	×	×
M	25	24	1.04	12	12	7	7	1.00	20/200		×
N	20	18	1.11	12	12	7	7	1.00	20/240		×
O	50	50	1.00	24	24	5	5	1.00	20/80		×
P	64	62	1.03	12	12	10	14	1.41	20/480		×
Q	66	68	0.97	24	24	14	14	1.00	20/480		×
R	0	0	—	12	12	—	40	—	—		×

Since both predictors *f* and *m* have only two possible values, there are only four predicted reading rates: 132 words/minute for central intact and clear media, 95 words/minute for central intact and cloudy media, 39 words/minute for central loss and clear media, and 28 words/minute for central loss and cloudy media. This simple four-way prediction accounts for 64% of the variance in peak black-on-white reading rate. Presumably, a more quantitative measure of the state of the central field would account for even more of the variance.

Table 2 also lists the ratio of peak reading rates for the two contrast polarities, and the ratio of *M* acuities for the two contrast polarities. We did a multiple regression analysis using the ratio of *M* acuities, as well as the variables described above, as predictors of reading rate ratio. The results are shown in Table 3. The *best predictor* of reading rate ratio is the state of the ocular media, accounting for 61% of the variance. Adding the *M* acuity ratio to the regression model accounts for an additional 9% of the variance. The regression equation is

$$R_{\text{ratio}} = 0.69 + 0.20m + 0.32M_{\text{ratio}}$$

where R_{ratio} is the ratio of white-on-black to black-on-white peak reading rates, $m = 0$ if the ocular media are clear and $m = 1$ if the media are cloudy, and M_{ratio} is the ratio of black-on-white to white-on-black *M* acuities.

M acuities and state of the central fields and media allow good prediction of optimal character size, peak reading rate, and contrast polarity effects for scanned text. State of the central fields and media account for 64% of the variance in peak reading rate. Conventional *M* acuity alone accounts for 72% of the variance in optimal character size. State of the media and the ratio of black-on-white to white-on-black *M* acuities account for 70% of the variance in the ratio of peak reading rates for the two contrast polarities.

Effects of sample density

We used matrix-sampling to limit the amount of information available to low-vision observers. For this purpose, we placed a black, plastic sheet with a regular array of transparent, circular holes over the face of the TV monitor.

Figure 5 shows the dependence of reading rate on sample density for one normal and three low-vision observers. The *X*-axis shows the number of samples/character and the *Y*-axis shows the corresponding reading rate. For both normal and low-vision observers, graphs of reading rate vs sample density possess a critical point beyond which increased sample density has no effect on reading rate, i.e. the reading rate is the same as that obtained without a sampling grid. The X-coordinate of this point is the *critical sample density*. The critical sample density is the minimum sample density required for optimal reading. In Fig. 5, the critical sample density for the normal observer is about 11 × 11

Table 3. Multiple regression analysis for low vision subjects*

Predictor	Optimal character size (b/w) r	Optimal character size (b/w) r^2	Optimal character size (b/w) r^2+	Peak reading rate (b/w) r	Peak reading rate (b/w) r^2	Peak reading rate (b/w) r^2+	Reading rate ratio r	Reading rate ratio r^2	Reading rate ratio r^2+
M acuity (w/b)	$\underline{0.87}$	$\underline{0.76}$	—	−0.60	0.36	0.03	0.16	0.03	0.01
M acuity (b/w)	0.85	0.72	0.01	−0.57	0.32	0.04	0.22	0.05	0.03
Snellen acuity	0.73	0.53	0.00	−0.28	0.08	0.03	0.44	0.19	0.03
State of central field	0.61	0.37	0.02	$\underline{0.77}$	$\underline{0.59}$	—	−0.45	0.20	0.00
State of ocular media	−0.01	0.00	0.00	0.29	0.08	0.05	$\underline{0.78}$	$\underline{0.61}$	—
M acuity ratio							0.57	0.33	0.09

*r is correlation coefficient.

r^2 is proportion of variance accounted for.

r^2+ is proportion of variance accounted for in addition to that accounted for by best predictor (underlined).

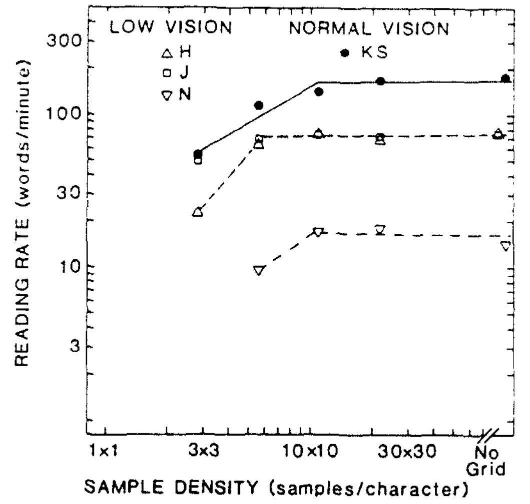

Fig. 5. Effects of sample density on reading rate. Reading rate is plotted as a function of sample density for one normal observer (solid symbols) and three low-vision observers (open symbols). Each observer's data have been fit with a rising straight line and a horizontal straight line. The abscissa value at the intersection of these two lines is called the critical sample density.

samples/character. One of the low-vision observers has the same critical density. For the other two low-vision observers, the critical sample density is lower, about 5 x 5 samples/character.

Figure 6 presents critical sample densities as a function of character size for several experiments with low-vision observers. Each point in the figure is derived from an experiment like the ones whose data are graphed in Fig. 5. Each letter refers to a low-vision observer listed in Table 1. Critical sample densities were estimated by noting the sample density below which reading rates begin to decline.* The rising solid curve represents the results for normal observers [see Fig. 5(a) of Legge *et al.*, 1985]. For normals, the critical sample density ranged from about 4 x 4 samples/character for 0.1° characters to 13 x 13 samples/character for 24° characters. This means that observers with normal vision benefited from more and more samples/characters as character size increased.

The results in Fig. 6 show that the critical sample densities for low-vision observers are, for the most part, less than those for normal observers. As with normals, the low-vision observers show a trend toward increasing critical sample density with increasing character size. The data of Figs 2 and 3 indicated that the low-vision observers with central field loss read best with very large character sizes, 12–24°. Figure 6 indicates that a low-vision aid need supply no more than about 13 x 13 samples/character for characters subtending up to 24°.

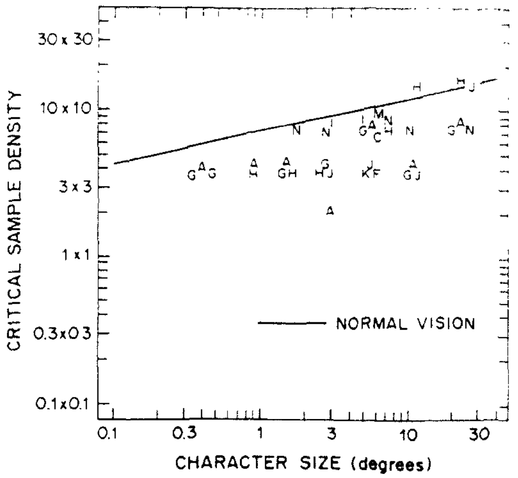

Fig. 6. Effects of character size on critical sample density. Critical sample density is plotted as a function of character size for white-on-black text. Letters refer to low vision observers listed in Table 1. The solid line represents average data from four observers with normal vision.

We found no systematic differences in the values of critical sample densities between observers with and without central field loss. Nor did contrast polarity have any obvious effect on critical sample density.

Effects of window width

In the experiments discussed so far, the display was always 10 character spaces wide. We also measured reading rate as a function of window width, specified in character spaces. Reduced windows were achieved by occluding portions of the TV screen.

Figure 7 presents data from several experiments with low-vision observers. For each set of data, reading rate has been normalized by the reading rate for a 10-character window for the particular experiment. Reading rate is plotted as a function of window width. The two-limbed solid curve was derived from the results of normal observers (Legge *et al.*, 1985). It also fits the low-vision data very well. The effects of window width were the same for our normal and low-vision observers. Reading rate increased with window width up to about four character spaces, after which it increased no further. The rising straight line has a slope of 1/2 in these log–log coordinates. Such a line represents a square-root dependence of reading rate on window width. Beyond the critical window width of about four, there is no further increase in reading rate.

The two-limbed fit to the data in Fig. 7 appears to be a very general description of the effects of window width on scanned reading. It applies to both normal and low-vision observers. It applies to both contrast polarities and across a wide range of character sizes. We had expected to find that observers with varying forms of field loss would show unusual window-

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*The *critical sample density* was defined as the geometric mean of the lowest sample density for which reading rates equal no-grid reading rates, and the next lower sample density. For example, reading rates for observer H in Fig. 2 decline for sample densities less than 5.6 x 5.6 samples per character. The critical sample density would be the geometric mean of 2.8 x 2.8 and 5.6 x 5.6 samples/character, or 4 x 4 samples/character.

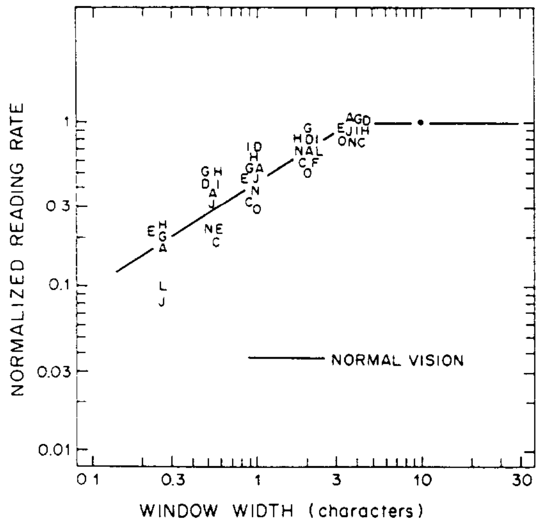

Fig. 7. Effects of window width on reading rate. Normalized reading rate is plotted as a function of window width (measured in number of character spaces) for 6° white-on-black letters displayed with 22 × 22 samples/character. Each observer's reading rates were normalized with respect to the observer's reading rate for a 10-character window. The straight lines represent average data for four observers with normal vision.

width effects. However, for our sample, this was not the case.*

Figure 7 indicates that only four characters are necessary for optimal reading of scanned text. Legge *et al.* (1985) suggested that this limit may be related to retinal inhomogeneity and the pattern of eye movements. Preliminary data from eye-movement recordings suggest that normal observers' eye movements are entrained by the scanned text. The eyes travel with the text across the screen. Then the eyes "snap back" to the starting point with a saccadic movement. The cycle repeats, and a sawtooth pattern similar to optokinetic nystagmus results. The slow phase of the eye-movement pattern has an amplitude that permits four or five new characters to be "painted" on the retina. Perhaps a similar process occurs for many low-vision observers. In fact, we have been surprised by the good reading performance of some low-vision observers who exhibit involuntary nystagmus. For example, observer H, who has moderate nystagmus, has a peak reading rate of 190 words/minute. It may be the case that scanned text is particularly helpful for these observers because the moving images may entrain the eyes, causing their pattern of movement to be more normal that it otherwise would be.

Effects of character spacing

We measured reading rates for two normal observers and four low-vision observers with text having 6°

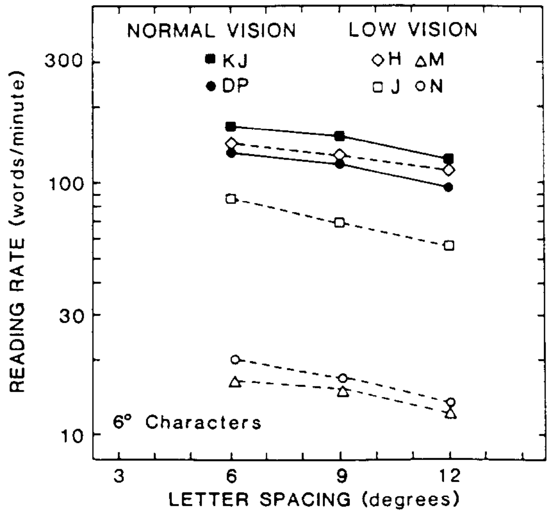

Fig. 8. Effects of character spacing on reading rate. Reading rate is plotted as a function of center-to-center character spacing (measured in degrees of visual angle). Data are shown for two observers with normal vision (solid symbols) and four low-vision observers (open symbols).

letters and 6°, 9°, or 12° center-to-center letter spacing. We occluded portions of the screen so that four letters would be simultaneously present, regardless of the character spacing.

The results of this experiment are presented in Fig. 8. Center-to-center letter spacing is plotted along the horizontal axis, normal at the left and double-width at the right. Each point represents one reading rate measurement. The closed symbols for the two normal observers show a very slight decline in reading rate as letter spacing is increased. All four low-vision observers show a similar decline. H and J have cloudy ocular media but intact fields. M and N have clear media, but central-field loss. No "crowding effect" was found for any of these observers; there was no instance in which reading rate improved when letter spacing was increased. Paradoxically, virtually all observers, normal and low-vision alike, expressed a preference for the condition of intermediate spacing. *M* thought he was reading much better and particularly enjoyed this text. Nevertheless, his reading rate was lower than for text with regular spacing. Previous studies of the effects of character spacing have used letter sizes that approach the acuity limits of normal observers. In the present study, the letters subtended 6°, well within the acuity limits of both the normal- and low-vision observers we tested. The "crowding effect" may not be relevant for such large letters.

Observer-controlled scanning

We had an opportunity to compare our laboratory results with a low-vision subject's performance using his familiar reading aid. Observer J has secondary corneal opacification, an intact field, and a Snellen acuity of 20/960. He makes extensive use, 2 or 3 hours per day, of a closed-circuit TV magnifier. He prefers to operate his CCTV so that white letters are

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*Unfortunately, we were unable to obtain window data from observer B. It may be the case that for large character sizes, he would show a marked departure from the general pattern of window results.

presented on a black background. Typically, he sits at a viewing distance of about 30 cm from the screen and adjusts the magnification so that the height of individual letters is about 6–8 (3–4 cm), with six or seven adjacent characters visible at a time. Characters of this size lie at the peak of his reading-rate curve in Fig. 3, panel J.

In one series of measurements, we fixed the magnification of this subject's CCTV so that the screen was 10 character spaces wide, as in most of our experiments. By varying his distance from the screen, we varied the angular subtense of the characters. We measured reading rates, in words/minute, by counting the words read aloud correctly in intervals of one minute while he manually scanned the text in his customary manner.*

In Fig. 9(a), the open symbols show reading rate as a function of character size, measured in this manner. Each point is the mean of two separate measurements. The solid symbols are laboratory measurements replotted from Fig. 2, panel J. The solid curve that lies above the two sets of data represents performance of normal observers in the laboratory situation. In Fig. 9(b), character size was fixed at 6°, and the effects of window width were measured. Again, open and solid symbols represent reading rates for observer-controlled and experimenter-controlled scanning. The solid curve represents normal performance. It has been vertically shifted to coincide with subject J's data for a 10-character window. The similarity between observer- and experimenter-controlled data in Figs 9(a) and (b) encourages us to believe that our laboratory measurements of low-vision reading are relevant to the use of low-vision reading aids. Finally we compared subject J's oral reading rate with his silent reading rate. The silent rate was only 10% higher than the oral rate, consistent with previous results in normal observers (Legge *et al.*, 1985).

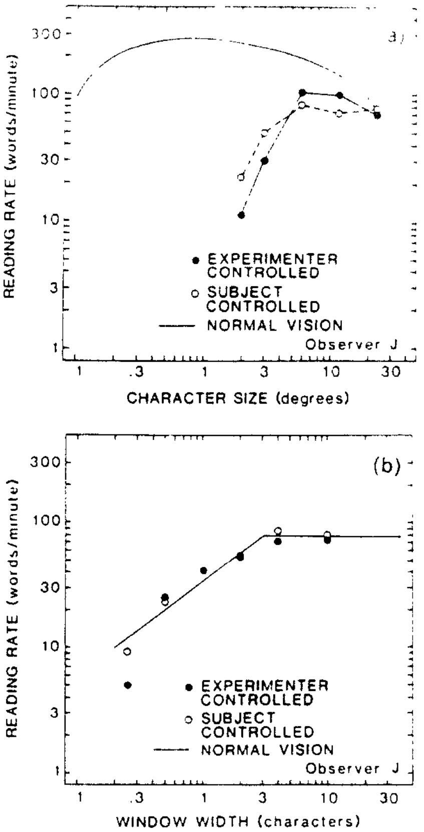

Fig. 9. Effect of experimenter vs subject-controlled scanning on reading rate. (a) Reading rate is plotted as a function of character size for text scanned under experimenter control (solid symbols) or subject control (open symbols). Data are shown for observer J. Data for experimenter-controlled scan are replotted from Fig. 2J. The solid curve represents average data for four observers with normal vision. (b) Reading rate is plotted as a function of window width for experimenter-controlled (solid symbols), or subject-controlled (open symbols) scanning. The straight lines represent average data for four observers with normal vision. They have been shifted vertically to coincide with subject J's data for a 10-character window.

SUMMARY AND CONCLUSIONS

Low-vision reading is similar to normal reading in the following respects:

(1) When the rate at which text is scanned through the visual field is increased, reading remains essentially perfect until some critical scanning rate is reached. For faster scans, reading rapidly breaks down. The critical scan rate depends on stimulus properties of the text, and varies widely among low-vision observers.

(2) When text is subjected to matrix sampling, reading is slowed or made impossible unless the sample density exceeds some critical value. The critical sample density tends to be slightly larger for larger characters. A sample density of 13 × 13 samples/character is equal to or greater than the critical sample density for virtually all conditions.

(3) A field width of four character spaces was sufficient for optimal reading rate by all observers. Reading is slower for fields narrower than four character spaces.

(4) Reading is slowed by increasing character spacing beyond values used in normal text.

There is wide variation in reading performance among low-vision observers. Much of this variation can be traced to two major distinctions: intact central fields vs. central-field loss, and clear vs cloudy ocular media. These two variables account for 64% of the variance in peak reading rates. Observers with intact central fields read 90 words/minute or faster (median 130 words/minute) with suitable magnification and contrast conditions. However, magnification beyond some optimal value (usually around 3° to 6°) results in reduced reading rates. Observers with central-field

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*CCTV magnifiers commonly have a movable X–Y table upon which a page of text rests. The user moves the table by hand to move the text across the screen or to pass to the next line.

loss read more slowly than 70 words minute (median 25 words minute) and seem to benefit from ever-increasing magnification, at least up to 12 –24 character sizes. *M* acuity was a better predictor of optimal character size than Snellen acuity, and accounts for 72% of the variance of optimal character size.

Some low-vision observers read white-on-black text faster than black-on-white text. Most of our subjects with cloudy ocular media fell into this group, while those with clear media showed no difference. The effects were relatively small, never exceeding 50%. Nevertheless, it was possible to predict which observers would read better with white-on-black text by noting the state of the ocular media and comparing *M* acuities measured with black-on-white and white-on-black *M* cards.

Our findings open up three avenues for further study. First, Legge *et al.* (1985) showed that the visual requirements for normal reading are modest. This led us to predict that many low-vision observers would read well, given optimal stimulus conditions. We have confirmed this in the present paper, but with a critical exception. People with central-field loss tend to read very slowly. We are left with an important unresolved question. Does central vision possess unique capacities that are necessary for rapid reading? Or, are the reading deficits associated with central-field loss mediated indirectly by some other cause, such as inadequate eye-movement control? We may further ask whether central vision plays a similar critical role in other everyday tasks, such as face recognition or mobility.

Second, our results suggest that a few commonly available clinical facts are sufficient to predict optimal text characteristics and best reading performance for any low-vision observer. Further study is needed to confirm that specification of the state of the central fields, state of the ocular media, and *M* acuity are all that are required. If so, we have a simple set of measurements to guide clinical evaluation and prescription.

Finally, our results provide design specifications for new low-vision reading aids. In fact, we have developed a fiberscope low-vision reading aid (Pelli *et al.*, 1985) that exploits our findings concerning the low-resolution and modest field requirements for reading.

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