Psychophysics of Reading

Clinical Predictors of Low-Vision Reading Speed

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Clinicians need to estimate how well their low-vision patients will perform everyday visual tasks such as reading or driving. Typically, it is not practical to measure task performance directly or to administer a lengthy series of special tests. Recent laboratory research has suggested that some routine clinical data may be useful in predicting reading performance. The purpose of the present study was to determine whether a promising set of simple measures—Snellen acuity, status of the central fields and ocular media, diagnosis, and age—could be used in a clinical setting to predict reading speed. One hundred and forty one patients who entered the low-vision clinic of the Minneapolis Society for the Blind received thorough eye examinations and a test of reading speed. Snellen acuity accounted for only 10% of the variance in reading speeds overall, but played a more important role for subjects with central loss. Age was a better predictor than acuity. A diagnosis of age-related maculopathy predicted slower reading speed than other causes of central-field loss, but the difference was attributed to age. Media status (clear or cloudy) had no predictive value. Our set of clinical predictors accounted for only about 30% of the variance in low-vision reading speeds. While data from more detailed visual testing might improve prediction, nonvisual factors such as age probably also contribute to the variance. Rather than relying on predictions from visual testing, clinical assessment of low-vision reading may be accomplished most easily with a suitably designed reading test. Invest Ophthalmol Vis Sci 33:677–687, 1992

According to a recent estimate,[1] over three million Americans have impaired vision (corrected visual acuity less than 20/40). About 900,000 of these have acuity less than or equal to 20/200 (a common criterion for legal blindness). For many people, reading difficulty is the most serious consequence of eye disease. Inability to read the newspaper with the best optical correction at a normal reading distance is sometimes used as a definition of low vision.

In a series of studies in our laboratory, we have investigated the stimulus requirements for reading and the effects of visual impairment on reading. We have shown how reading speed depends on the number of characters in the field, angular character size (ie, magnification), blur, contrast, and the colors of text and background.[2-8]

In addition to identifying the stimulus conditions that maximize reading performance, it is important to estimate the maximum performance level. For example, recommendations will be very different for two patients with maximum reading speeds of 25 and 250 words/min. Most clinicians do not specialize in low-vision care and cannot afford the time or expense of labor-intensive special testing or large inventories of low-vision aids. Many low-vision patients never see a low-vision specialist. It would be useful for clinicians to have a simple method for assessing low-vision reading performance. They could use the results to make practical recommendations to their patients or to refer them to specialized low-vision clinics.

Previous research indicates that some routine clinical measures may help estimate reading performance. In this study, we tested 141 patients who entered the low-vision program of the Minneapolis Society for the Blind (MSB). We measured reading speed after a thorough eye examination. Our purpose was to determine how accurately reading speeds could be predicted from a set of routine clinical measures—central field status, ocular media status, Snellen acuity, diagnosis, and age.

Status of the Central Fields and Ocular Media

Legge et al[3] measured reading speed as a function of character size for 16 well-practiced low-vision subjects. From the resulting data, they obtained each subject's maximum reading rate and the character size at

which it occurred. Just two clinical variables—status of the central fields (presence or absence of scotomas) and status of the ocular media (clear or cloudy)—accounted for 64% of the variance in reading speeds. This study confirmed previous clinical findings[9] in showing the particularly deleterious effect central-field loss can have on reading. It also demonstrated that, under laboratory control, clinical data (ie, status of fields and ocular media) are good predictors of maximum reading speed.

The purpose of the Legge et al[3] study was to isolate visual from nonvisual sources of variability in reading performance and to examine the effects of character size (and several other stimulus variables) in low vision. There are difficulties with applying their results to clinical prediction of reading rates. First, nonvisual factors such as motivation and cognitive skills will contribute more variance in a clinical study of reading performance than in a laboratory study that seeks to minimize these factors. In a clinical study, it is not practical—and perhaps not desirable—to go to great lengths to isolate the visual from the nonvisual component of reading. Second, the subject sample was relatively small and somewhat unrepresentative of the low-vision population at large. Many of the subjects were students under 30 years old (median = 28). Only one of the 16 subjects had age-related maculopathy (ARM), the most common cause of low vision. As a whole, the subject sample in the earlier study was a younger, more motivated, highly educated and homogeneous group than would typically be encountered in a clinic.

In the present large-sample study, we evaluated the binary classifications of central fields and media for predicting reading speed in a clinical context. The binary classification of central field status—scotomas present or absent—is obviously very crude. A subject with a huge scotoma that covers the entire macula is classified with a subject with a small parafoveal scotoma. Nevertheless, while it is reasonable to ask a clinician whether there is a central scotoma, it is not reasonable to ask for a detailed central field map. Only sophisticated laboratory techniques—the magnetic search coil method[10] and the scanning-laser ophthalmoscope[11]—are capable of providing reliable maps of central scotomas. Even if such maps were available, how they should be used in the clinical prediction of reading performance is not clear. Similarly, only a binary classification of media status—clear or cloudy—is clinically feasible at present. No agreed upon scale of graded clarity is in common use.

Snellen Acuity

Acuity provides an estimate of the smallest characters that can be read, but maximum reading speed usually occurs for characters far larger than the acuity limit.[3] A priori, it is not clear that acuity should be a good predictor of reading speed. In the Legge et al[3] study, Snellen acuity was only weakly related to maximum reading rate, accounting for just 8% of the variance. Sloan M acuity, based on the Sloan reading cards, was a better predictor of maximum reading rate, accounting for 36% of the variance. This, however, is not a common clinical test. Goodrich et al[12] measured reading speed as a function of the number of practice days for patients learning to use a conventional reading aid or a closed-circuit TV magnifier. They also measured distance acuity (for isolated letters) and near acuity (for text). Except for a weak correlation between reading speed and near acuity on day one for the "TV group," none of the correlations was statistically significant. Krischer et al[13] measured reading speeds and grating acuities for 150 patients in a rehabilitation center. They provided evidence for a linear relationship between reading speed and acuity for decimal acuities less than 0.15 (20/133). They reported correlation coefficients for diagnostic subgroups ranging from 0.83 (35 patients with "retinal disease including retinitis pigmentosa") and 0.81 (31 patients with "refraction anomalies") to zero for 17 cataract patients. The correlation was 0.24 for the nine patients with "macular degenerations."

Diagnosis

Because our selection criteria were very broad, our subject sample included a variety of diagnoses (see Methods). Our largest diagnostic group, age-related maculopathy (ARM), had 45 subjects. We considered the value of ARM diagnosis as a predictor variable. Does knowledge that a patient has ARM tell us anything about likely reading performance above and beyond information on central-field status and age?

We asked two additional questions concerning the ARM subjects. Does their reading performance differ from that of subjects with juvenile forms of macular degeneration (collectively referred to as JMD)? We had 11 JMD subjects with which to make this comparison. This question was motivated by the possibility that people who acquire macular degeneration early in life might adapt more successfully and achieve better reading performance. In a similar vein, we asked whether the number of years since onset of ARM is a predictor of reading performance.

Krischer et al[13] examined how reading performance differed for patients in the following six diagnostic categories (their terms): macular degenerations, refraction disorders, glaucoma, optic nerve atrophy, cataract, and retinal diseases including retinitis pigmentosa. The slopes of regression lines relating reading speed to acuity had different values for these

groups. The authors concluded that diagnosis is predictive of reading speed. Unfortunately, they provided no statistical analyses showing which, if any, of their category distinctions were significant predictors.

Age

Kirchner and Peterson[14] estimated that 71% of people with low vision are over 65 years old. Evidence exists for a variety of subtle changes in the normal aging eye, including deficits in high-spatial-frequency contrast sensitivity.[15,16] It is possible that normal aging may be accompanied by changes in reading performance as well. Recently, Akutsu et al[17] compared reading speeds of young-normal and old-normal subjects. There was no significant difference over the range of character sizes for which normal reading speed is maximum. However, the old subjects showed a slight reduction in reading speed (to about 70% of the young rate) for very small and very large characters. In the present study, we evaluated age as a clinical predictor of low-vision reading speed.

The accuracy with which our set of clinical variables predicts reading speed depends on at least three factors. First, our binary classifications of field status and ocular media status are crude and may imprecisely capture variations in reading speed. Second, some forms of visual deficit may affect reading but may be missed entirely by our set of clinical predictors. For example, spatial-frequency-selective losses in contrast sensitivity sometimes can have an impact on vision (and perhaps reading) without affecting acuity, field, or media as in multiple sclerosis.[18] Finally, nonvisual factors such as motivation, attention, or intelligence may vary across subjects enough to reduce the accuracy of reading-speed predictions.

Our methods in previous studies for measuring reading speed were time consuming and required specialized equipment. We have developed a new computer-based test called the Minnesota Low-Vision Reading Test, MNread for short, which is more suitable for clinical applications. It is described in detail by Legge et al[19] and briefly in the Methods section below. Its purpose is to provide a simple, quick (5 minute), and reliable (test-retest correlation = 0.88[19]) estimate of a low-vision person's maximum reading rate.

Methods

Subjects

There were 141 low-vision subjects and 17 normal subjects. All patients entering the MSB low-vision program participated in the study if they met the following criteria: (1) author JAR was present at MSB to test

the subject; (2) after the procedures were explained, the patient gave informed consent to participate; (3) the patient spoke native English; and (4) informal evaluation indicated no evidence of cognitive deficit.

The breakdown of the subject sample by primary diagnosis is as follows: ARM, 45 (31.91%), diabetic retinopathy, 16 (11.35%), optic atrophy, 15 (10.64%), JMD, 11 (7.8%), retinitis pigmentosa, 10 (7.09%), glaucoma, 8 (5.67%), congenital cataract, 4 (2.84%), retrolentalfibroplasia, 4 (2.84%), myopic retinal degeneration, 4 (2.84%), aphakia, 2 (1.42%), and 22 other diagnoses with one patient each (15.6%). Forty three subjects had secondary diagnoses, 21 of which were cataract. Many of the subjects classified as having cloudy media and central loss had a primary diagnosis of macular degeneration and a secondary diagnosis of cataract. Three of our 45 ARM subjects were excluded from analyses of subgroups with central loss because they had intact central vision. Two central loss subjects were excluded from these same analyses because cloudy media appeared to dominate visual performance. One set of analyses dealt with the 11 subjects who had juvenile forms of macular degeneration. Seven had Stargardt's, one had Leber's, one had Best's, and two were unspecified.

The sample consisted of 86 women and 55 men, with mean ages of 55.6 and 43.9 yr, respectively. There were no significant sex differences in reading rate or acuity. The overall distribution of age is shown in Fig. 1 (mean = 51 years, standard deviation = 22.7, median = 44, range = 14–96). The distribution is bimodal with peaks at 30–40 and 70–90 yr. The 70–90 peak is due primarily to ARM.

Fig. 2 shows the distribution of decimal acuities (mean = 0.146, median = 0.143, range = 0.017–1.0). Acuity values refer to the subject's better eye.

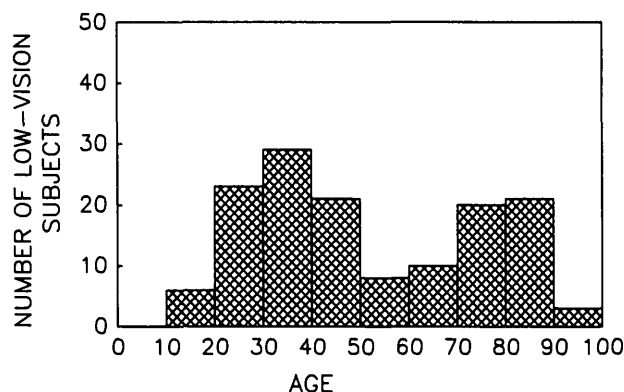How similar is our MSB low-vision sample to the populations seen in other low-vision clinics? We com-

Fig. 1. Frequency histogram of the ages of 141 low-vision subjects. Each subject's age falls into one of the nine 10-year intervals along the horizontal axis. Ages ranged from 14 to 96 years, with a mean of 51 years (SD = 22.7 years).
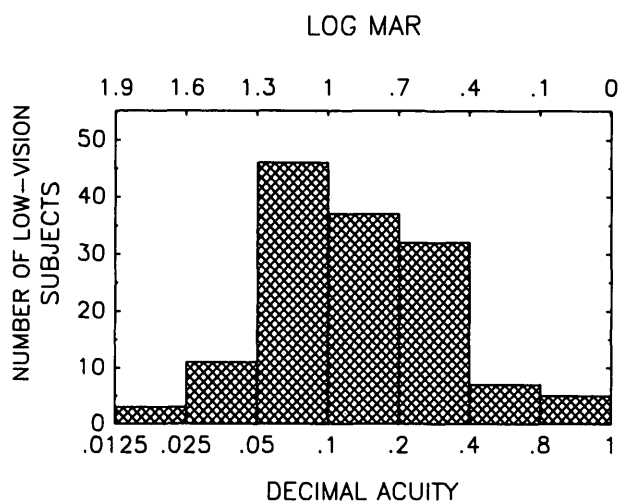
Fig. 2. Distribution of decimal acuities (with corresponding log MAR values) across the sample of 141 low-vision subjects. Decimal acuity is the decimal value associated with a Snellen ratio. For example, a Snellen acuity of 20/200 corresponds to a decimal acuity of 0.1 and log MAR of 1.0.

pared our sample with figures from The Lighthouse Inc. Low Vision Service (New York) on patients who received services there during the 1990 fiscal year (N = 1980). Like the Minneapolis Society for the Blind, the Lighthouse is a private agency that draws on a very broad community base. Only grouped frequency distributions were available from the Lighthouse. Overall, the Lighthouse population was older than our sample (the middle 50% of their distribution lay in the age range 65–84 compared to 32–74 for ours), had lower acuity (approximate median 20/200 compared to 20/140), and had a higher proportion of macular degeneration (53.3% compared to 40%). The low-vision sample studied by Krischer et al[13] (N = 150) was recruited from a rehabilitation center in Dueron, West Germany, in 1981, and was much younger (mean age 28), had about the same mean acuity as our MSB sample, and had a much lower proportion of macular degeneration (6%).

In addition to the 141 low-vision subjects included in the present study, there were nine whose data were not used. One lacked proper documentation, two had ambiguous field or media classification, and six were unable to perform the reading task. Of these six, two had intact central vision and clear media, three had

central loss and clear media (two ARM and one JMD), and one had cloudy media and central loss. Their ages were 30, 46, 25, 83, 82, and 36. The excluded subjects do not fall disproportionately into one category or age group.

Seventeen subjects had normal vision. Eight were relatives of low-vision subjects and were tested at MSB. Nine were recruited separately and were tested with the same procedures in our laboratory. All had acuities of 20/20 or better. Their distribution of ages was similar to the low-vision group (mean = 47.5 years, median = 57, range = 20–73).

Procedures

Prior to measurement of reading speed, each MSB subject was given a thorough eye examination by an optometrist associated with the MSB low-vision program. The exam included ophthalmoscopy, measurement of acuity (Lighthouse distance visual acuity chart), and measurements of fields (Goldmann's perimeter or tangent screen). Values of the clinical-predictor variables were determined in this examination. Each subject was assigned to one of four categories based on the status of the central fields and ocular media. The ocular media were classified as "cloudy" if there was any sign of corneal scarring, cataract, or vitreous debris. Otherwise, they were classified as "clear." A subject was classified as having "central loss" if an absolute scotoma (absence of pattern vision) covered all or part of the central 5° (diameter) of the visual field. Otherwise, the classification was "central intact." Table 1 shows descriptive statistics for the resulting four groups. There was no classification based on peripheral-field loss.

Reading speed was measured using the MNread procedure described in detail by Legge et al[19] Briefly, text was shown on the screen of an IBM color-graphics display connected to an IBM XT computer (IBM Corp.). At the viewing distance of 20 cm, each character subtended 6° (center-to-center spacing). An appropriate refractive correction was used, as indicated by the prior eye exam. Viewing was binocular.

For each subject, reading speed was measured in four conditions: sentences or unrelated words, and black-on-white or white-on-black print. The standard condition is sentence reading of black letters on a

Table 1. Descriptive statistics for four groups of low-vision subjects

Ocular media	Central field	Sample size	Mean age	Mean decimal acuity	Acuity range
Cloudy	Intact	16	44.2	0.120	0.021–0.2
Cloudy	Loss	29	64.0	0.126	0.040–0.5
Clear	Intact	26	39.0	0.257	0.050–1.0
Clear	Loss	70	51.7	0.131	0.017–1.0

white background, and only data from this condition are discussed in this paper. The luminance of the white background was 100 cd/m², and the Michelson contrast of the black letters was 99%. The screen luminance was calibrated periodically with a UDT 80X optometer (United Detector Technology, Orlando, FL).

The subject's task was to read aloud a sentence displayed on the screen. Figure 3 shows an example of a typical stimulus sentence.

Twenty eight sentences were available for presentation. Each sentence had the same display format, 13 characters on each of four lines. The sentences contained high-frequency, nontechnical words and were declarative in nature. Uppercase letters were used at the beginning of sentences, but no punctuation characters were used.

Subjects were instructed to read each sentence aloud as fast as possible without skipping words. The presentation time was reduced until a subject could no longer finish reading an entire sentence. Reading speed then was computed as the number of words correctly read divided by the presentation time. This method relies on oral reading, but silent and oral reading speeds obtained with this method are almost identical.[19]

Data Analysis

The data were analyzed using the pipe-STAT statistical package (G. Perlman, Columbus, OH) running on a SUN 3/160 workstation (Sun Microsystems, Mountain View, CA). In addition to descriptive statistics, we conducted several regression analyses, general-linear tests, and analyses of variance.

Statistical analyses were performed on log reading rates because of the wide range of values encountered and because variances are more homogeneous. Values cited in the text for mean reading speeds and standard deviations actually refer to the antilogs of the mean and standard deviations of log values. For example, mean and standard deviation of the log reading

The show ends very late but my brother is allowed to go

Fig. 3. Illustration of a typical black-on-white sentence used in the computer-based reading test.

rates of the normal group were 2.33 and .10. The antilogs of these, 215 and 1.27, express a mean reading rate in words/min and the standard deviation as a multiplier or percentage swing (27%) around the mean. We also used log decimal acuities in the statistical analyses, formally identical to using log MAR values. The relevant figures have separate scales for decimal acuity and log MAR. Age values were used directly (ie, no logs). The nonnumeric variables—intact/lost central vision, clear/cloudy ocular media, ARM/other diagnosis—were treated as binary indicator variables.

As a prelude to regression analysis, we compared the variability of reading rates for groups categorized by the ocular-media and central-field variables. The variances for groups with clear and cloudy media were almost identical (differing by only 4%). The variance of the central-loss group was 1.87 times greater than that of the central-intact group. Because acuity accounted for about 12% of the reading-rate variance for the central-loss group, and none for the central-intact group (see Results), the variances differed by a factor of 1.65 after acuity was considered. Both groups had much greater variance than the normal group—6.3 times greater for the central-intact group and 11.8 times greater for the central-loss group. Because of the unequal variances, we did not conduct multiple-regression analyses with the status of the central fields as a predictor variable. Instead, we separately examined the groups with intact-central and lost-central vision.

Regression analyses were performed to determine which predictors contributed significantly to explaining the variance in reading speeds. The general-linear test[20] can be used to test whether regression equations for two or more groups differ significantly from one another. We used this test to compare simple regressions of reading rate on decimal acuity for three subgroups of central-loss subjects. We performed the tests in two steps, first evaluating equality of intercepts, then equality of slopes.

Results

Our reading test used characters subtending 6°, about 70 times the acuity limit of normal vision. By using such large characters, we enabled most low-vision subjects to read close to their maximum rates. How effective is high magnification by itself at restoring people with low vision to normal reading? Our group of 17 normal subjects read the 6° text with a mean rate of 215 words/min and a standard deviation of 27%. Two standard deviations below the mean is 133 words/min, which we take as a criterion for low-normal performance. Figure 4 shows the proportions of our 141 low-vision subjects, grouped by decimal
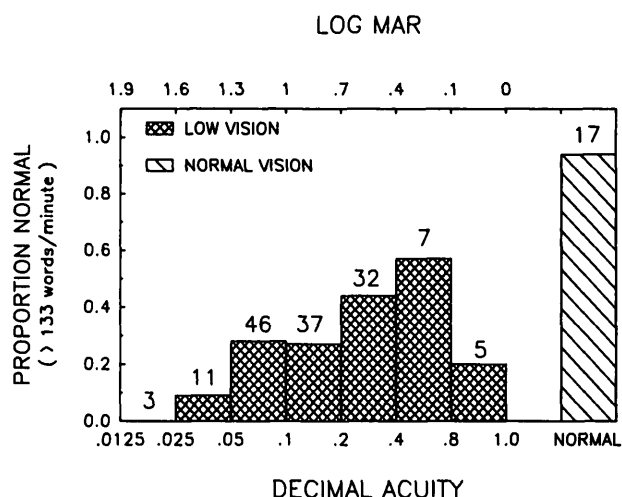
Fig. 4. Reading performance of low-vision subjects compared to low-normal performance. In the histogram, the bars represent the proportion of subjects whose reading rates exceed the low-normal reading rate of 133 words per minute, plotted as a function of decimal acuity. The actual number of subjects is shown above each bar. Low-normal reading rate is defined as 2 standard deviations below mean normal reading rate, based on a sample of 17 subjects with normal vision. The bar at the far right represents the proportion of normally sighted subjects whose reading rates exceed low-normal performance (16/17 = 93%).

acuity, that exceeded this low-normal criterion. The number of subjects in each group also is shown.

At or below a decimal acuity of 0.05 (20/400), only one of 14 subjects (7%) exceeded the criterion. The exceptional subject was a 40-year-old woman with an acuity of 0.05, diagnosed with retrolental fibroplasia. She read at 206 words/min, close to the normal mean of 215. Even for subjects with acuities above 0.4 (20/50), only five of 12 (42%) exceeded the criterion. Overall, 30% of the low-vision subjects exceeded the criterion for "low-normal" reading speed. Clearly, magnification per se is not sufficient to overcome low-vision reading problems.

The histogram in Fig. 4 suggests a link between reading performance and acuity, but the link turns out to be rather weak. For the low-vision sample as a whole, there was a low but statistically significant correlation of 0.309 between reading rate and decimal acuity ($P < .001$). This weak relationship accounted for only 9.53% of the variance in low-vision reading speeds, in good agreement with the value of 8% found in the Legge et al[3] small-sample study.

The four panels of Figure 5 show scatter plots of reading speed as a function of acuity for subjects classified by status of the ocular media and central fields. Regression lines also are shown. Table 2 gives the regression equations and other pertinent statistics. It also gives the regression equation for the low-vision sample as a whole.

For the two groups with intact central fields (top panels), there was no significant correlation between reading speed and acuity. Acuity had some predictive value for the groups with central loss (lower panels), accounting for 11.1% and 15.2% of the variance in reading speeds for central-loss subjects with clear and cloudy media, respectively.

The four groups had different sample sizes and acuity ranges (Table 1), factors that could influence the measured correlations. Range differences per se don't account for the group differences in correlation because the group with cloudy media and central loss had the largest correlation but the next to smallest range of log decimal acuity.

Our results are consistent with most previous research in showing that Snellen acuity has little or no relation to maximum reading speed.[3,12,21] Krischer et al[13] also showed a weak relation for their low-vision sample as a whole (overall correlation coefficient not reported in their paper.) They found zero correlation for their cataract patients (consistent with our field-intact groups) and only a weak correlation of 0.24 for their macular-degeneration group, also consistent with our findings. The higher correlations for their "retinal diseases" and "refractive anomalies" groups remain unexplained. The difference may be related to Krischer et al's use of a grating-detection method for measuring visual acuity.

The weight of the evidence indicates that a conventional test of distance-visual acuity says very little about a patient's best reading speed.

The 42 subjects with intact central vision (ie, no scotomas in the central 5°) had a mean reading rate of 112 words/min, below the "low-normal" criterion of 133 words/min. The nonsignificant correlations with acuity mean that knowing a subject's Snellen acuity provides no information about maximum reading speed. Because neither spatial resolution (acuity) nor central scotomas can be responsible for subnormal reading rates in these subjects, what is responsible? Contrast sensitivity was not among the clinical predictors in this study. Rubin and Legge[8] showed that low contrast sensitivity can explain reduced reading speeds for low-vision subjects with cloudy media and intact fields. Light scattered by the cloudy media reduces retinal-image contrast by an amount sufficient to affect reading performance. Even subjects with clear media and intact fields often exhibit reduced contrast sensitivity because of retinal disease, and the effective contrast signal may be reduced enough to affect reading. If this explanation is correct, then contrast sensitivity must be decoupled from acuity and might be measured usefully for its own sake as a clinical predictor of reading speed.

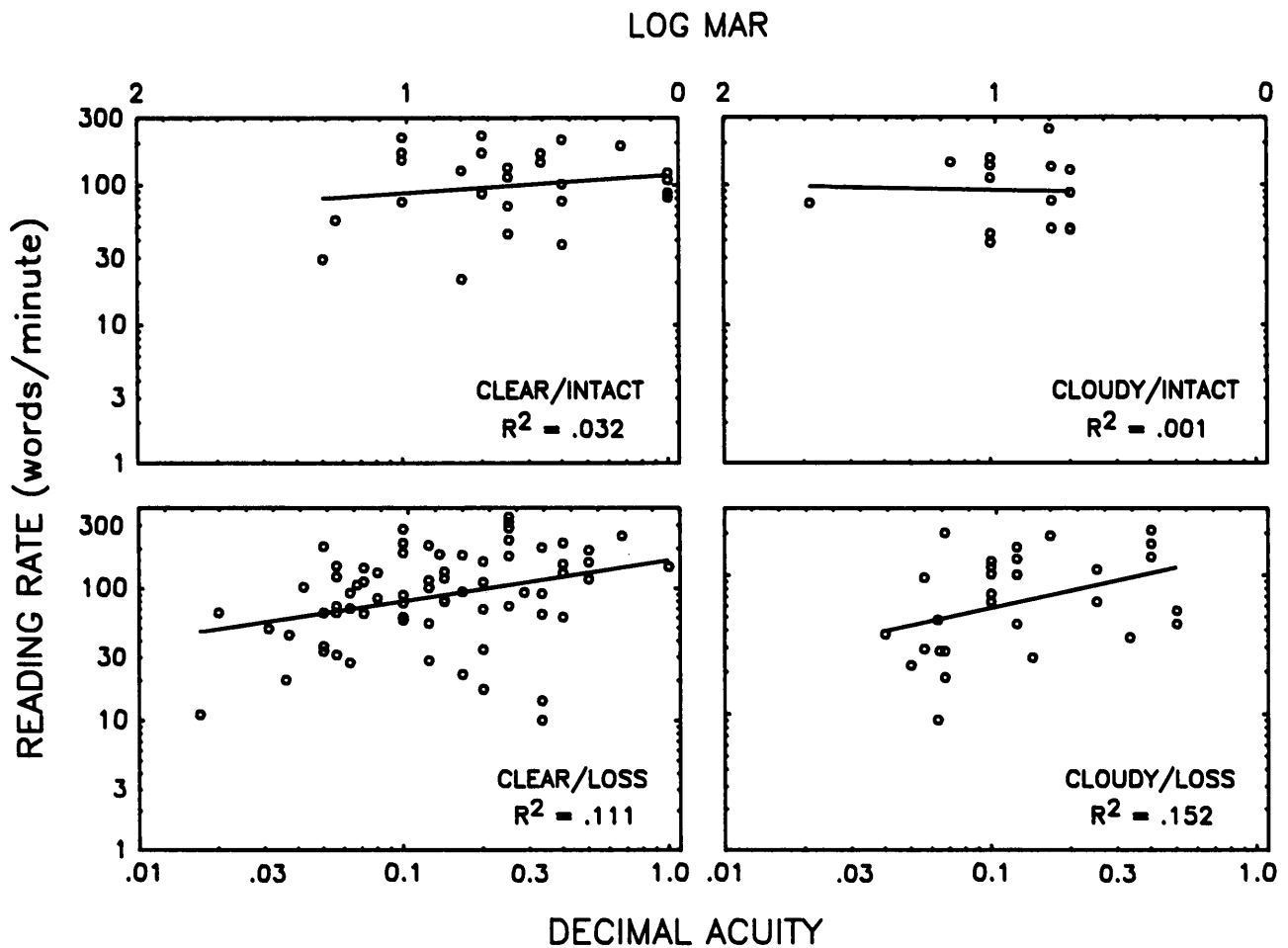Media status (clear or cloudy) was not a significant

LOG MAR

Fig. 5. Relation of reading rate to acuity for four groups of low-vision subjects. Each of the four panels is a scatter plot of reading rate as a function of decimal acuity. Subjects are classified by the status of the central field and ocular media. Regression lines are shown, and R^2 values indicate the proportion of variance accounted for. Only in the two central-loss groups does acuity account for a significant proportion of reading rate variance.

predictor of reading speed for the central-intact or central-loss groups. This variable accounted for a small but significant proportion of the variance in reading speeds in the Legge et al[3] study. As that study showed, however, media status played a more important role in predicting contrast-polarity effects. Legge et al[3] showed that people with cloudy ocular media usually read contrast-reversed text (white letters on a black background) faster than conventional black-on-white text. Status of the media probably can be used as a clinical predictor of best contrast polarity, even if it is not useful in predicting absolute reading speed.

The reading rates of the central-loss group were more variable than those of the central-intact sub-

Table 2. Results from regressions of log reading rate on log decimal acuity for low-vision groups

Group						
Ocular media	Central field	Regression equation*	r	r^2	F	P
Cloudy	Intact	$\log R = 1.919 - 0.037 \log A$	0.038	0.001	0.020	0.890
Cloudy	Loss	$\log R = 2.183 + 0.422 \log A$	0.390	0.152	4.847	0.036
Clear	Intact	$\log R = 2.071 + 0.131 \log A$	0.178	0.032	0.782	0.385
Clear	Loss	$\log R = 2.216 + 0.313 \log A$	0.333	0.111	8.473	0.005
Entire sample		$\log R = 2.155 - 0.278 \log A$	0.309	0.095	14.636	<0.001

* R is reading rate; A is decimal acuity.

Table 3. Comparing three groups of subjects with central field loss

Group	Sample size	Mean decimal acuity		
JMD	11	0.113		
ARM	41	0.147		
OTHER	45	0.116		

Groups	Regression equation*	r	r^2	F	P
ARM vs. JMD	$\log R = 0.373 \log A - 0.294\ D1$	0.471	0.222	6.980	0.0022
ARM vs. OTHER	$\log R = 0.392 \log A - 0.285\ D2$	0.509	0.259	14.488	<0.0001

* R is reading rate; A is decimal acuity; $D1$ is 1 if diagnosis is ARM, 0 if JMD; $D2$ is 1 if diagnosis is ARM, 0 is OTHER.

jects, suggesting greater heterogeneity. We subdivided the subjects with central loss into three groups: ARM (n = 41), JMD (n = 11), and OTHER central-loss subjects (n = 45). Table 3 lists descriptive statistics for these three groups. Analyses of variance indicated that acuity did not differ significantly between groups.

ARM subjects read more slowly than other subjects with central loss. Figure 6A shows reading rate vs acuity for ARM subjects (open circles) and JMD subjects (filled circles). Separate regression lines are shown for the two groups (Table 3).

A general-linear test (see Methods) indicated that the slopes of the regression lines do not differ significantly but the intercepts do. The two lines have a constant vertical separation of about 0.3 log units, close to a factor of two. We can summarize this result by saying that for any given acuity, the average reading rate of JMD subjects was about twice that of ARM subjects. Extrapolating to a decimal acuity of 1.0 (20/20), the regression model predicts JMD subjects to read 230 words/min and ARM subjects 117 words/min. This means that as normal acuity is approached (presumably corresponding to very small central scotomas), JMD subjects read 6° characters at normal rates, but the ARM subjects have subnormal rates, falling below the "low-normal" criterion of 133 words/min. Turning to the low end of the acuity scale, the regression model predicts that JMD and ARM subjects with acuities of 0.02 (20/1000) will read at 53 and 27 words/min, respectively. Notice that both of these values are below the average rate of 112 words/min for the intact-fields group whose performance does not depend on acuity. Subjects with central-field loss and low acuity tend to read very slowly.

Figure 6B compares ARM with OTHER central-loss subjects. As with the ARM/JMD comparison, the general-linear test produced a predictive model in which the regression lines have the same slope but a vertical offset. In fact, the OTHER group behaved much like the JMD group, with predicted reading rates about twice those of ARM subjects at any particular acuity. (A general-linear test comparing JMD and OTHER groups revealed no significant group differences.)

Why do ARM subjects read more slowly than other central-loss subjects? We considered two possibilities: years since disease onset and age. One possibility is that the ARM subjects were tested closer in time to the onset of visual impairment and had less time to
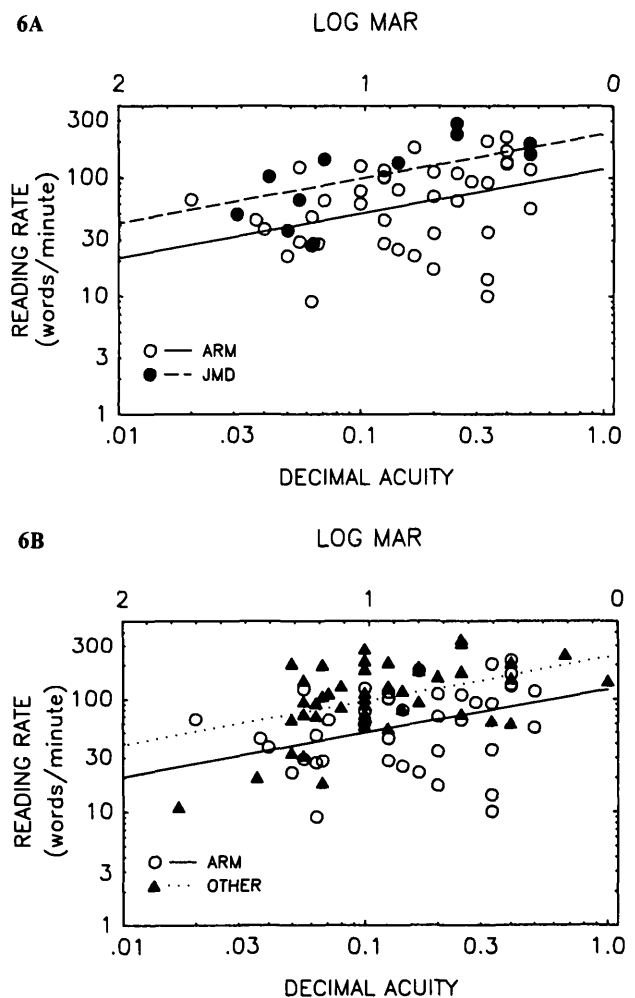
Fig. 6. Relation of reading rate to acuity for central-loss subjects divided into three diagnostic categories. (A) Reading rate is plotted as a function of acuity for ARM and JMD subjects. Also included are regression lines based on a general linear test. Predicted reading rates are higher for JMD subjects than for ARM subjects by a constant factor of nearly two. (B) A similar pattern of results is shown in a comparison of ARM with OTHER central-loss subjects.

adapt to their disability. If so, we would expect years since onset of the disease to be a predictor of reading speed in ARM subjects. The number of years since onset ranged from 0 to 20 for the 41 ARM subjects, but was skewed toward 0. The median was 2.5 yr and the average was 3.8 yr. Sixteen of the 41 ARM subjects were diagnosed one year or less prior to testing. Their reading speeds (and acuities) did not differ significantly from the remaining 25. In addition, a regression analysis showed no significant correlation between reading speed and years since onset in the ARM group.

Our failure to find an effect of time since onset of disease should not be taken as definitive. Our study was not designed to address this question. A longitudinal design would be better for this purpose than our cross-sectional design. In addition, adaptation to central loss may occur very quickly, far faster than the scale of years on which our analysis was based. It also is likely that our measure of "time since onset" is noisy, reflecting more the time since diagnosis and not taking into account changes associated with the progression of disease. Recent evidence pointing to the possibility of adaptation has come from the work of White and Bedell.[22] They have shown evidence that an adaptive shift in the oculomotor reference to a nonfoveal retinal site tends to be more complete for bilateral-maculopathy patients with a longer time since onset of the disease.

What about the effect of age? Our group of normal subjects did not show an age effect, but the low-vision subjects showed a large age effect. Across our entire low-vision sample, age was a better predictor of low-vision reading rate than acuity. A simple regression of reading rate on age accounted for 20.4% of the variance in reading speeds, compared with 9.5% for acuity. In a multiple-regression, acuity and age together accounted for 29.7% of the variance. The regression equations in Table 4 provide estimates of the effects of age and acuity on reading speed.

The age effect can account for the difference in reading rates between ARM subjects and other central-loss subjects. The mean age of the ARM subjects was 78.3 yr, compared with a mean of 37.7 yr for the other central-loss subjects. A multiple-regression analysis on acuity, age, and diagnosis (ARM or other) showed that diagnosis was no longer a significant predictor of reading rate. In other words, once acuity and

age have been considered, the reading performance of ARM subjects did not differ from other subjects with central loss. (In an additional regression analysis, we asked whether any of the six leading diagnostic categories in our sample [see Methods] were useful predictors of reading speed. As with ARM, once acuity and age were taken into account, diagnosis was no longer a significant predictor.)

The large age effect in low-vision reading is puzzling, given that age per se has very little effect on normal reading speed. Apparently, there is an interaction of unknown origin between age and presence of low vision that depresses reading speed. One possibility is that extra attentional capacity is required to read in the face of visual impairment and that less attentional reserve is available in old age.

Age should be treated cautiously as a clinical predictor. Our results do not mean that all elderly people with low vision read slowly. As the scatter in our data shows, some ARM patients can read very quickly. The age effect is a statistical result, indicating that, on average, older people with low vision read substantially more slowly than younger people with the same visual condition.
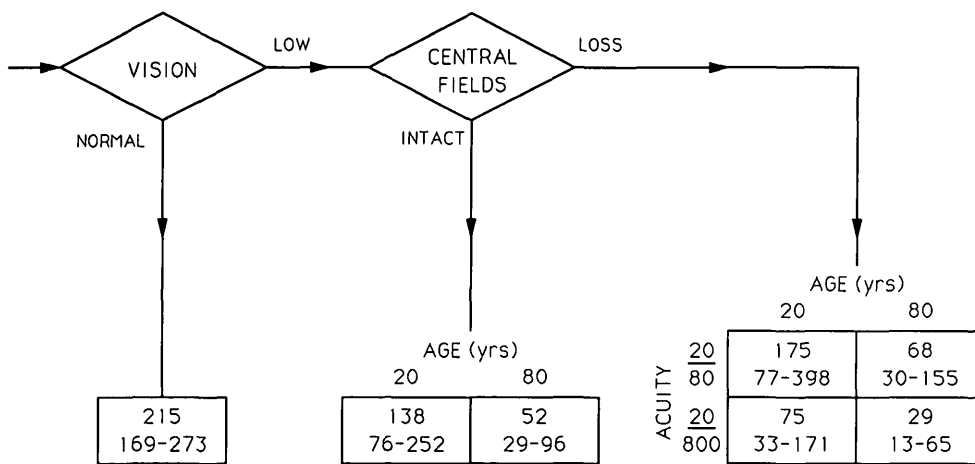
Discussion

Suppose a clinician or rehabilitation specialist wants to estimate the maximum reading speed a new patient is likely to achieve. Figure 7 summarizes predictions based on the clinical variables in this study.

The diamonds divide all patients into three categories: normal, low vision with intact central fields, and low vision with central loss. The boxes along the bottom give predicted mean reading rates and ranges based on the regression models in Table 4. If the patient has normal vision, reading speed usually will be in the range of 169–273 words/min with a mean of 215 words/min. (The range is asymmetric about the mean because it is based on plus or minus one standard deviation of log reading rates.) If the patient has low vision, central-field status must be taken into account. If the central fields are intact, age is the only additional predictor. For example, the estimated rate for a 20-year-old is 138 words/min, but for an 80-year-old it is only 52 words/min. If there is central-field loss, both age and acuity are of predictive value. For example, 20-year-olds with acuity of 20/80 are

Table 4. Results from regressions of log reading rate on log decimal acuity and age for low-vision groups

Group	Regression equation*	r	r²	F	P
Entire sample	$\log R = 2.486 - 0.007\,G + 0.273\,\log A$	0.543	0.295	28.894	<0.0001
Central intact	$\log R = 2.280 - 0.007\,G$	0.518	0.268	15.675	<0.001
Central loss	$\log R = 2.621 - 0.007\,G + 0.377\,\log A$	0.568	0.323	22.851	<0.0001

* R is reading rate; A is decimal acuity; G is age in years.

```
         LOW                    LOSS
─►  VISION  ──────►  CENTRAL  ──────────────────────►
                     FIELDS

  NORMAL              INTACT
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AGE (yrs)		
	20	80
ACUITY 20/80	175	68
	77-398	30-155
20/800	75	29
	33-171	13-65

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     215
   169-273
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AGE (yrs)	
20	80
138	52
76-252	29-96

ESTIMATED READING RATE AND RANGE
(words/minute)

Fig. 7. Predicted reading rates based on clinical variables. The diamonds in this chart divide all patients into three categories: normal, low vision with intact central fields, and low vision with central-field loss. The arrows point to boxes that give predicted reading rates based on the clinical variables relevant for each category. The predictions were calculated using the regression equations in Table 4. Predictions for other ages and acuities can be calculated using these equations. Included in each box is a range of reading rates representing 1 standard deviation above and below the predicted rate.

predicted to read about 175 words/min, within the normal range. An 80-year-old with central loss and acuity of 20/800 still can read but at a predicted rate of only 29 words/min.

The range values represent plus or minus one standard deviation around the mean and should include 67% of the cases. Even for the normals, there is a considerable spread, from 169–273 words/min, covering a factor of about 1.6 in reading speeds. Presumably, this dispersion represents nonvisual influences on reading speed. These influences may include subject factors such as cognitive abilities or motivation, and procedural factors associated with the reading test. The dispersion of low-vision rates is much greater, a factor of nearly 4 in reading speed for the central-loss subjects. The wider range undoubtedly results in part from visual determinants of reading performance not captured by our set of clinical predictors. As discussed earlier, contrast sensitivity might be a useful addition.

We did not include contrast sensitivity as one of our predictors because its status as a routine clinical measure still is unclear. However, previous research allows us to estimate an upper bound on its contribution. A promising candidate for a routine clinical test of contrast sensitivity is the Pelli-Robson test,[23] which is used to measure contrast sensitivity for recognizing letters. In a laboratory study of 19 well-practiced low-vision subjects, Rubin and Legge[8] found a correlation of 0.50 between peak reading speed and letter contrast sensitivity (ie, 25% of the variance accounted for). If contrast sensitivity were added to our set of clinical predictors, we would expect a maximum of 55% of the variance to be accounted for, 30% from the original set and an additional 25% (maximum) from con-

trast sensitivity. It is unlikely that contrast sensitivity would add the full 25%. First, as evident from the present study, clinical measures of any visual variable are noisier than laboratory measures. Second, while there is evidence for some decoupling of acuity and contrast sensitivity in low vision,[24] we would not expect contrast sensitivity to be completely uncorrelated with our other predictor variables. In short, we estimate that addition of a Pelli-Robson measurement of contrast sensitivity to our set of clinical predictors would account for no more—and probably less—than an additional 25% of the variance in reading speeds.

Clinical experience and previous work in our laboratory make it clear that central-field loss often is associated with poor reading.[3,9] The results of this study, however, show this is not invariably the case. Figure 6 shows that patients with central loss run the gamut from slow to fast readers. For a given acuity, the variability in reading rates is high. Presumably, this variability is due in part to characteristics of scotomas beyond their mere presence or absence. Future research will be needed to determine what features of scotomas—size, shape, etc—predict poor reading.

Self selection may play a role in accentuating the clinical and research opinion that central loss (especially ARM) is prognostic of poor reading. People with small central scotomas who are having little trouble with reading are unlikely to seek help from a clinician. The people having trouble with reading (and other important everyday tasks) are the ones who find their way into clinics and research studies. Of our 35 subjects with lowest reading speeds (lowest quartile, <53 words/min), 26 (74%) had central loss and 18

(51%) were ARM. These proportions are likely to be higher in an older population of low-vision patients such as the one served by the Lighthouse (see Methods). In other words, while central loss does not necessarily indicate poor reading, the majority of poor readers have central loss.

Nonvisual sources of variability may be greater in low vision than in normal vision. In fact, the results of this study show that age, one nonvisual factor, has more predictive power in low vision than in normal vision. It is possible that effects of factors such as motivation or cognitive skill may be amplified in low vision.

The results of this study indicate that a set of common clinical predictors provides only a crude estimate of a low-vision patient's likely reading performance. Knowledge of a patient's Snellen acuity, field and ocular-media status, diagnosis, and age do not provide a basis for a useful evaluation of reading potential. Until we have a more complete understanding of the visual and nonvisual determinants of reading, clinical prediction will be imprecise. Until these problems are solved, precision in the estimation of reading speeds will require a direct measure of reading performance.

Key words: low vision, reading, acuity, aging, macular degeneration

Acknowledgments

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