PSYCHOPHYSICS OF READING: VIII. THE MINNESOTA LOW-VISION READING TEST[1]

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Abstract - This is the eighth in a series of papers dealing with the role of vision in reading. In previous papers, we have evaluated the effects of stimulus and subject variables on reading rate using a drifting-text procedure. In this paper, we describe a new test of reading rate that uses static text, called the Minnesota Low-Vision Reading Test (MNread). It is microcomputer-based, and more easily set up and administered than the drifting-text procedure. It is of potential value as a standardized psychophysical test of reading and should be useful in research, clinical, and educational applications. Some types of low-vision aids rely on drifting text and others on static text. Is reading performance different for these two modes of text presentation? We measured reading rate as a function of angular character size for normal and low-vision subjects with drifting and static text. Although reading rates were highly correlated for the two modes of text presentation, normal subjects usually read static text more rapidly. The reverse was true for low-vision subjects; their reading rates for drifting text were slightly higher (average 15%) than for static text.

Most people with low vision are handicapped in reading. For many people, reading difficulty is the most serious consequence of eye disease. In our laboratory, we have been studying the role of vision in reading with two major goals: to understand the role of sensory mechanisms in normal reading and to understand how visual disorders impair reading.

In the first two papers of this series (Legge *et al.*, 1985a; Legge *et al.*, 1985b) we measured how reading rate is affected by several important stimulus variables including character size, field size, and spatial-frequency bandwidth. In addition, we identified two subject variables that have major effects on reading performance - central field loss and cloudy ocular media. Our results helped guide the development of a fiberscope low-vision reading aid (Pelli, Legge, and Schleske, 1985). In subsequent papers, we have examined how reading is affected by wavelength (Legge and Rubin, 1986), contrast (Legge, Rubin, and Luebker, 1987; Rubin and Legge, 1989) and contrast polarity (Legge *et al.*, 1987). Recently, we examined the dependence of comprehension on reading speed and evaluated comprehension as a psychophysical measure of reading performance (Legge *et al.*, 1989).

Our measure of performance is reading rate in words/minute (wpm). We use a drifting-text method. A subject reads aloud a line of text that drifts across the face of a TV monitor. At low drift rates, the subject reads the text perfectly. The drift rate is adjusted upward until the subject makes a small number of errors. By this means, we find the drift rate at which oral reading departs from 100% accuracy. There is a sharp transition from perfect reading (no errors) to ineffective reading (many errors). This sharp transition can be used to give a good estimate of maximum reading speed (Legge *et al.*, 1985a).

The drifting-text method is an objective psychophysical means of evaluating the visual component of reading. It was designed to be insensitive to nonvisual factors that influence

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everyday reading, such as text complexity, cognitive or linguistic ability, reading strategy (skimming, etc.), motivation, and skill in manipulating magnifiers. It is a "forced march" method in which subjects are pushed to their limits. It permits easy, computer-based control of stimulus parameters and objective scoring of reading performance. Our experience has shown that it yields highly reproducible data.

However, there are several reasons for developing a simpler, more standardized test of reading speed for low-vision subjects. There is growing interest among vision researchers in using reading rate as a psychophysical measure. It has been used to study low vision, and to evaluate the outcome of treatments for eye disease. Although useful for such purposes, the drifting-text method is quite difficult to set up and time consuming to administer. A simpler test could facilitate comparison of results from one site to another or one study to another.

A new test might also be helpful to optometrists, ophthalmologists, or rehabilitation specialists for evaluating low-vision patients. It could provide a standardized measure of the visual component of low-vision reading performance, one not limited by the characteristics of particular reading aids. A clinician could use the test score as a benchmark for judging the success of any prescribed reading aid. For example, if a patient reads 100 wpm on a standardized test but only 50 wpm with a prescribed magnifier, there is room for improvement through training or an alternative prescription. (Of course, factors besides maximum reading speed must be considered in prescribing low-vision aids.) The test could also be used to chart progress of patients with central-field loss as they learn to use peripheral vision in reading.

Results from a standardized test might also be useful to teachers of low-vision children. Currently, there is debate among special educators over the best mode of reading instruction: magnified print, tape recordings, or Braille. A well controlled measure of best visual reading performance could guide teachers who must recommend one of these alternatives for their students.

We have developed a test called The Minnesota Low-vision Reading Test or MNread. It is a computer-based test that runs on IBM PCs and compatibles. Its purpose is to provide a simple, quick, and accurate estimate of a low-vision person's maximum reading rate. Sentences (or unrelated words) are presented at high magnification for timed periods. The exposure time is reduced until the reader can no longer complete the entire text. Reading rate can then be computed as the number of words correctly read, divided by the exposure time. A major purpose of this paper is to describe this test in enough detail for implementation elsewhere.

The Pepper Visual Skills for Reading test is another new low-vision test (Baldasare *et al.*, 1986). Rather than being a psychophysical test demanding rigid control of stimulus characteristics, the Pepper test was designed to assess several aspects of everyday reading by low-vision subjects. The test is printed on cards. The subject selects his or her preferred lighting and viewing distance (angular character size). The card contains 13 rows of unrelated words graded in word length (1 to 10 letters) and line spacing (triple to single). The subject reads the material aloud and the examiner notes accuracy and speed. The Pepper test has high retest reliability (Baldasare *et al.*, 1986). The purpose of the Pepper test is to assess everyday low-vision reading in situ, whereas the purpose of MNread is to isolate visual factors in reading.

Our new test differs in an important way from the drifting-text method; it uses static rather than drifting text. What effect might this difference have? We have argued elsewhere (Legge, Rubin, and Luebker, 1987) that reading rate depends on a reader's contrast sensitivity and on the spatiotemporal spectrum of the text stimulus. Because the dynamics of drifting and static text are very different, there may exist differences in reading performance.

A major difference between these two types of reading is the pattern of eye movements, but there is a striking functional similarity between the two. Eye-movement recordings in our laboratory (Legge *et al.*, 1985a) and elsewhere (Buettner *et al.*, 1985) show that for drifting text, the eyes fixate on a letter, track it across the screen through a distance of four or five character spaces, then saccade back to pick up a new letter. The resulting sequence of retinal images mimics that for static text; there is a series of foveal pauses on letters separated by saccades spanning a few letter spaces. The functional equivalence of eye-movement patterns implies that the spatiotemporal characteristics of retinal images are very similar for reading drifting and static text. We might therefore expect the stimulus dependence of reading rate to be similar for these two types of text presentation. We have confirmed this for normal subjects in experiments on wavelength (Legge and Rubin, 1986), contrast (Legge, Rubin, and Luebker, 1987), and in a limited study of character size (Legge *et al.*, 1985a).

Many people with low vision have problems with eye-movement control, particularly those with central-field loss (Timberlake *et al.*, 1987; Whittaker *et al.*, 1988). It is possible that the different oculomotor requirements for reading drifting and static text might affect performance in these two tasks. A priori, it is difficult to predict whether drifting or static text would be better. Drifting-text requires the reader to execute smooth-pursuit eye movements between saccades, potentially more difficult than simple fixations. Static presentation requires the reader to detect the ends of lines and to execute long retrace saccades to find the beginning of new lines. A second major purpose of this paper is to report on a comparison of low-vision reading rates for drifting and static text.

Insight into differences in reading static and drifting text is relevant to the design and prescription of low-vision reading aids. Usually, aids that provide high magnification contain few letters in the field. Text must be moved through the field, approximating a drifting-text presentation. The "drift" is controlled by hand in the case of handheld magnifiers, stand magnifiers, and closed-circuit TVs. In the case of head-borne telescopes and microscopes, the reader may move the text by hand or use scanning head movements. When lower magnification aids are used, more letters are present in the field and the reader uses eye movements to scan through the static text.

DESCRIPTION OF THE MNread TEST

Apparatus and Stimuli

We have implemented the test on IBM PC/XT and AT computers but the testing principles are not computer-specific. In our configuration, stimuli are presented on an IBM color monitor using an IBM color-graphics adapter (CGA). The experimenter interacts with the program via keyboard and menus printed on a monochrome display.

MNread has four subtests: subjects see either complete sentences or unrelated words, and the text appears as either black letters on a white background or white letters on a black background. Fig. 1 shows examples.

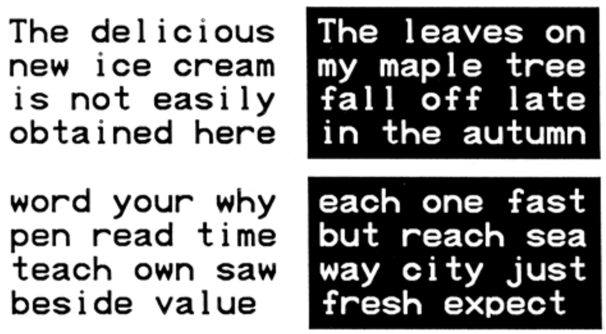

Figure 1. Illustration of the four types of text displays used by MNread.

We regard the black-on-white sentence test as the standard to which other measurements should be compared. Contrast reversal is included to identify and characterize those people with low vision who have higher reading rates with white-on-black text (Legge *et al.*, 1985b; Rubin and Legge, 1989; Legge *et al.*, 1987). A subtest using unrelated words is also included. It has been suggested (Baldasare *et al.*, 1986) that such a test might be more effective in revealing the reading deficits of people with central scotomas than a test containing words in context (i.e., sentences).

In each stimulus display, words are arranged in 4 rows of 13 character spaces. The white parts of the stimuli (background or letters) have a luminance of approximately 100 cd/m^2, close to the recommended value (National Research Council Committee on Vision, 1980) of 85 cd/m^2 and within the range of the IBM color monitor. The Michelson contrast of the letters, $(L_{white} - L_{dark}) / (L_{white} + L_{dark})$, is greater than 0.85, in keeping with another recommended standard (National Research Council Committee on Vision, 1980). (We measured the contrast of the IBM color monitor to be 0.99.)

Between trials, the screen has uniform luminance, matching the background of the letters. At the beginning and end of the timed stimulus exposure, the words appear or disappear abruptly. In our IBM implementation of the test, a solid white or black background is displayed while text is transferred to the graphics buffer. The text is hidden by either clamping the CGA video off (black) or by modifying the CGA screen background color (white), depending upon the contrast polarity. To display the text, the computer waits for a new vertical blanking signal, then unclamps the video or changes the background color to make the text visible. The computer counts off the desired number of video frames, and then hides the text again. For the IBM, exposure durations are limited to integer multiples of 16.7 ms due to the 60 Hz frame rate of the color monitor.

The type font we used is the same as the largest font used by PC-LENS (ARTS Computer Products Inc., Boston, MA). It is fixed-width, with serifs and descenders, similar to Courier (see Fig. 1). Although this font is called "20x36," most of the uppercase letters are 20x28 pixels, and most of the lowercase letters are either 20x20 or 20x28 pixels. (The 20x36 size is required for lowercase descenders.) In our displays, the center-to-center character spacing is 24 pixels (horizontal) and 40 pixels (vertical).

The test is conducted with an angular character size of 6° (defined as the center-to-center spacing of horizontally adjacent characters). This size falls within the acuity limit of nearly all low-vision subjects (equivalent to a Snellen acuity of 6/432). In addition, low-vision reading rates obtained with 6° characters are highly correlated with maximum reading rates (see also Results). For the IBM color monitor, 6° characters are achieved at a viewing distance of 20 cm and the entire text display subtends approximately 78° horizontally by 40° vertically. Character size can be changed by adjusting the subject's viewing distance. When necessary, refractive correction is used for the subject to focus on the display.

Sentence Test

MNread uses 28 sentences for testing (Appendix 1). Each sentence fits precisely into the 4-line by 13-character display format without use of hyphenation or extra blank spaces. No punctuation is shown, and uppercase letters are used only for initial capitalization of sentences and proper names. The 28 sentences are presented in random order without repetition until the entire series is exhausted.

The 28 sentences have an average length of 11.1 words (range = 9 to 13 words/sentence). There are 202 unique words and an average word length of 4.2 letters/word (range = 1 to 10 letters/word). The number of words by rank order of use in written English is shown in Table 1. We have constructed an additional set of 170 sentences having approximately the same characteristics for use in research applications requiring many measurements on the same subject.

Unrelated Words Test

Eleven unrelated words are selected from a lexicon of 302 words (Appendix 2) and presented on the screen. The number of words by rank order of use in written English is shown in Table 1. Every trial uses a standard "template" for arranging words on the screen. The four lines consist of words with the following number of letters: 3-4-4, 3-4-4, 3-3-5,. and 5-6. The order of the four lines and the word slots within each line are randomized for each trial. Two examples of unrelated-word displays are shown in Fig. 1. Words are selected at random with replacement. This means that words can repeat on different trials, or even (rarely) during the same trial.

Test Procedure

The subject is seated at the appropriate viewing distance from the screen. The room lights are extinguished to eliminate glare. Viewing is binocular. The subject is given time to adapt to the uniformly illuminated display.

Table 1. Minnesota Low-Vision Reading Test (MNRead): word frequencies.

Rank	Number of Words	
	Sentence test	Unrelated-words test
1–1000	140	227
1001–2000	20	52
2001–3000	7	14
3001–4000	11	7
4001–5000	6	1
5001–6000	2	1
>6000	16	0
	202	302

Table 2. Calculation of reading rate: an example.

Exposure Time (sec)	No. of Words		Rate (wpm)	Comments
	Correct	Missed[a]		
20	All	None		Practice
15	All	None		Practice
10	All	None		Subject barely finished
8	11	1	83	First valid estimate
6	10	2	100	Valid estimate
4	6	5	90	Valid estimate
	Reading Rate = 90.7			Geometric mean

[a] Missed means either that the subject failed to read a word or read a word incorrectly.

Subjects are told to read aloud through the sentence (or unrelated words) as rapidly as possible. They are instructed not to return to missed words. They are pushed to read faster until they reach a speed at which they make occasional errors. Only if occasional errors occur can we be sure that maximum reading rate is being measured.

During testing, stimuli are presented for timed exposures. Typically, the first few exposures are quite long and regarded as practice. If the subject finishes reading the text with time to spare, the exposure time is reduced and another trial is run. This process is repeated until the subject fails to finish the text. Only when the exposure time is too short for the subject to finish the text can a valid estimate of reading rate be obtained. Reading rate in words/minute is computed as the number of words correctly read, divided by the exposure time. The experimenter proceeds to reduce exposure time still further (we recommend steps of about 25%) to obtain additional estimates of reading rate. Although the subject will read fewer words with the shorter exposures, the computed reading rates should be similar. The overall estimate of reading rate is the geometric mean of the set of valid estimates. Table 2 illustrates a sequence of measurements; such a sequence requires less than 5 min.

We have used MNread in recent laboratory research dealing with eye stability during reading (Parish and Legge, 1989) and color contrast (Legge *et al.*, 1990). In ongoing clinical studies at the Minneapolis Society for the Blind, we have tested more than 200 low-vision subjects with MNread.

Before describing comparisons of reading performance with drifting and static text, we report four experimental findings bearing on properties of MNread itself.

Comparing Reading Rates for Sentences and Unrelated Words

Fig. 2 shows a scatterplot of sentence and word reading rates measured with MNread for 147 lowvision subjects; open symbols for 100 with central loss and filled symbols for 47 with residual central vision. Separate regression lines (based on $\log_{10}$ values) are shown for the two groups because they are significantly different. (We used an F test to evaluate the null hypothesis that the slopes and intercepts of the regression lines through the two sets of data were the same (Neter and Wasserman, 1974). The criterion for rejecting the null hypothesis was $p < 0.05$.) Slopes and intercepts are given in the figure caption. Despite the significant difference, the slope and intercept parameters of the regression fits are quite similar. A single regression line through the combined set of data has a correlation coefficient of 0.95. Its slope and intercept are also given in the caption to Fig. 2. Sentence rates are roughly 15 to 30% higher than word rates, reflecting the advantage of context.

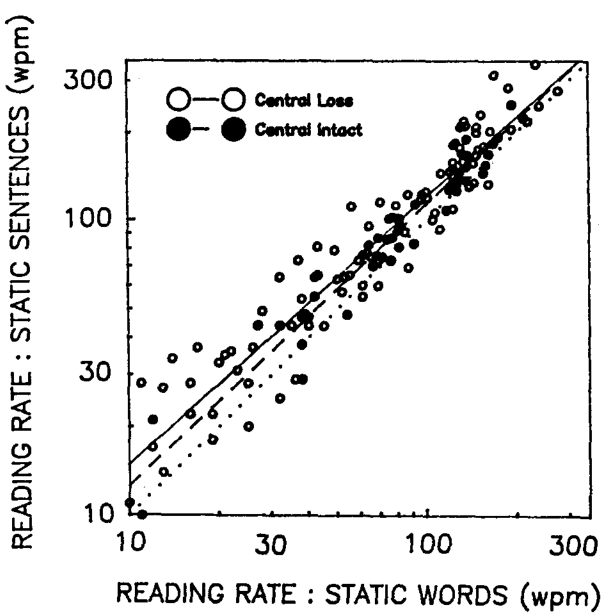

Figure 2. Scatterplot of reading rates for sentences and unrelated words, both measured with MNread. Each point represents results for one low-vision subject. The dotted line represents equality in the two rates. Regression lines fitted to the data have the form: LOG (sentence reading rate) = mLOG (word reading rate) + k, where m and k are slope and intercept parameters. The regression lines are characterized by the following parameter values: Central Loss (N = 100) m = 0.903, k = 0.272; Central Intact (N = 47) m = 1.09, k = -0.125; Combined (N = 147) m = 0.935, k = 0.201.

The results of this experiment indicate that there is a roughly constant relation between sentence and word reading rates for subjects with different forms of low vision. For most purposes, separate measurements are unnecessary.

Test-Retest Correlation

Twenty-two low-vision subjects with stable visual conditions were retested after periods ranging from 1 month to 1 year. The test-retest correlation on sentence reading rates was 0.88. This compares with a test-retest correlation of 0.93 for the Snellen acuities of the same subjects.

Comparing Oral and Silent Reading Rates

MNread relies on oral reading, but most everyday reading is silent. We measured silent rates with MNread using a variant of the unrelated-words test. Subjects were asked to read silently through the text and report the last word they saw when the display turned off. Assuming all words were correctly read up to and including the word reported, and knowing the display duration, we computed a silent reading rate. We compared the silent and oral rates of five normal subjects. Each was tested at three character sizes - 0.15°, 1°, and 6°. A repeated measures analysis of variance revealed a significant effect for character size (see discussion of Fig. 3 below), but no significant effect of silent/oral reading and no interaction. We conclude that rates obtained with MNread characterize both silent and oral reading.

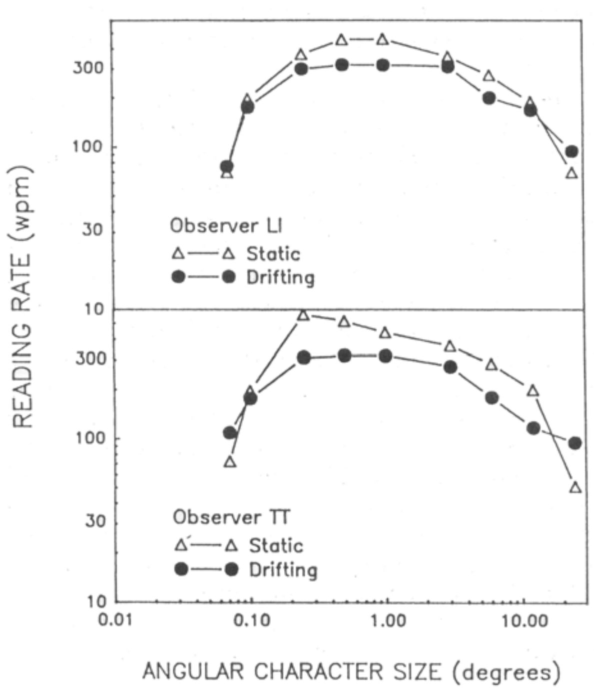

Figure 3. Reading rate as a function of angular character size for two observers with normal vision. Circles: drifting text procedure. Triangles: static text measurements with MNread.

Masked and Unmasked Reading

Reading rates obtained with MNread depend on the presentation of text for timed periods. It is possible that some form of stimulus persistence associated with the decay time of the cathode ray tube phosphor or iconic images (Sperling, 1960) within the subject might prolong the effective display time and inflate measured reading rates. A standard procedure for preventing the use of stimulus persistence is to present a masking stimulus immediately after the target. We compared MNread rates for text presented in the normal way (no mask) with text followed immediately by a masking display of X's. Five subjects with normal vision were tested. There were no statistically significant differences between the masked and unmasked reading rates.

METHODS

Reading Rates for Drifting and Static Text

Subjects

Six subjects with normal vision participated. All had corrected visual acuity of 6/6 (20/ 20) or better. Viewing was binocular with natural pupils. Twenty seven low-vision subjects participated. Clinical histories were available for all subjects. Their ages, diagnoses, Snellen, and Sloan M acuities are listed in Table 3. The table also indicates whether the subjects had central field loss or cloudiness of the ocular media. These are variables known to be important in low-vision reading (Legge *et al.*, 1985b). In Figs. 4 to 6, "Central Loss" refers to absolute scotomas covering all or part of the central 5° (diameter) of the field. "Central Intact". refers to an absence of absolute scotomas in this area. Our goal in selecting the low-vision sample was to obtain a wide range of reading speeds and at the same time a broad distribution of types and severity of eye disease.

Apparatus and Procedure. Reading rates for static text were measured with MNread. Reading rates for drifting text were measured as follows (for more details, see Legge, Rubin, and Luebker, 1987). Text was displayed on a Conrac SNA 17/Y monochrome monitor driven by a Grinnell GMR274 frame buffer and LSI-11/23 computer. To eliminate glare, room lights were extinguished during testing and the monitor's screen was black except for a horizontal strip (25 cm wide by 4 cm high) through which a single line of text drifted. The letter font was the same as in MNread (see above). The letters were displayed as black characters on a white (110 cd/m^2) background. The Michelson contrast of the characters was 0.96. Angular character size was controlled by changing viewing distance. Text drifted smoothly from right to left across the screen. The 25-cm wide rectangular strip contained 11 character spaces. Previous research (Legge *et al.*, 1985a; Legge *et al.*, 1985b) has shown that a window width of five characters or more permits maximum reading rates for drifting text.

Before a trial, the first character of an 80-character line of text was visible at the right margin of the screen. After giving a warning signal, the experimenter initiated the drift of the line of text across the screen. The subject read the text aloud. If no errors were made, the experimenter increased the drift rate and tested the subject on a new line. This procedure continued until the subject made a small number of errors. Because the transition from perfect reading to ineffective reading (many errors) is so sudden, a bracketing process quickly located the transition drift rate. Final adjustments in drift rate were 5% or less. Once the transition drift rate was located, a single measurement of reading rate was based on at least two lines of text. Reading rate in words/minute is equal to the corresponding drift rate in words/minute, multiplied by the proportion of words correctly read.

Table 3. Low-vision subjects.

Subject	Age (yr)	Diagnosis	Acuity		Cloudy Media	Central Loss
			Snellen	Sloan M		
A	41	Optic atrophy	6/90	7		yes
B	82	Macular degeneration	6/30	5		yes
C	42	Macular degeneration	6/60	2		yes
D	43	Macular degeneration	6/120	10		yes
E	44	Pseudoxanthoma elasticum	6/90	8		yes
F	71	Macular degeneration	6/120	7		yes
G	24	Tumor on optic nerve	6/72	14		yes
H	32	Optic atrophy	6/72	7		yes
I	28	Retrolental fibroplasia	6/96	5		yes
J	32	Optic atrophy	6/36	2		yes
K	41	Macular degeneration	6/192	14		yes
L	37	Optic neuritis	6/120	10		yes
M	50	Diabetic retinopathy	6/60	3	yes	yes
N	61	Retinitis pigmentosa + cataracts	6/120	5	yes	yes
O	83	Macular degeneration + cataracts	6/24	4	yes	yes
P	55	Macular degeneration + staphyloma	6/60	3	yes	yes
Q	24	Congenital cataracts	6/36	4	yes	
R	21	Corneal decompensation	6/36		yes	
S	38	Retinitis pigmentosa	6/60	10	yes	
T	41	Congenital cataracts	6/60	7	yes	
U	33	Congenital cataracts	6/36	2	yes	
V	35	Albinism	6/60	5		
W	37	Optic neuritis	6/24	2		
X	29	Retinitis pigmentosa	6/36	1.5		
Y	33	Macular pucker	6/60	2.5		
Z	23	Congenital glaucoma	6/18	1		
AA	37	Optic nerve hypoplasia	6/36	3		

RESULTS

Reading Rates for Drifting and Static Text

Fig. 3 shows reading rate as a function of character size for two normal subjects. Circles and triangles represent mean reading rates for static and drifting text, respectively. The pattern of results is the same for the two subjects.

The drifting-text curves replicate previous findings (Legge *et al.*, 1985a) There is a broad peak extending over about 1 log unit in character size from 0.25° to 3°. For smaller character size, reading rate declines rapidly, whereas for characters larger than 3° there is a more gradual decline.

The static-text curves are qualitatively similar but have some quantitative differences. They are more peaked and have higher values than the curves for drifting text. The largest difference was for subject TT at 0.25°: 561 and 311 wpm for static and drifting text, respectively. The static curves decline more sharply and drop below the drifting-text curves for the largest and smallest character sizes.

Earlier, we argued for functional equivalence in the spatiotemporal characteristics of retinal images during the reading of static and drifting text. The qualitative similarity of the curves in Fig. 3 is consistent with this view. The quantitative differences may relate to differences in the accuracy of eye movement control. Static text is read with fixational pauses between saccades, whereas drifting text is read with smooth pursuit between saccades. For high-speed reading of characters of intermediate size, imprecision in smooth-pursuit tracking may account for differences in peak reading rates.

We compared reading performance on drifting and static text for 27 low-vision subjects. Static text measurements were done with 6° characters using MNread. Drifting text measurements were done over a range of character sizes to identify the subject's maximum rate.

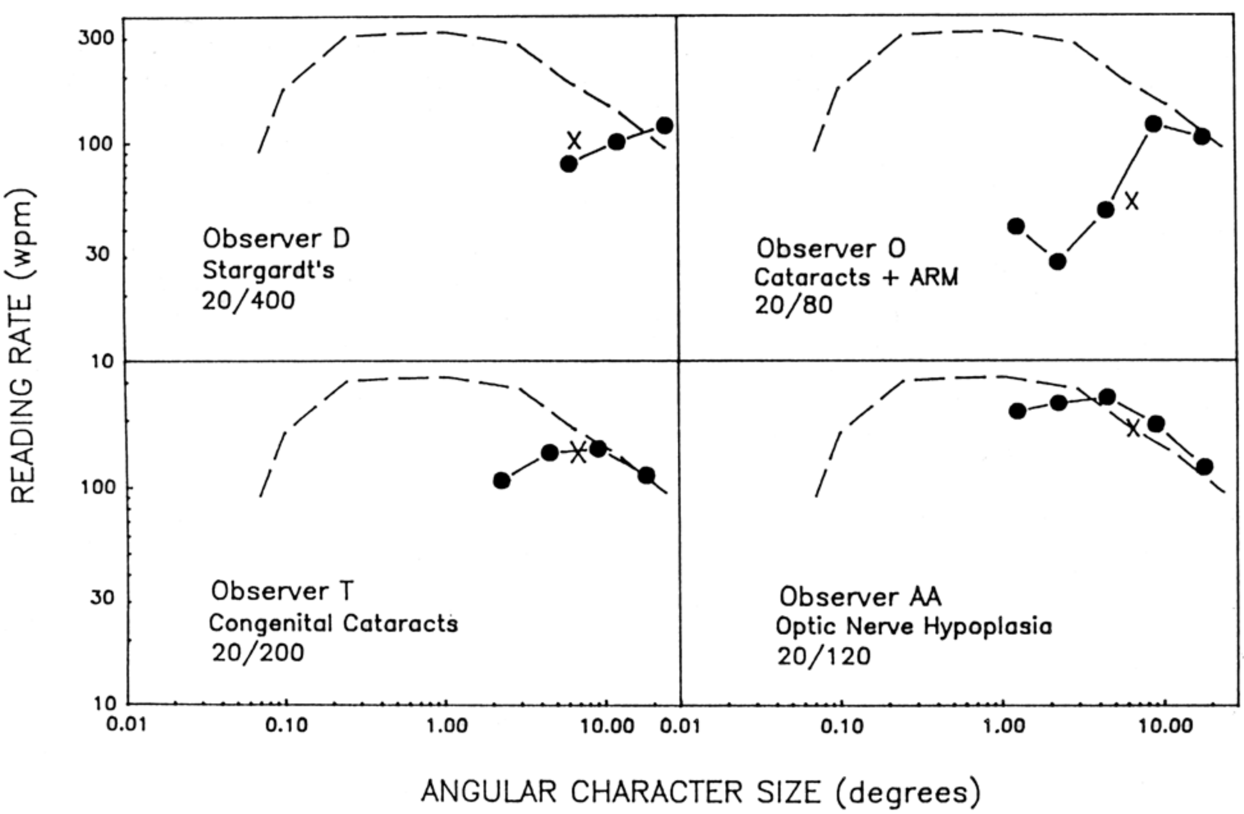

Figure 4. Illustrative data for four low-vision subjects. Reading rate is plotted as a function of angular character size. The upper dashed curve re-plots drifting-text reading rates from Fig. 3, averaged for two normal subjects. The filled circles show drifting-text reading rates for the low-vision subjects. The X shows the static-text rate measured with MNread.

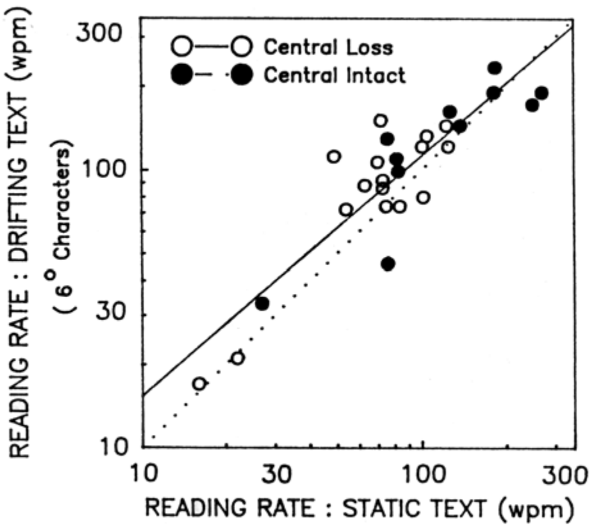

Figure 5. Scatterplot of reading rate for drifting text and reading rate for static text. For both, text was composed of characters subtending 6° (center-to-center spacing). Each point represents results for one low-vision subject. The dotted line represents equality. A single regression line (solid line) fits both sets of data. Its slope and intercept are 0.863 and 0.322, respectively.

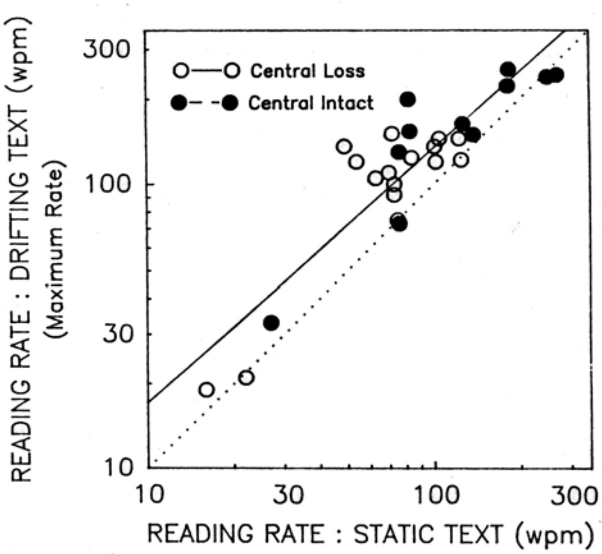

Figure 6. Scatterplot of reading rates for drifting text and reading rate for static text. For drifting text, maximum rates were taken from curves like those in Fig. 4. The rate for static text is for 6° characters and was measured with MNread. The dotted line represents equality. The regression line (solid line) through the data has slope and intercept values of 0.896 and 0.336, respectively.

Fig. 4 shows sample data from four low-vision subjects. In each panel, the upper curve shows mean values for two normal subjects (from Fig. 3). The filled symbols show the low-vision subject's reading rates for drifting text. The X shows the subject's reading rate for static text. Subject D has central field loss resulting from Stargardt's disease. His curve shows a pattern that we have seen before for subjects with central loss; monotonic growth of reading rate with character size. Subject O is an 83 year-old woman with age-related maculopathy and cataracts.

Despite rather high acuity, her static text reading rate is only 54 wpm. She reads faster with drifting text: maximum rate = 120 wpm. Subject T has cloudy media due to cataract but no known retinal involvement. In earlier studies (Legge *et al.*, 1985b) we have found that subjects who retain central vision often have peaked curves, i.e., read fastest for some intermediate range of character sizes. There is evidence for such a peak in T's data but the peak is not very pronounced. Subject AA, who suffers from optic-nerve hypoplasia, has a more distinct peak occurring at about 4.5°. She retains central vision and has clear media.

Do low-vision subjects read static text faster than drifting text? Fig. 5 shows a scatter plot of reading rates for drifting and static text for 6° characters. (In some cases, the drifting-text measurements did not include a measurement precisely at 6° so linear interpolation in log-log coordinates was used to estimate the value.) Open symbols refer to the 16 subjects with central loss and filled symbols to the 11 subjects with residual central vision. Separate regression lines for the two groups did not differ significantly, so a single regression line through the combined data set is shown (solid line). It fits the data quite well (correlation coefficient = 0.88). Its slope and intercept are given in the caption to Fig. 5. The dotted line represents equal rates for drifting and static text. Unexpectedly, there is a clear advantage for drifting text over static text. The mean ratio of rates across all 27 low-vision subjects is 1.15. By comparison, six subjects with normal vision read text composed of 6° characters faster when it was static than when it drifted (mean ratio = 1.44).

Notice that the regression line in Fig. 5 converges with the equality line. This indicates that there is a greater advantage of drifting text for slower readers. For example, according to the regression line, a subject who reads static text at 50 wpm will read drifting-text at 61.5 wpm (a 23% advantage), but there will be no difference in rates for a subject who reads 200 wpm. Why do low-vision subjects read faster with drifting text than static text, whereas the reverse is true for normal subjects? G. T. Timberlake (personal communication), using a scanning laser ophthalmoscope, has observed that some patients with macular scotomas execute an erratic pattern of forward and backward saccades while reading static text. Perhaps the forced-march character of drifting text requires a more orderly sequence of saccades during reading. Alternatively, low-vision readers may lose time in the return sweep from the end of one line to the beginning of the next. Glare may also play a role. For drifting text, it is natural to darken the display except for the line being read. For static text, light from the display above and below the current line may act as a source of glare that reduces reading rate.

Finally, we ask what an MNread score tells us about a subject's maximum reading rate. Because people with low vision appear to read a little faster with drifting text, we rephrase the question to ask how MNread scores relate to maximum rates obtained with drifting text. From the peaks of curves like those shown in Fig. 4, we identified subjects' maximum reading rates for drifting text. Fig. 6 shows a scatter plot of maximum rates against MNread scores for our 27 low-vision subjects; open symbols for subjects with central loss and filled symbols for subjects with residual central vision. Separate regression lines for the two groups did not differ significantly, so a single regression line through the combined data set is shown (solid line). It fits the data quite well (correlation coefficient = 0.89). Its slope and intercept are given in the caption to Fig. 6. The dotted line represents equal rates for drifting and static text.

The results are very similar to those shown in Fig. 5 for the 6° character comparison. This is not surprising because previous research (Legge *et al.*, 1985b) has shown that maximum reading rates with drifting text are highly correlated with rates at 6°. Averaged across all of our 27 low-vision subjects, the ratio of maximum rate with drifting text to MNread rate was 1.37.

The high correlations in the scatter plots of Figs. 5 and 6 forge a link between static reading rates and drifting-text reading rates. Subjects who read rapidly with one form of text presentation read rapidly with the other. This means that roughly the same information is obtained regardless of the mode of text presentation.

DISCUSSION

Evaluation of reading ability is an important part of assessing functional low vision. Snellen acuity is not a good predictor of reading performance for subjects with low vision. For the 27 subjects studied in this paper, the correlation between reading rate as measured by MNread and Snellen acuity was 0.13. Although Sloan M acuity is a better predictor (Legge *et al.*, 1985b), a direct measure of reading performance is preferable. What we offer is a standardized test, appropriate for clinical and research applications, that is sensitive to visual deficits in reading.

In this paper, we have described a computer-based test of reading speed called the Minnesota Low-Vision Reading Test, MNread for short. This test was designed to provide a simple, quick, and accurate estimate of a low-vision person's maximum reading rate. One purpose of this paper is to describe the test in sufficient detail so that it can be reproduced elsewhere. All critical stimulus parameters are specified and the appendices contain the sentences and words used in the test.

We conducted four ancillary experiments relevant to the use of MNread. In one, we found that its test-retest correlation is high ($r = 0.88$). In a second experiment, we found a very high correlation in reading rates for simple sentences and unrelated words. Contrary to suggestion (Baldasare *et al.*, 1986), this result was true for subjects with central-field loss as well as other forms of low vision. This high correlation implies that tests of reading speed based on sentences or unrelated words are roughly equivalent. In a third experiment, we found no significant difference in silent and oral reading rates. This means that MNread accurately reflects silent reading ability, even though it relies on oral reading. Finally, in a masking experiment, we showed that stimulus persistence does not lead to an inflated estimate of reading rates.

MNread uses static text. A second major purpose of this paper was to compare reading rates measured with static and drifting text. There are three reasons for making this comparison. First, several previous psychophysical studies of reading have used a drifting-text paradigm. Second, it has been suggested that people with low vision, particularly those with central loss, might perform very differently with static and drifting text. Third, high magnification reading aids tend to display only a few characters and require scanning (i.e., drift) of text through the field. Low magnification devices display many more characters in the field and rely on eye movements to scan static text. Any important difference in reading performance for drifting and static text is thus germane to the prescription of reading magnifiers for low vision.

In an experiment with normal subjects, we measured reading rate as a function of character size for static and drifting text. The curves were qualitatively similar and replicated findings from earlier research (Legge *et al.*, 1985a). However, in the range of character sizes for which reading rate is maximum - 0.25 to 3° - normal subjects read the static text faster than the drifting text (Fig. 3). Curiously, the opposite was true of low-vision subjects. Although there was a high correlation between rates for drifting and static text (r = 0.88), there was an overall advantage for drifting text. On average, reading rates with drifting text were 15% higher than with static text. This small difference, though noteworthy, is probably not large enough to be of clinical significance in the prescription of magnifiers. Subjects with central loss showed no greater differences in reading drifting and static text than subjects with other forms of low vision. The high correlation in reading rates for the two modes of text presentation implies that tests using either form of text presentation are roughly equivalent.

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Appendix 1. MNread: Sentences

You must type precisely one space between all the words	Our tiny bird ate the seeds before flying off its perch	His friend is also involved in the latest charity event	He made plans to go camping and hiking in the mountains
Children find the chocolate factory to be very exciting	An electrical appliance may be useful for certain tasks	Students know class will be held outdoors on sunny days	The secretary who last used the copier is getting paper
She could not listen to the records while studying late	We never open the window in the winter or summer months	The bakery in that town has pastries that are wonderful	The show ends very late but my brother is allowed to go
My sister was going to play the piano but it was broken	The day began with a friend coming to see me and my dog	A young child cried for the bird who fell to the ground	The walls are made of brick and the steps made of stone
The leaves on my maple tree fall off late in the autumn	The night sky sparkled with shining stars until morning	My pants were too short and the neighbors laughed at me	This chair is so large that I feel like I am very small
The telephone rang only one time before I walked inside	My babysitter told me to go to bed before Mom came home	Everyone went outside after I started the painting task	Our old clock chimes hourly if I remember to wind it up
Every Tuesday the jazz band took requests to play songs	The delicious new ice cream is not easily obtained here	Pirates never bury treasure before making a careful map	The sounds of the waves and the gulls are very peaceful

Appendix 2. MNread: Unrelated Words

THREE-LETTER WORDS (60 words)

act	art	day	get	lip	own	six	way
age	ask	ear	hat	low	pay	son	who
ago	bad	end	her	man	pen	sun	why
air	bed	eye	him	new	sat	ten	you
all	big	far	his	not	saw	two	
and	boy	few	how	now	say	use	
any	but	fix	law	one	sea	war	
arm	buy	for	lie	our	sit	was	

FOUR-LETTER WORDS (103 words)

able	care	ever	gold	land	only	seat	town
also	case	face	good	last	open	send	tree
back	city	fact	grow	lead	pair	shut	turn
bear	cold	fall	hair	life	part	side	wait
beat	dear	fast	half	like	play	soon	walk
best	deep	fear	hand	look	poor	stop	week
bill	done	feel	help	love	pull	such	were
body	door	find	high	mean	pure	sure	when
book	drop	fine	hour	miss	read	talk	wife
born	duty	firm	just	name	real	tear	wish
both	each	form	king	need	rich	that	word
busy	else	four	know	none	rule	then	your
call	even	give	lady	once	save	time	

FIVE-LETTER WORDS (67 words)

about	chief	doubt	judge	quiet	table	trust	world
after	child	drive	laugh	reach	teach	under	would
alone	class	enter	month	serve	there	value	wrong
among	close	field	order	shape	think	watch	young
being	could	fight	other	sight	three	water	
black	count	fresh	party	since	throw	where	
brave	court	glass	pound	stand	today	which	
bring	crowd	great	prove	state	touch	white	
catch	death	heart	quick	story	train	whole	

SIX-LETTER WORDS (72 words)

accept	behind	circle	during	inside	notice	prince	stream
across	belong	common	expect	letter	number	public	street
almost	beside	defend	family	little	object	remain	strike
always	better	demand	famous	matter	office	return	strong
amount	bottom	desire	father	member	people	sample	sudden
answer	center	dinner	figure	moment	person	second	suffer
appear	chance	direct	forget	narrow	please	settle	tongue
attend	choose	divide	friend	nation	powder	simple	window
become	church	doctor	higher	nature	pretty	sister	wonder