

PSYCHOPHYSICS OF READING: VII. COMPREHENSION IN NORMAL AND LOW VISION¹

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Abstract- This is the seventh in a series of papers describing the role of vision in reading. In the previous studies, we have relied on a subject's fastest reading rate as a psychophysical measure of performance, but comprehension is the ultimate goal of reading. In this paper, we ask how comprehension depends on reading rate and we evaluate comprehension as a psychophysical measure of reading performance. Subjects read passages that drifted across a TV screen at rates ranging from 10 to 450 words/min. Comprehension was assessed by multiple-choice questions. There were 109 subjects with normal vision and 24 subjects with low vision. Normally sighted subjects showed roughly constant comprehension for rates less than 200 words/min (roughly 2/3 of their fastest reading rates). The view that reading comprehension deteriorates at very slow rates was not supported. Above 200 words/min there was a steady decline in comprehension. However, the lack of a sharp transition from good to poor comprehension means that comprehension is a poor psychophysical measure. When low-vision subjects read at 2/3 of their fastest reading rates, most of their comprehension scores (21 out of 24) were within 1SD (standard deviation) of normal scores. This encouraging result emphasizes the need for prescription of reading aids, even for people with severely impaired vision.

INTRODUCTION

Reading is one of the most important visual tasks. Often the first sign of eye disease is reading difficulty. Frequently, eye patients are more worried about the effects of the disease on reading than anything else. In our lab, we have been studying the visual requirements of reading with two major goals: to understand the role played by vision in this task, and to understand how visual disorders hinder reading.

In the first two papers of this series, we measured the spatial-frequency-bandwidth and field-size requirements for reading, as well as the effects of several other important stimulus variables (Legge *et al.*, 1985a; Legge *et al.*, 1985b). In addition, we identified characteristics of impaired vision--central-field loss and cloudy ocular media--that have major effects on reading performance. Our results helped guide us in the development of a fiberscope low-vision reading aid (Pelli, Legge, and Schleske, 1985). In subsequent papers, we have examined the effects on reading of wavelength (Legge and Rubin, 1986), contrast (Legge, Rubin, and Luebker, 1987; Rubin and Legge, 1989), and contrast polarity (Legge, Rubin & Schleske, 1987).

In all of these studies, our measure of reading performance has been *reading rate*. Subjects are asked to read aloud lines of text that drift across the face of a TV monitor. The drift rate is increased from a low value until the subject makes a small number of errors. By this means, we

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discover the drift rate at which oral reading departs from 100% accuracy. We have found that the transition from perfect reading (100% accuracy) to ineffective reading (many errors) is sharp (Legge *et al.*, 1985a). From the transition drift rate we compute the subject's *reading rate* in words/min as the product of the drift rate and the proportion of words correctly read. We use this method to find the reading rate as a function of the stimulus or subject variables under study. This procedure has the advantages of allowing for easy experimental control of stimulus parameters and straightforward measurement of reading performance. It yields highly reproducible data. Moreover, the reading of drifting text is similar to much low-vision reading. People with low vision typically scan text across the screen of a closed-circuit TV magnifier or through the field of a high-power optical magnifier.

Sensory limitations to reading have the effect of reducing the rate at which information can be processed. Reading rate as just defined has turned out to be a useful and sensitive measure of these limitations. *Accuracy of comprehension* might be useful as an alternative measure. Just as we can score the accuracy with which subjects read aloud text presented at different drift rates, we can test how well subjects understand text presented at those rates. Comprehension is typically tested with multiple-choice questions after presentation of the text.

One purpose of our study was to examine the viability of comprehension as a measure of reading performance. How does comprehension accuracy depend on drift rate? Like oral reading accuracy, is there a sharp transition from good comprehension to poor comprehension? If so, how does the transition rate at which comprehension fails compare with the drift rate at which oral reading fails? A sharp transition in the comprehension curve, if it exists, could be used to define an alternative measure of maximum reading performance for a given set of conditions. To answer these questions, we measured comprehension as a function of drift rate for a large group of normally-sighted subjects.

It is possible that comprehension of drifting text on a TV screen may differ from comprehension of printed text on a page. We compared comprehension of subjects who read printed text on paper at their natural rates with the comprehension of subjects reading TV text drifting at similar rates.

A second purpose of our study was to determine how comprehension varies for medium and low drift rates. This question is motivated by our interest in low vision. Most people with low vision are limited by their handicap to relatively low reading rates, often less than 100 words/min, sometimes as low as 10 or 20 words/min. There exists the view that comprehension breaks down at low reading rates because it is difficult to integrate ideas across words or phrases or because it is difficult to maintain attention on the text. To quote from Gibson and Levin (1975, p. 539): "There is a minimal speed of reading below which the syntactical and meaningful relations within a sentence or a larger unit of discourse do not come through. Reading one word at a time with pauses between makes it nearly impossible to extract information beyond the word." If this view is correct, we would expect comprehension to deteriorate at slow drift rates.

A third purpose of our study was to measure low-vision comprehension and to compare it with comprehension of normal subjects reading at similar rates. People with low vision often read much more slowly than people with normal vision. Does a person with macular degeneration

who reads only 50 words/min (with the aid of a magnifier) comprehend as much as a normally sighted person who slows down to read at 50 words/min? One view holds that as long as the low-vision subject can read the words accurately, comprehension is limited only by cognitive factors so comprehension should be normal. By another view, the low-vision subject must allocate additional cognitive and attentional resources to gathering information through a deficient sensory channel. With reduced resources at hand, comprehension should be subnormal.

We digress briefly to mention a related issue in educational psychology. Beginning with Abell (1894), there have been many studies of the relation between accuracy of comprehension and natural reading speed. Typically, subjects in these studies read standardized passages at their normal rates and then answer questions testing their understanding of the material. The results of such studies promoted the view, widespread during the first half of the 20th century, that faster readers read with better comprehension. Stroud (1942) reported a consensus correlation coefficient of 0.4 between comprehension accuracy and reading speed. Stroud, however, contended that this value was inflated by artifacts in the traditional methods of measurement. Carlson (1949) studied 330 fifth-grade pupils. He found that the correlation between comprehension and reading speed was always low, sometimes positive and sometimes negative, and depended in complex ways on the intelligence of the subjects, difficulty of the text, purpose for reading, and several other variables. In short, there appears to be no simple relationship between natural reading speed and comprehension.

METHOD

Subjects

109 subjects with normal vision participated. They were University of Minnesota students, ages 18-36 yr, enrolled in an introductory psychology course. All had corrected visual acuity of 20/20 or better (Goodlight 10-ft chart) and were native English speakers. Viewing was binocular with natural pupils.

24 low-vision subjects participated. Their ages, diagnoses, Snellen and Sloan *M* acuities are listed in Table 1. The table also indicates whether there was central field loss or cloudiness of the ocular media since these are variables known to be important in low-vision reading (Legge *et al.*, 1985b). Four of the low-vision subjects were University of Minnesota students at the time of testing. All 24 were native English speakers. Our goal in selecting the low-vision sample was to obtain a fairly wide range of reading speeds and at the same time a fairly broad distribution of pathologies and severity of eye disease.

Table 1. Low vision subjects

Subject	Age	Diagnosis	Acuity		Cloudy media	Central loss	Reading rate (wpm)
			Snellen	Sloan <i>M</i>			
A.	33	Congenital cataract	20/120	4	Yes		100
B.	40	Congenital cataract	20/200	7	Yes		135
C.	24	Congenital cataract	20/50	4	Yes		145
D.	39	Secondary corneal vascularization	20/960	20	Yes		95
E.	37	Congenital cataract	20/120	2	Yes		201
F.	33	Macular pucker	20/200	2.5			159
G.	29	Autosomal-recessive RP	20/120	1.5			105
H.	40	Diabetic retinopathy	20/80	3			129
I.	28	Macular degeneration	20/400	7			70
J.	37	Optic-nerve hypoplasia	20/120	3			266
K.	35	Albinism	20/200	5			158
L.	41	Optic atrophy	20/300	7		Yes	110
M.	42	Macular degeneration	20/200	2		Yes	73
N.	43	Macular degeneration	20/400	10		Yes	70
O.	24	Tumor on optic nerve	20/480	14		Yes	45
P.	32	Optic-nerve atrophy	20/240	7		Yes	14
Q.	28	RLF	20/320	—		Yes	77
R.	32	Optic atrophy	20/120	2		Yes	102
S.	41	Macular degeneration	20/640	14		Yes	111
T.	23	Diabetic retinopathy	20/320	7		Yes	50
U.	37	Optic neuritis	20/400	10		Yes	99
V.	83	Macular degeneration, cataracts	20/80	4	Yes	Yes	22
W.	61	RP, cataracts	20/400	5	Yes	Yes	145
X.	55	Macular degeneration, staphyloma	20/200	5	Yes	Yes	101

Apparatus and test materials

For a more complete description of the apparatus, see Legge, Rubin, and Luebker (1985). 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. See Fig. 1. The letters were displayed as black characters on a white (300 cd/m²) background. The Michelson contrast of the characters (difference in luminance between the white and black divided by their sum) was 0.96.

We created a character set by digitizing upper- and lower-case letters, digits and punctuation marks (Zipatone Century Schoolbook font) using a high-resolution RCA CT-1005/01 video camera. Each character was stored as a 32 x 36 (pixel) x 8 (gray-scale bits) image.

Text drifted smoothly from right to left across the screen. The 25-cm wide rectangular strip contained 8 character spaces. Previous research has shown that a window width of five characters or more permits maximum reading rates for drifting text (Legge *et al.*, 1985a; Legge *et al.*, 1985b). Drift rates were controlled by a computer program which synchronized the

panning of text with the frame buffer's vertical blanking signal. This technique was used to present either single 80-character lines of text or 150-word passages.

The text materials were revisions of six passages from the McCall-Crabbs (1926) comprehension series, level five (sixth grade reading material). The passages were edited to a length of approx. 150 words. The McCall-Crabbs multiple-choice test questions were also revised. First, for each passage, only the six questions most pertinent to the edited passages were retained. Second, for each question, three main answer alternatives were chosen. Answer alternatives too simple for college students were deleted or replaced. Two alternatives were constructed as combinations of the first three, e.g. "A and B" or "all of the above." Thus, for each passage, there were six multiple-choice questions, each with five answer alternatives. In all cases, subjects were required to select one of the alternatives. They could not leave a question blank.

Procedure

There were four series of measurements. In the first series, comprehension was tested for 68 subjects with normal vision as a function of drift rate. Groups of 3-7 subjects were seated about 350 cm from the screen at which distance characters subtended 0.5° (center-to-center spacing). This character size lies in the range yielding maximum rates for subjects with normal vision (Legge *et al.*, 1985a). Prior to presentation of a passage, the first letter was visible at the right margin. Subjects were warned that the trial was about to begin. Following a verbal cue from the experimenter, the passage drifted continuously across the screen at its specified rate until it was complete. The room was then illuminated with a small lamp, bright enough for subjects to read their question sheets and circle their answers. The subjects were given as much time as they required to complete their answers. The lamp was then turned off and a new trial began.

Six passages were tested, taking about 1 h. The six drift rates were 10, 30, 100, 200, 300 and 450 words/min. All subjects were tested on the same six passages. The orders of passage presentation and drift rate were randomized across groups of subjects. Subsequent analysis of variance indicated that comprehension did not vary significantly with serial position (first to last) in the sequence of six tests. However, there were significant differences in the difficulty of the six passages. Four of them yielded about the same average comprehension scores, but one was distinctly harder and another distinctly easier than the rest. The randomization procedure ensured that these differences in difficulty did not affect average comprehension performance as a function of drift rate.

Five subjects were tested on the multiple-choice questions without reading any passages to establish a "chance level." They were instructed to read the questions carefully and answer to the best of their ability.

A second series of measurements was very much like the first. 25 additional subjects with normal vision were tested individually rather than in groups. Comprehension was measured at four drift rates rather than six-100, 200, 300 and 400 words/min. The four equally difficult passages were used. In addition to comprehension, reading rate was measured for each of these subjects as follows: prior to a trial, the first character of a 80-character line of text was visible at the right margin of the screen. After a warning signal, the experimenter pressed a key that

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 proportion of errors. Because the transition from errorless to error-prone reading 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 performance on at least two lines of text drifting at that rate. Reading rate in words/min is equal to the corresponding drift rate in words/min multiplied by the proportion of words correctly read.

In a third series of measurements, 11 normally sighted subjects read passages printed on paper. In order to measure natural reading speeds, these subjects were instructed to read continuously through the passages at their normal rate. The time to read each passage was measured. Reading speed was computed as the length of the passage (in words) divided by the reading time. The passages were printed on white paper (8.5 by 11 in). The text was printed as high-contrast black, Courier letters on single-spaced lines 70-character spaces long. Luminance of the white page was about 200 cd/m². The characters subtended about 0.5° although reading distance was not rigidly controlled. The six passages and comprehension tests from the first series were used.

In the fourth series, 24 low-vision subjects were tested. These subjects viewed the screen from 30 cm at which distance the characters subtended 6°. Previous work has shown that low-vision reading rates for 6° are close to maximum rates (Legge *et al.*, 1985b). (Subject O was tested with 12° characters because she could not read 6° characters.)

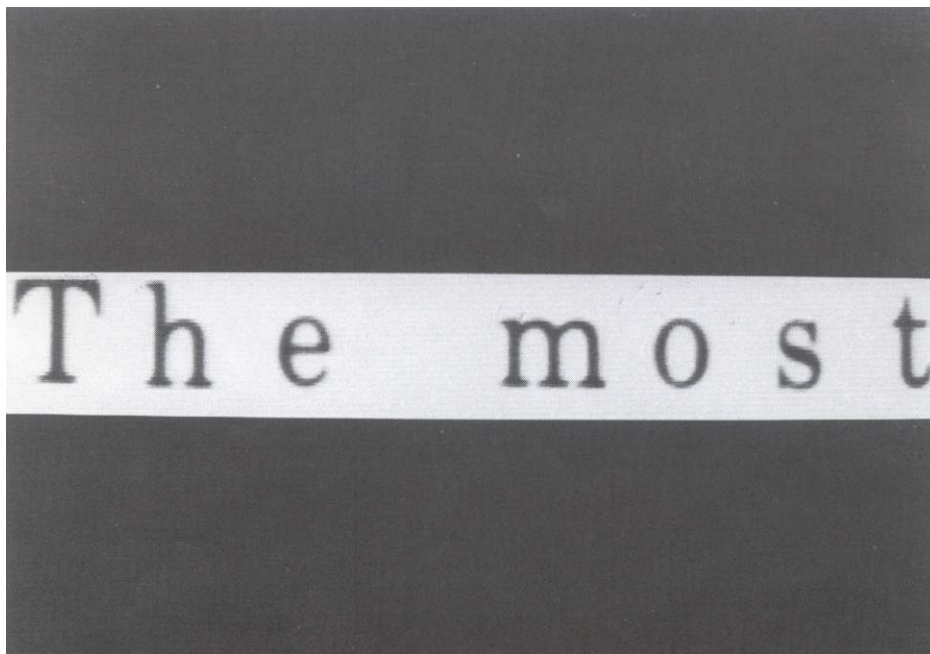


Fig. 1. This photo illustrates the stimulus display. Text drifted continuously across a video monitor but only eight characters were visible at a time.

Each low-vision subject was tested individually. First, *reading rate* was measured using the method just described for normal subjects. Next, four comprehension tests were administered

using the four equally-difficult passages. Two were conducted at a "fast" drift rate averaging 84% of the oral reading rate, and two at a "slow" rate averaging 67% of the oral rate. The aim was to measure comprehension close to the subjects' oral reading rates. We used slightly lower drift rates because our results with normal subjects suggest that failures of comprehension occur at slower rates than failures of oral reading (see below). Test questions were administered verbally to low-vision subjects, and the experimenter marked the subject's answers on the score sheet.

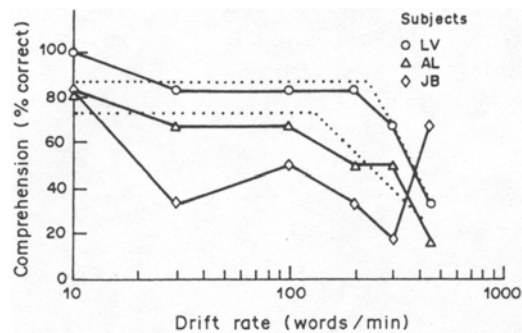


Fig. 2. Individual comprehension as a function of drift rate. Data are shown for three individuals with normal vision. The points represent percent correct on six multiple-choice questions. Dotted lines through the upper two sets of data represent bilinear fits to the data (see text).

RESULTS AND DISCUSSION

In the first experiment, comprehension was tested for 68 normally sighted subjects. There were six drift rates ranging from 10 to 450 words/min. Figure 2 shows illustrative data for three subjects. Each point represents percent correct based on six multiple-choice questions on one passage. Since each question had five choices, the chance level is 20%. As Fig. 2 shows, individual results differed substantially. Part of the variability is due to the statistics of small numbers. Figure 3 presents group data. The circles show mean comprehension scores for the 68 subjects. (The triangles will be discussed below.) The dashed lines indicate ± 1 SD about the mean. The horizontal dotted line at 21% represents performance of the control group who answered questions without reading the passages.

The mean comprehension scores drop slowly from 71.2% to 60.5% as drift rate increases from 10 to 200 words/min. A further increase in drift rate results in a more rapid drop in comprehension. At all drift rates, standard deviations are large, ranging from 19.8 to 28.4%. (Standard errors are smaller by a factor of $\sqrt{68}$.) Binomial variability alone would be expected to yield standard deviations of 19% (6 questions, each having a probability correct of about 0.7). The somewhat greater variability present in the data is probably due to cognitive differences among the subjects.

One of our purposes was to determine whether comprehension might serve as a useful measure of performance in psychophysical studies of reading. Does comprehension, like oral reading accuracy, exhibit a sharp transition from good to bad performance as drift rate increases? Figure 4 shows a set of reading-accuracy data (diamonds) from one subject. The subject read aloud lines of text presented at the indicated drift rates. The percentage of words correctly read is plotted

against drift rate. The mean comprehension scores for 68 subjects are replotted from Fig. 3. The reading-accuracy data show a sharp transition, declining from 97% at 300 words/min to 31% at 450 words/min. These data are typical and resemble our previous findings . (Legge *et al.*, 1985a).² Compared with single-subject comprehension data (Fig. 2), they yield a much cleaner performance limit. Even in comparison with the group comprehension data, the oral-reading measurements yield a much sharper transition, and hence a more precise measure of reading performance.

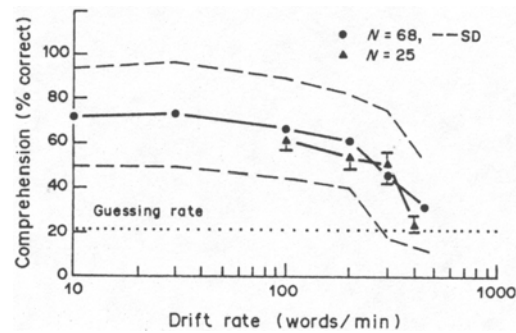


Fig. 3. Mean reading comprehension as a function of drift rate. The circles are mean comprehension scores from 68 normally sighted subjects. Dashed lines show ± 1 SD. The triangles show means for a second group of 25 normal subjects. Vertical bars through the data points indicate ± 1 SE and are sometimes smaller than the symbols. The line labeled "Guessing Rate" represents the performance level of a control group who took the comprehension quizzes without reading the test passages.

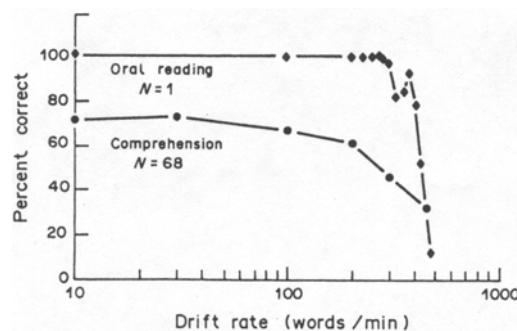


Fig. 4. Comparing oral reading and comprehension as measures of performance. Mean comprehension data (circles) for 68 normal subjects have been replotted from Fig. 3. The diamonds represent the percentage of words correctly read aloud by one subject. Compare the sharp corner in the oral-reading data with the more gradual decline in the group comprehension data and the noisiness of the individual comprehension data (Fig. 2).

Next, notice that comprehension does not decline for drift rates below 100 words/min. If anything, comprehension improves a little at 10 and 30 words/min. Clearly, subjects can understand text read very slowly as well as text read at higher rates. There is no support for the view that comprehension fails at very low reading speeds. This finding is encouraging for low vision, because it indicates that it is possible to comprehend while reading very slowly.

² We have shown . (Legge *et al.*, 1985a) showed that the sharp transition is not due to overtaxing the speech-production system. Equally sharp transitions occur for situations in which reading rate is much lower, e.g. low contrast.

In a second set of measurements, 25 normally sighted subjects were tested individually. First, oral reading rate was measured. Then, comprehension was measured at four drift rates ranging from 100 to 400 words/min. The mean comprehension scores for this group are plotted as triangles in Fig. 3. This second set of data lies close to the first.

The goal of the second set of measurements was to study the relation between oral reading rate and the drift rate at which comprehension fails. We hypothesized that subjects who can achieve higher reading rates might maintain good comprehension at higher drift rates. To examine this question, we fit a bilinear curve to the comprehension data of each of our 25 subjects. The bilinear curve consisted of a horizontal line (flat branch) at low drift rates and a downward-sloping line (descending branch) at higher drift rates. The three parameters of the curve were the slope of the descending branch, and the coordinates of the point of intersection of the two branches. The parameters were searched to select the values yielding the best bilinear fit (least squares criterion). We defined the maximum rate at which best comprehension can be sustained as the drift rate at the point of intersection. The dotted curves through the two upper sets of data in Fig. 2 are examples of the fits.

This curve-fitting procedure was only partially successful. Of the 25 sets of data, only 14 could be satisfactorily fit with the bilinear function. For some of the remaining 11 sets, no point of intersection could be found. (The lower set of data in Fig. 2 is of this sort.) For others, the least-squares solution yielded an ascending rather than descending branch. For the 14 subjects for whom fits were possible, the correlation between oral reading rate and the drift rate at which comprehension began to fail was -0.31 . The lack of a strong relationship is due in part to the inherent difficulty in obtaining a meaningful transition drift rate for comprehension. An additional problem is the relatively small variation in oral reading rates among the 14 subjects. Their mean reading rate was 321 words/min, $SD = 34.2$, $SE = 9.1$. By comparison the mean drift rate for comprehension failure was 230 words/min, $SD = 73.2$, $SE = 20.3$. Although the correlation is weak, the mean values indicate that comprehension began to fail when subjects read at about 70% (230 vs 320 words/min) of their maximum rates.

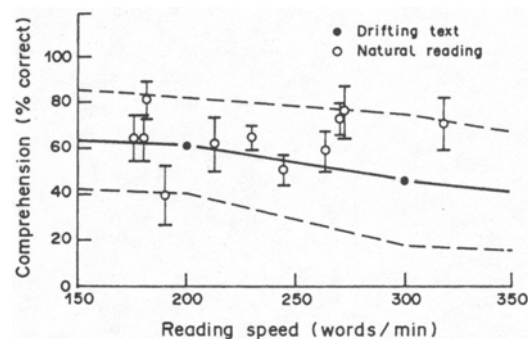


Fig. 5. Comparing comprehension for drifting text and natural reading. The filled circles, replotted from Fig. 3, represent mean comprehension scores for 68 subjects who read drifting text. The dashed lines show ± 1 S.D. The open circles represent comprehension scores and reading speeds for 11 subjects who read printed passages on paper at their natural rates. Each open circle is the mean score from six passages. The vertical bars show ± 1 SE.

In a third series, 11 normally sighted subjects read test passages printed on paper. We asked how comprehension during natural reading, compares with comprehension of drifting text. The results

are illustrated in Fig. 5. Mean values and standard deviations have been replotted from the group data in Fig. 3. The data points and error bars represent mean values and standard errors for the 11 subjects. Results are based on comprehension scores from six passages. Data for all 11 subjects lie within one standard deviation of the mean scores for drifting text. The mean ratio of comprehension scores for static to drifting text is 1.13, indicating a small advantage of 13% for natural reading. We conclude that subjects can comprehend text that drifts at rates equal to their natural reading speeds at nearly normal levels.

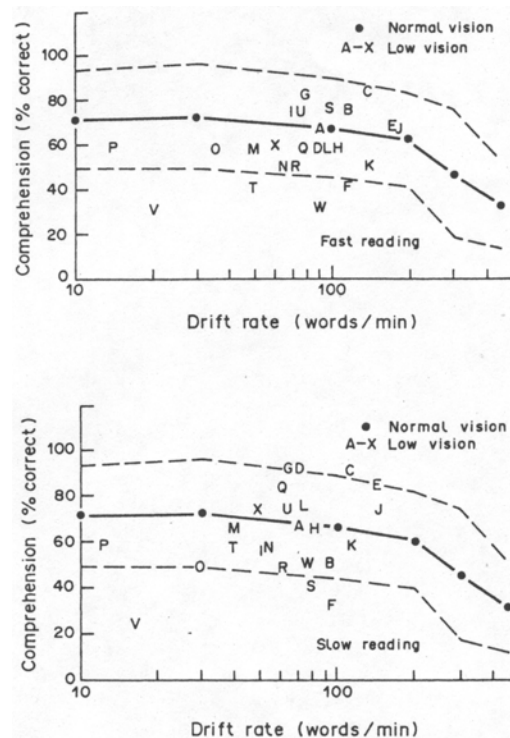


Fig. 6. Low-vision reading comprehension. Comprehension was tested at two drift rates for each low-vision subject. Fast reading (upper panel) refers to a drift rate averaging 84% of the subjects' fastest reading rates. Slow reading (low panel) refers to a drift rate averaging 67% of subjects' fastest reading rates. The filled circles represent mean comprehension and the dashed lines ± 1 SD for 68 normal subjects (from Fig. 3). The letters A-X are individual data for the 24 low-vision subjects listed in Table 1.

Returning to an issue raised briefly in the Introduction, the correlation between percent correct comprehension and natural reading speed for the 11 subjects is 0.29. This low value is fairly close to the consensus value of 0.4 reported by Stroud (1942).

The final series of measurements was conducted with 24 low-vision subjects. Their oral reading rates are listed in Table 1. For each subject, comprehension was measured at two drift rates: the faster averaged 84% of the oral reading rate and the slower 67%. The results are shown in the two panels of Fig. 6.

Once again, means and standard deviations from the original normal group have been replotted from Fig. 3. The letter symbols give comprehension results for individual low-vision subjects and correspond to the letters in Table 1.

The general pattern of results is fairly similar in the two panels. Comprehension was slightly better for the slower rate (mean across subjects = 64% correct) than for the faster rate (mean = 60%). These values are only slightly less than mean comprehension scores for normal subjects in the same range of drift rates (72.3% at 30 words/min, 66.2% at 100 words/min and 60.5% at 200 words/min). For both drift rates, most of the low-vision subjects (21 out of 24) had scores lying within one standard deviation of the mean for normally sighted subjects. A substantial number of the low-vision subjects had comprehension scores above the normal mean.

Subject V fell more than one standard deviation below the normal mean for both drift rates. She was a lucid, 83 year-old woman suffering from macular degeneration and cataracts. Because her reading rate was very low, her comprehension was tested at drift rates of 16 and 20 words/min. It is possible that she was unable to maintain adequate attention to the text throughout the 8-10 min required to read the 150-word passages.

There are several reasons why our low-vision subjects might have had lower comprehension scores than our normal subjects. The two groups were not well matched for age. Our normal subjects ranged in age from 18 to 36 yr but only 11 of our 24 low-vision subjects fell in this range. However, a comparison of mean comprehension scores for low-vision subjects under 36 and over 36 showed no significant differences in either the "fast" or "slow" conditions. Fortuitously, our groups were fairly well matched for educational level. All of our normal subjects were college undergraduates at the time of testing. 13 of our 24 low-vision subjects were college graduates, 9 were enrolled in college or had some post-secondary education, one was a high school graduate and information was unavailable for one.

There are two more reasons why low-vision comprehension might have been subnormal. Low-vision subjects were tested at drift rates quite close to their limiting rates for oral reading. These same drift rates were much further from limiting oral rates for normal subjects. Correspondingly greater sensory- or information-processing demands on the low-vision readers might have adversely affected comprehension. Finally, while some of our low-vision subjects read a good deal with the use of magnifiers in their everyday activities, others read only occasionally or rarely. It is possible that comprehension skills are linked in some way to the amount of daily reading. Given all of these reasons for subnormal comprehension, it is quite remarkable how little low-vision comprehension deviates from normal.

Our results are encouraging for low-vision reading. They indicate that good comprehension is possible at low reading speeds. Our sample of low-vision subjects, having a variety of pathologies, read with nearly normal comprehension in most cases.

There are many purposes for reading. Books may be read cover to cover for reasons of pleasure or vocation. It is impractical for people with very low reading rates to do reading of this sort. A person reading at 10 words/min would take approx. 800 hr to read *Gone with the Wind*. But reading short passages can be even more important. People with low vision may need to read letters and memos, recipes, medicine bottles, check books and personal records, telephone numbers and short newspaper articles. We now know that nearly normal comprehension is

possible for such tasks, even if reading is very slow. This finding emphasizes the importance of prescription of appropriate low-vision reading aids, even in cases of severe visual impairment.

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