PSYCHOPHYSICS OF READING IV. WAVELENGTH EFFECTS IN NORMAL AND LOW VISION [1]

GORDON E. LEGGE AND GARY S. RUBIN

Abstract - Does the color of text influence its legibility? There are reasons why it may do so for specific groups of low-vision observers. We used psychophysical methods to measure the effects of wavelength on the reading performance of four normal observers, two dichromats, and 25 low-vision observers. Reading rates were measured for text scanned across the face of a television (TV) monitor. We compared performance under four luminance-matched conditions in which sets of neutral-density and Wratten color filters were placed in front of the TV screen-blue (λ_{max} = 430 nm), green (λ_{max} = 550 nm), red (λ_{max} = 650 nm), and gray. Under photopic conditions, the reading rates of normal subjects were independent of wavelength, with the exception of characters near the acuity limit. At lower luminances, wavelength effects could be explained by the shift from photopic to scotopic vision. It was hypothesized that light scatter or absorption in eyes with cloudy ocular media would result in depressed performance in the blue. Only one of seven subjects demonstrated this effect, which we traced to wavelength-specific absorption. Observers with advanced photoreceptor disorders tended to read blue text faster than red text. This could not be explained on the basis of photopic spectral sensitivities alone. Finally, the presence of central or peripheral field loss was not predictive of wavelength-specific effects in reading. On the whole, wavelength only occasionally plays a significant role in reading. When it does, performance tends to be depressed either in the red or the blue and to be nearly optimal for green or gray.

INTRODUCTION

In our society, reading is one of the most important visual tasks. We have been studying reading performance of observers with normal and low vision. Although definitions of low vision abound (Faye, 1976), we define it to be the inability to read the newspaper, with best optical correction, at a normal reading distance (40 cm).

In the first two papers of this series (Legge *et al.*, 1985a and Legge *et al.*, 1985b), we measured the minimum spatial-frequency bandwidth and field size needed for reading as well as the effects of other stimulus variables likely to be important in low vision, e.g., contrast polarity. Our results helped to guide us in the development of a fiberscope low-vision reading aid (Pelli *et al.*, 1985).

In this paper, we ask how wavelength affects reading performance. We approached this question by measuring observers' reading rates for text composed of letters of different colors presented on a dark background. Although the most direct application of our results is to text on video displays, our results may generalize to the wavelength composition of illuminants used in reading of conventional printed -text. Control experiments to be reported below support this generalization.

In the following paragraphs, we briefly review literature pertinent to the effects of wavelength on reading performance. First, we consider normal vision, then low vision.

For a normal eye that is diffraction limited by a small pupil, the diameter of the Airy disk is proportional to wavelength for monochromatic light. This implies that visual resolution should be higher in the blue than in the red. Van Nes and Bouman (1967) measured contrast-sensitivity functions in monochromatic light -- 450, 525, and 650 nm. They concluded that wavelength effects could be accounted for by differences that are due to diffraction. However, in the absence of a diffraction limitation, the results are inconsistent. Pokorny *et al.* (1968) found lower acuity with narrow-band blue illumination than with green, yellow, or red illumination for four of five subjects. Nelson and Halberg (1979) found no color differences for contrast sensitivities measured with red, green, and achromatic gratings [cathode-ray tube (CRT) viewed through Wratten filters]. Tinker and Paterson (1931) measured reading speeds for various combinations of colored text printed on colored backgrounds. They found that the legibility of the text was determined primarily by the luminance contrast between the text and the background rather than the specific colors used. Therefore, except when the eye is diffraction limited, there is little evdence to suggest that wavelength should be an important variable for reading by observers with normal vision. Our measurements were conducted at low photopic levels where pupil size does not impose a diffraction limit on visual resolution.

Light scatter and absorption by the ocular media are known to be important factors in both normal and low vision. According to the Rayleigh-scattering formula, spherical particles that are small compared with the wavelength of light will scatter light with an intensity distribution that varies inversely as the fourth power of wavelength. Blue light is scattered more than red light. However, Wyszecki and Stiles (1967) state that there are no wavelength differences for light scatter in the normal eye. Presumably, scattering centers in the normal eye are large compared with the wavelength of light. Nevertheless, there may exist a wavelength dependence for low-vision eyes that exhibit abnormal scattering. There is some clinical indication that yellow filters are helpful to cataract patients in reading, possibly because the filters cut out scattered blue light. However, Bailey *et al*. (1978) found that six different types of yellow filters, worn in spectacle frames or overlaid on the page, had no significant effect on the reading speed of nine cataract patients. Apparently, even in the cataractous eye, scattering centers are not small compared with the wavelength of light. Bruckner (1978) has used a picosecond light-scattering technique and Mie theory to estimate the size distribution of scattering centers in traumatic cataract induced in a rabbit. His results indicate that most of the scattering centers are larger than the wavelength of visible light.

Lenticular absorption is greater in the blue than in the red, even in the normal eye. The difference increases with age (Mellerio, 1971; Said and Weale, 1959). Eyes with cloudy media, e.g., dense cataract, sometimes absorb more strongly in the blue than in the red (Pokorny *et al.*, 1979). It is possible that selective absorption could result in wavelength-specific effects on reading performance by reducing the effective retinal illuminance.

Since the fovea plays a major role in normal reading, we may ask whether observers with abnormalities of foveal cones show wavelength-dependent reductions in reading performance. Protanopes and deuteranopes, although having normal acuity, are thought to lack long-

wavelength-sensitive and medium-wavelength-sensitive cones, respectively. Relative to the photopic spectral sensitivity of normal observers, protanopes show reduced sensitivity for wavelengths greater than 580 nm, with the difference becoming substantial at long wavelengths. Deuteranopes show a smaller reduction in sensitivity below 580 nm. (See Pokorny *et al.*,1979, Chap. 7 for a review.) If reading performance is related to photopic sensitivity, we might expect to find that a protanope reads more slowly in the red than in the blue for text matched for normal photopic luminance. A deuteranope might read more slowly in the blue than in the red. Diseases of the retinal photoreceptors, e.g., retinitis pigmentosa (RP), can have profound effects on vision. Although deficiencies of rod vision are most commonly associated with RP, histological changes in foveal cones are observed even in relatively early stages of the disorder. For a brief review, see Young and Fishman (1982). Van Meel and van Norren (1983) report a reduction in the optical density (light absorbing capacity) of foveal cones in RP patients, some of whom had normal acuities. Psychophysical studies using color matching and the Stiles two-color increment-threshold technique indicate abnormalities of the perifoveal and foveal cones in RP(Young and Fishman, 1982; Sandberg and Berson, 1977; Young and Fishman, 1980; Young, 1982). Sandberg and Berson (1977) demonstrate reductions in sensitivity of the blue- and green-cone systems as well. These findings indicate that cone degeneration is common in RP, possibly beginning with the blue cones.

Since central vision plays a primary role in normal reading, it is not surprising that observers with central-field loss demonstrate major reading deficits (Legge *et al.*, 1985b; Krischer and Meissen, 1983). These observers must rely on peripheral vision. Abramov and Gordon (1977) found that photopic spectral-sensitivity curves in peripheral retina of normal observers showed enhanced sensitivity for short wavelengths compared with the middle and long wavelengths. Therefore it is possible that observers with central field loss who read text that has been matched for normal, foveal photopic luminance might perform better with blue than with red.

Acquired color-vision defects are associated with many forms of ocular disease (Pokorny *et al.*, 1979). There are no standard procedures for assessing color vision in low-vision observers. Conventional tools such as the Farnsworth-Munsell 100-hue test (FM-100), Nagel anomaloscope, or AO-HRR pseudoisochromatic plates rely on stimuli subtending small visual angles. Such stimuli and the tasks involved are often inappropriate for low-vision observers. As an alternative, one might administer the FM-100 or the Farnsworth dichotomous test for color blindness (D-15) with enlarged color chips. However, large-field tests of color vision have been found to yield results different from those obtained with the standard targets (Breton and Cowan, 1981). Nevertheless, we used an enlarged version of the D-15 test to provide a crude assessment of the color vision of our subjects. We asked whether the type or the extent of the color defect identified by the tests would be predictive of wavelength effects in reading.

Implicit in much of the foregoing are the ideas that shifts in relative spectral sensitivity and reductions in retinal illuminance will have significant effects on reading. For example, if abnormal ocular media are optically more dense in the blue than in the red, then blue and red stimuli that are matched for normal photopic luminance will yield retinal images that are more intense in the red than in the blue. This difference might result in better reading performance for red text. It is therefore important to know whether reading performance declines rapidly with target luminance. Reductions in luminance ultimately result in a shift from photopic to scotopic

spectral sensitivity, i.e., increased sensitivity in the blue relative to the red. Therefore an examination of the role of luminance in reading will also provide information on effects of change in relative spectral sensitivity.

Previous measurements of the effect of luminance on reading at photopic levels reveal only a very weak dependence (Legge *et al*., 1985a; Tinker, 1963). In a recent study, Krischer and Meissen (1983) have investigated how blur and luminance interact in their effects on reading performance. Results, not shown in their paper, indicate that reading rate is proportional to log luminance much like acuity (Krischer, personal communication).

We addressed these issues experimentally by measuring reading performance for five groups of subjects. In all cases, reading rates were compared for text of restricted wavelength composition but matched for foveal, photopic luminance.

The first group consisted of normal observers, for whom the wavelength comparisons were made across a range of luminances. We also measured reading performance in protanopic and deuteranopic observers. The third group consisted of low-vision observers with cloudy ocular media. We predicted that any wavelength dependence resulting from absorption or scatter would result in reduced performance in the blue compared with the red. The fourth group consisted of subjects with relatively advanced forms of photoreceptor degeneration, such as RP. If such diseases affect blue cones first, we might expect reduced reading performance in the blue. However, it is probable that blue cones play a less important role in spatial vision than the green- and the red-cone systems (Boynton, 1978). It is therefore difficult to predict how wavelength might affect reading in these disorders. The fifth group consisted of low-vision subjects with heterogeneous pathologies but classified as having central- or peripheral field loss. We predicted that any wavelength dependence exhibited by observers with central-field loss should reduce performance in the red compared with the blue, owing to the shift in peak relative spectral sensitivity toward the blue in peripheral vision.

We have selected our low-vision groups according to visual criteria, such as presence or absence of central vision, rather than diagnostic categories, such as diabetic retinopathy. It has been shown that visual criteria are better than medical diagnoses for predicting the success rates for the utilization of low-vision reading aids (Sloan and Brown, 1963; Sloan, 1968). We are concerned with the effects of visual abnormalities, whatever their cause, on reading performance. We have found (Legge *et al.*, 1985b) that reading performance can be predicted from visual measures that transcend diagnostic categories.

METHOD

Apparatus

The display was a Visualtek Model MV2 Miniviewer closed-circuit television (TV) system with P-4 phosphor. (In some of the later experiments, the display was a Conrac Model SNA 17/Y monochrome monitor, used in conjunction with an RCA TC1005/01 black and white video camera.) Text was scanned one line at a time from right to left across the screen. The screen was masked to an aperture 20 cm wide by 7 cm high. The text, printed on cards, rode through the

camera's field of view on a motor-driven platform. (For a more detailed description of this apparatus see Legge *et al*., 1985a.) The text was printed with Diablo Elite 12 type, with serifs, in both uppercase and lowercase letters. Text was prepared with left and right justification on 80-character lines. Text was selected from materials designed to test reading ability and ranged in difficulty from Grade 4 to secondary school levels. In all cases, care was taken to ensure that the level of difficulty of the text did not exceed the reading level of the observer.

Magnification of the TV camera was set so that eight character spaces filled the 20-cm screen width. Previous studies (Legge *et al*., 1985a and Legge *et al*., 1985b) have shown that a window width of five character spaces or more permits maximum reading rates to be achieved. The color and the luminance of the text was changed by placing Kodak Wratten filters over the TV screen. The filters were #47B (deep blue), #58A (green), #29 (deep red), and #96 1.6 ND (neutral density). A 1.0ND filter was used in combination with the green filter to equate luminance across color conditions (f4%). Except in the control experiments, text appeared as bright, colored letters on a dark background. The luminance of the characters (measured with a UDT Model 80X Opto-Meter) was 6 cd/m^2, and the Michelson contrast exceeded 94%.
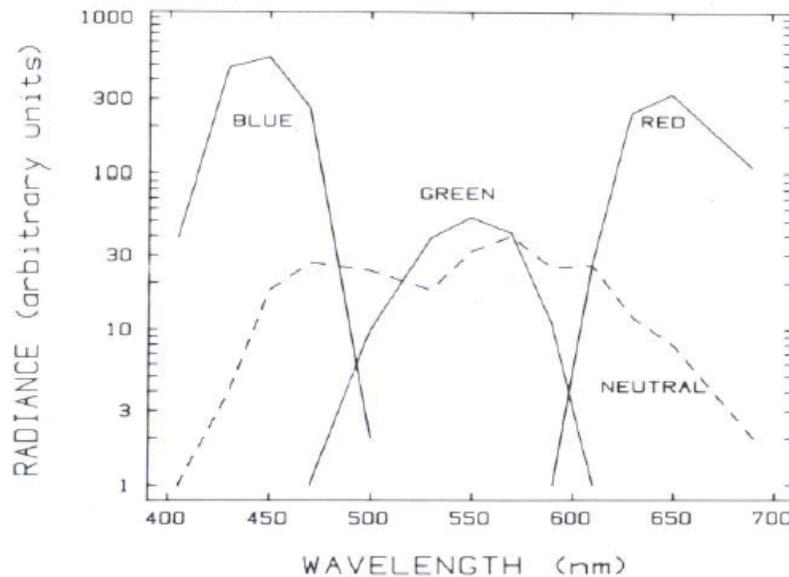

Figure 1. Wavelength distribution of radiance (in arbitrary units) of the stimuli as seen by the observer. The shapes of the curves reflect both the spectrum of the P-4 phosphor of the CRT and the transmission properties of the Wratten filters. The stimuli were matched for photopic luminance.

Spectral characteristics of the display and the filters were measured with a calibrated silicon photodiode (UDT Model 1221) and bandpass interference filters (6-10-nm bandwidths). Figure 1 shows radiance (in arbitrary units) as a function of wavelength for the three color distributions used in the experiment (solid lines) and for the luminance-matched neutral condition (dashed line). The peak wavelengths for the text viewed through the blue, green, and red filters were 430, 550, and 650 nm, respectively.

In some experiments, the luminance of the text was reduced with additional ND filters. These filters were contained in goggles worn by the observer. Luminances of 0.06, 0.006, and 0.0006 cd/m^2 were achieved this way.

Procedure

Before experiments were carried out with a low-vision observer, a brief clinical history was obtained. In most cases, reports from ophthalmologists were also available. Visual fields were measured with a tangent screen when current measurements did not accompany the ophthalmologist's report. Snellen acuity was measured with the Goodlight 10-ft chart. Near acuity was obtained with Sloan M cards (Sloan and Brown, 1963). The M cards contain short sentences to be read at 40 cm. The card with the smallest print is labeled 1 M because the height of the lowercase letters subtends 5' at 1 m. The other cards contain print scaled in integer multiples of this basic size. M acuity has proven to be more useful than Snellen acuity in prescribing low-vision reading aids (Sloan and Brown, 1963) and in predicting optimal magnification (Legge *et al*., 1985b).

Color vision of the normal and most of the low-vision observers was tested with an enlarged version of the Farnsworth dichotomous test for color blindness, D-15 (Farnsworth, 1947). The D-15 test was designed to detect severe color defects such as dichromacy. It will not distinguish most forms of anomalous trichromacy from normal trichromacy. In our version of the test, color samples measuring 1.6 cm x 2.3 cm were used. Viewing distance was not rigidly controlled but was about 40 cm, so the samples subtended about 2.3° x 4.2°. Illumination was provided by a Macbeth Easel lamp (illuminant C), and the luminance of the samples was about 22 cd/m^2.

Following the color-vision testing, reading trials were conducted. Room lights were turned off, and all sources of glare illumination were blocked from the observer. The trial began with the first letter of a line of text stationary and visible at the right margin of the screen. After a warning signal, the experimenter pressed a button that initiated the sweep of a line of text across the screen. The sweep terminated when the last character of the line disappeared at the left margin. The observer was required to read the line of text aloud. The experimenter recorded the period, in seconds, of each sweep and counted the number of errors made by the observer. The experimenter adjusted the scanning rate until the observer made a nonzero but low proportion of errors. The number of words correctly read was divided by the scan period to give a reading-rate measure in words/minute. A single reading measurement was based on performance on two lines of text scanned at the same rate. In previous experiments (Legge *et al*., 1985a) we have found that this procedure quickly locates the scanning rate corresponding to the maximum reading rate.

Table 1. Characteristics of low-vision subjects.

Subject[a]	Age	Diagnosis	Snellen Acuity	M Acuity	Ocular Media	Visual Field	Enlarged D-15 Color Test
A*	33	Secondary corneal vascularization	20/960	20	Cloudy	Intact	Normal
B*	22	Cong. cataract	20/240	2.5	Cloudy	Intact	Normal
C	33	Cong. cataract, aphakia	20/120	2	Cloudy	Intact	Normal
D	33	Cong. cataract, aphakia	20/640	8	Cloudy	Intact	Normal
E	27	Cong. cataract, aphakia	20/120	4	Cloudy	Intact	Normal
F	22	Cong. cataract, aphakia	20/400	5	Cloudy	Intact	Normal
G	25	Cong. cataract	20/160	2	Cloudy	Intact	Normal
H*	43	Cone–rod degeneration	20/200	3	Clear	Central scotoma (5°)	Failed, no axis
I	23	Cone–rod degeneration	20/240	7	Clear	Central scotoma (5°)	Red–green deficit
J*	41	Autosomal recessive RP	20/200	5	Clear	Central island (10°)	Failed, no axis
K*	21	Sex-linked recessive RP	20/60	1	Clear	Central island (15°)	Blue–yellow deficit
L	26	Autosomal recessive RP	20/120	1.5	Clear	Central island (10°)	Normal
M	21	Congenital achromatopsia	20/160	4	Clear	Not available	Failed, no axis
N*	21	Sex-linked recessive RP	20/70	1.5	Clear	Central island (15°)	Blue–yellow deficit
O	29	Macular degeneration (Stargardt's)	20/480	14	Clear	Central scotoma (10°)	Normal (2 minor errors)
P	32	Macular chorioretinitis	20/320	7	Clear	Central scotoma (10°)	Normal (1 major error)
Q	27	Optic-nerve atrophy	20/240	7	Clear	Temporal island[b]	Normal (2 minor errors)
R	71	Age-related maculopathy, aphakia	20/50	7	Clear	Central scotoma (10°)	Normal (2 minor errors)
S	39	Macular degeneration (presenile)	20/120	2	Clear	Central scotoma[c]	Normal
T*	27	Cong. cataract, aphakia, undiagnosed field constriction	20/400	14	Cloudy	Central island (15°)	Congenital red–green
U	33	Optic-nerve hypoplasia	20/120	3	Clear	Central island (7°)	Normal
V	35	Occipital lobe damage	20/15	1	Clear	Superior hemianopia (with macular sparing)	N/A
W	46	Diabetic retinopathy	20/40	1	Cloudy	Scattered scotomata	Normal
X	22	Optic atrophy	20/160	2.5	Clear	Temporal field loss (to 20°)	Normal
Y	28	Retinopathy of prematurity, glaucoma	20/120	1.5	Cloudy	Constricted field (±45°)	Normal

[a] Asterisks indicate subjects who showed a statistically significant wavelength effect (see Results).
[b] Doctor's report incomplete. Unable to return for field measurement.
[c] Severe nystagmus prevented accurate field measurement.

Reading rates were measured for letters subtending 6° (center-to-center distance) at a viewing distance of 25 cm. This size lies within the acuity limit of all subjects in our study. We have previously shown (Legge *et al*., 1985b) that characters subtending 6° yield maximum or nearly maximum reading rates for most low-vision subjects. We also tested our normal subjects with character sizes near their acuity limits. Character size was changed by changing viewing distance. When appropriate, observers were refracted for different distances and for different colors to compensate for chromatic aberration. Special care was taken to refract aphakic subjects for each condition.

In a typical experimental session, reading rates were obtained from one observer at a single luminance. Text color was varied in random order. A typical session took about 1 hour. However, several of our low-vision observers tired quickly, and several read very slowly.

Accordingly, some returned for as many as four sessions on separate days to complete all measurements.

Two control experiments were conducted with normal subjects. In the first , two subjects were tested with text composed of black letters on a colored background rather than the colored letters on black backgrounds used throughout the main experiments. This contrast reversal was achieved by inverting the video signal sent to the monitor. In a second control experiment two subjects read stationary text printed on white cards. The letters subtended either 6° or 0.5°. The cards were illuminated by a 20-W tungsten-halogen lamp. The subjects viewed the cards through the same Wratten filters used elsewhere in the experiments but this time mounted in goggles. The text appeared to the subjects as conventional, stationary black text on colored backgrounds. ND filters were used to match the back-grounds in luminance at 11 cd/m^2. Reading rates were computed by timing the subjects as they read silently six consecutive 40-character lines of the text as rapidly as they could without skimming.

Photopic spectral sensitivities were measured for three normal and five low-vision observers. Light from a 100-W tungsten-halogen lamp was passed through narrow-band interference filters (6-10-nm bandwidth) and rear-projected as a 2.3° diameter disk onto a sheet of ground glass. The colored disk was optically superimposed upon a white adapting field by means of a beam splitter. The uniform field was obtained by placing a sheet of diffusing Mylar over the face of a CRT with P-4 phosphor. The adapting field had a luminance of 14 cd/m^2 and subtended 37.7° horizontally by 28.7° vertically. The luminance of the colored disk was controlled with ND filters. Observers viewed the field monocularly with natural pupils through an eyepiece that excluded stray light.

Detection thresholds were measured for 430-, 550-, and 650-nm disks by a modified method of limits. After the observer adapted to the uniform field, the disk was presented at a bright enough level for the observer to distinguish it clearly from the background. Then a series of trials was initiated in which the intensity of the disk was reduced in 0.25-log-unit steps until the observer reported that it was no longer visible. The intensity was then raised in 0.25-log unit steps until the disk became visible. The disk was occluded between trials, and viewing time was unlimited (although it seldom exceeded 1-2 sec). About 10% of the trials were catch trials in which the disk remained occluded. No fixation marks were used, so, to aid our low-vision observers in locating the stimulus, additional trials were interspersed in which the disk was clearly visible. Threshold was defined as the average transition point between two descending and ascending series. Three thresholds were measured for each wavelength.

Observers

We studied reading performance in 25 low-vision observers, one protanope, one deuteranope, and four normal observers. Normal observers had Snellen acuities of 20/20 or better (with spectacle correction, if necessary) and normal color vision, as measured by the D-15 test. Dichromatic observers had 20/20 acuities and were diagnosed on the basis of the Nagel anomaloscope test. Table 1 presents characteristics of the low-vision observers.

Reading-rate measurements were usually made binocularly with natural pupils. For one observer, reading was possible and sufficiently different in the two eyes to merit separate measurement. These measurements were conducted monocularly and are shown as C and D in Table 1.

Both eyes of observers E, K, M, Q, T, W, and X had the same characteristics. These characteristics are shown in Table 1. The remaining observers had large differences in the conditions of the two eyes, with their "better" eye determining their reading performance. The characteristics of this eye are given in Table 1.

RESULTS AND DISCUSSION

Observers with Normal Vision

Data for four observers with normal vision are shown in Fig. 2(a). Reading rate in words per minute is plotted as a function of the peak wavelength of the stimuli seen through the red, green, and blue filters. Data for the ND (gray) filter are shown to the right of the break in the abscissa. Each point represents the average of two measurements of reading rate for scanned text. The variability was small. The average standard error for these observers was 5%, and the largest standard error was 13%. Filled symbols in Fig. 2(a) show data for 6° letters. There were no important effects of wavelength. The largest variation in reading rates across wavelength was less than 20% (subject MK). In an additional experiment with subjects HR and MK, the conditions were identical, except for contrast reversal: 6° dark characters appeared on bright backgrounds. Neither contrast reversal nor wavelength affected reading performance. (For further discussion of contrast-polarity effects in reading, see Legge *et al.,* 1985a.)

We also examined the effects of wavelength on reading performance when the text was composed of letters near the subjects' acuity limits [open symbols in Fig. 2(a)]. Subjects NH and DR still showed no effect of wavelength, although their overall reading rates were lower. However, subjects MK and HR exhibited depressed performance in the blue. Despite repeated attempts at improved refraction to compensate for chromatic aberration, the effects persisted. When character size was increased to 0.5° the blue effect disappeared. These results may be related to those of Pokorny *et al*. (1968). In a careful study, they found that acuity in the blue was lower than acuity at longer wavelengths for four of five subjects. Having excluded dioptric factors and light scatter as explanations, they attributed the effect to complex neural interactions. Since reading rate drops rapidly near the acuity limit (Legge *et al.*, 1985a and Legge *et al.*, 1985b) a small reduction of acuity in the blue could account for our findings.

In our experiments, subjects were asked to read aloud lines of text that drifted across a screen. This task differs in several ways from ordinary reading. In order to generalize our findings to everyday reading, we asked subjects MK and HR to read stationary text composed of black letters on bright backgrounds (see Method). Silent reading rates were measured for letters subtending 6° (filled symbols) and 0.5° [open symbols in Fig. 2(b)]. Once again, there was no important effect of wavelength. We have also shown (Legge *et al.*, 1985a) that reading rate varies with character size in the same fashion for drifting and stationary text and for silent and oral reading.
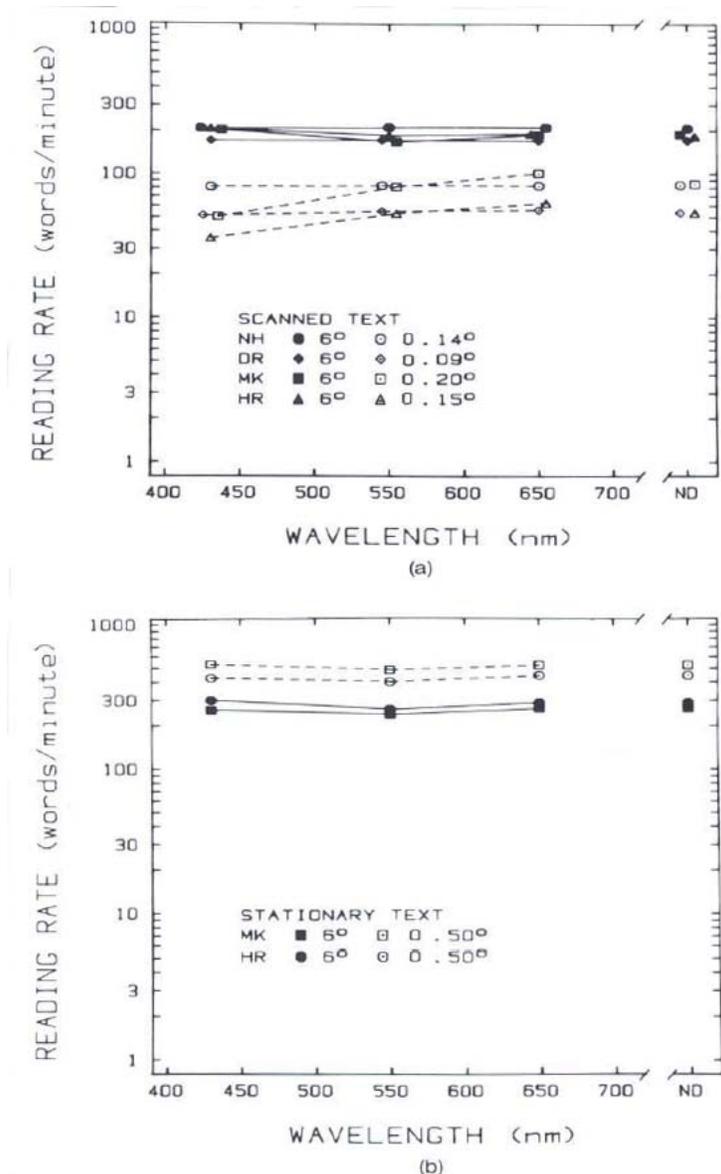
Figure 2. Reading rate versus wavelength for observers with normal vision. (a) The observers read text that was scanned across the screen of a TV monitor. Filled symbols refer to text composed of 6 ° characters and open symbols to text composed of characters near the observer's acuity limit. Each point is based on two measurements of reading rate. The maximum standard error was 13%. (b) Observers read stationary text printed on cards. Filled symbols refer to 6 ° characters and open symbols to 0.5° characters. In both (a) and (b), ND refers to the neutral-density or gray condition.

A major difference in the reading of static and drifting text is the pattern of eye movements, but there is a striking functional similarity between the two. Recordings (Legge *et al.*, 1985a; Buettner *et al.*, to be published), 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, and then saccade back to pick up a new letter. Repetitions produce a pattern that resembles optokinetic nystagmus. The resulting sequence of retinal images is like that found for stationary text: There is a series of foveal fixations on letters, separated by saccades spanning a few letter spaces. Together these

findings encourage us to believe that much of what we learn in our studies of scanned text will generalize to everyday reading.
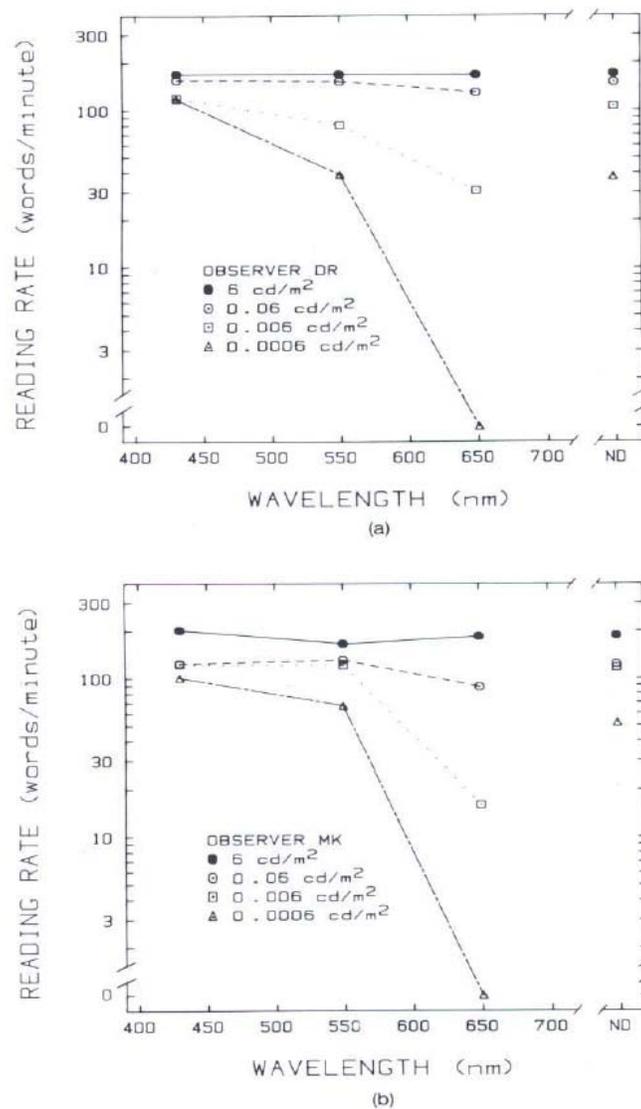

Figure 3. The effect of luminance on reading rate for normal observers. The four curves in each panel show reading rate as a function of wavelength for luminances ranging from 6 to 0.0006 cd/m^2. The text was composed of 6 ° letters. Neither observer could read the red text at the lowest luminance. (a) Observer DR, (b) observer MK.

We conclude that for luminance-matched text, there is no important effect of wavelength on reading performance for normal subjects, except possibly for letters quite near the acuity limit.

Figure 3 shows the effects of luminance on reading rate for two observers with normal vision, DR and MK. The letters were matched for foveal, photopic luminance. Different sets of data correspond to viewing of the display through different ND filters. No attempt was made to control pupil size. However, for the lowest luminance used, observers were unable to identify hues and were unable to read centrally fixated letters. We therefore believe that scotopic vision

was used for the reading of the dimmest text. Under these conditions, observers were annoyed at first by the need to read with peripheral vision. After a few minutes of practice, however, they readily performed the task and rapidly achieved asymptotic performance. For both observers, reading rate declined slowly with luminance in the blue and more rapidly in the red. For example, decreasing the luminance by 3 log units reduced subject DR's blue reading rate from 170 to 120 words/min. His red reading rate decreased from 168 to only 31 words/min. For both observers, luminance must be reduced by more than 3 log units to cause a twofold reduction in reading rate for the neutral, gray letters.

From the results of Fig. 3, we conclude that reading is possible in scotopic vision, reading rates climb slowly with luminance, and wavelength effects can be explained qualitatively in terms of the shift from photopic to scotopic vision.
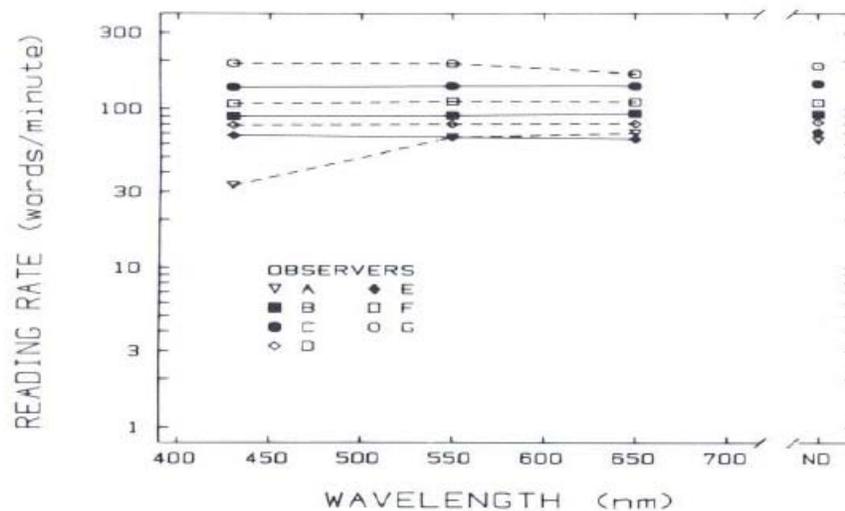

Figure 4. Reading rate versus wavelength for observers with cloudy ocular media. In this and all subsequent figures, reading rates were measured with 6 ° letters. A, B, C, D, E, F, and G refer to the individual observers described in Table 1.

Observers with Cloudy Ocular Media

Figure 4 shows data for seven eyes with cloudy ocular media. In this and all subsequent figures, the text was composed of 6° letters. For this group, we predicted that if reading performance were affected by wavelength, it would be better in the red than in the blue. This was true only for subject A.

The remaining subjects showed no wavelength effects. Observer A suffers from severe corneal vascularization and has an acuity of only 20/960. His reading rates were about 65 words/min for all colors except blue where they dropped to 30 words/min. Observer A produced a normal ordering on the enlarged D-15 test.

We conducted four supplementary experiments to study subject A's depressed performance in the blue. First, we measured contrast-sensitivity functions for sine-wave gratings on a CRT display (P-31 phosphor) viewed through luminance-matched blue and red Kodak Wratten filters

(# 29 and # 48A). Sensitivities were measured from 0.02 cycles/degree (c/deg) to near subject A's high-frequency cutoff at 1 c/deg. For all but the lowest spatial frequency, subject A's sensitivities were slightly higher in the red than in the blue, with a maximum difference of 0.3 log unit. In a second experiment, we measured subject A's contrast thresholds for the identification of isolated letters. White letters subtending 6° were presented against a gray background on a TV monitor (P-4 phosphor). Contrast was varied by changing the intensity of the background. Contrast thresholds were measured while subject A viewed the screen through luminance-matched Wratten filters. Again, subject A demonstrated enhanced sensitivity in the red relative to the blue with a difference of about 0.3 log unit. The results of these two experiments show that subject A's depressed reading performance in the blue is symptomatic of a more general reduction of pattern sensitivity in the blue. This reduction is probably due to one of two factors: reduced retinal-image contrast in the blue resulting from wavelength-dependent scatter or reduced retinal illuminance in the blue resulting from wavelength-dependent absorption. In the third supplementary experiment, we sought to distinguish between these factors by assessing the wavelength dependence of absorption by subject A's optics. To do this, we compared subject A's scotopic spectral sensitivity with that of a normal subject (subject DR in Figs. 2 and 3). To equate the two subjects for light scatter, both of them viewed the light source through a diffusing screen that spread the image across the entire visual field. Assuming that both observers' dark-adapted thresholds are mediated by rods, any deviations in the shape of subject A's spectralsensitivity curve relative to the normal observer's curve can be attributed to wavelength-dependent light attenuation by subject A's optics. The stimulus was derived from a xenon source passed through interference filters (bandwidths of 610 nm). Thresholds were obtained by settings of a calibrated ND wedge in the path of the light source at 50-nm intervals from 400 to 700 nm. The results show that subject A's spectral sensitivity was depressed at all wavelengths relative to the normal but more so in the blue than in the red-0.4 log unit at 700 nm, 0.75 log unit at 550 nm, and 1.16 log units at 400 nm. This indicates that when stimuli are matched for photopic luminance, subject A's retinal illuminance is roughly 0.6 log unit higher in the red than in the blue. In the final supplementary experiment, we asked whether attenuation of the red text with an additional 0.6-log-unit ND filter would have the same effect on subject A's reading rate as a change from red to blue text. We therefore measured subject A's reading rate for the red text with and without the additional ND filter. Addition of the filter led to reduction in reading rate to 61% of the unfiltered rate. By comparison, Fig. 4 indicates that subject A's blue reading rate was 46% of his unfiltered red rate. This near agreement means that wavelength-specific absorption by subject A's optics can account for the wavelength dependence of his reading performance.

From our experiments with observers with cloudy ocular media, we conclude that wavelength-specific effects on reading are uncommon. However, we did discover one observer with reliably depressed performance in the blue that was probably due to absorption.

Observers with Photoreceptor Abnormalities

Figure 5 shows data for a protanope and a deuteranope. These are observers with normal visual acuity but classic forms of color deficiency.

The results of Fig. 3 indicate that relatively large changes in luminance are required to produce relatively small changes in reading performance. On the whole, the photopic spectral sensitivities of dichromats do not differ greatly from normal, with one exception: Protanopes show a major reduction of sensitivity in the red. According to Hsia and Graham (1957), protanopic foveal absolute sensitivity at 650 nm is almost one log unit below normal. By comparison, at 430 nm and 550 nm, protanopic spectral sensitivities do not differ from normal. A simple prediction is that a protanope's reading performance in the red is depressed by an amount equal to the depression exhibited by a normal observer who views the screen through a 1-log-unit ND filter. We can test this prediction by looking at the data in Figs. 3 and 5. By interpolation, the data in Fig. 3 indicate that at 650 nm one log unit of luminance reduction would result in reading rates of about 90% (subject DR) and 70% (subject MK) of the unfiltered rates. By comparison, the protanope in Fig. 5 reads at a rate of 135 words/min at 650 nm and 180 words/min at 550 nm; that is, his reading rate at the longer wavelength was reduced to about 75% of maximum. This falls within the range predicted on the basis of the normal data in Fig. 3.
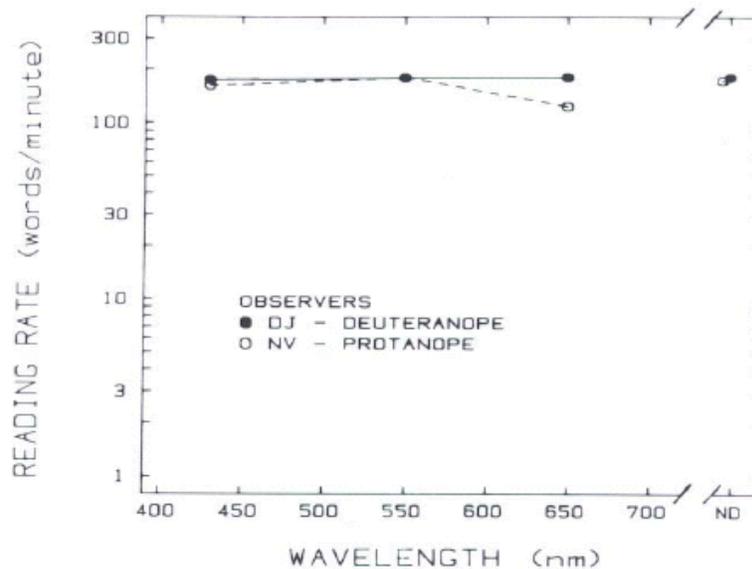

Figure 5. Reading rate versus wavelength for two dichromats. Filled symbols, subject DJ, a deuteranope; open symbols, subject NV, a protanope. Both have normal acuity.

On the other hand, the deuteranope in Fig. 5 showed no wavelength dependence of reading. This is not too surprising since the deuteranopic spectral-sensitivity function differs by no more than 0.3 log unit at 430 nm and 0.1 log unit at 550 and 650 nm. A luminance reduction of 0.3 log unit or less would result in reading rates of at least 90% of the unfiltered rates.
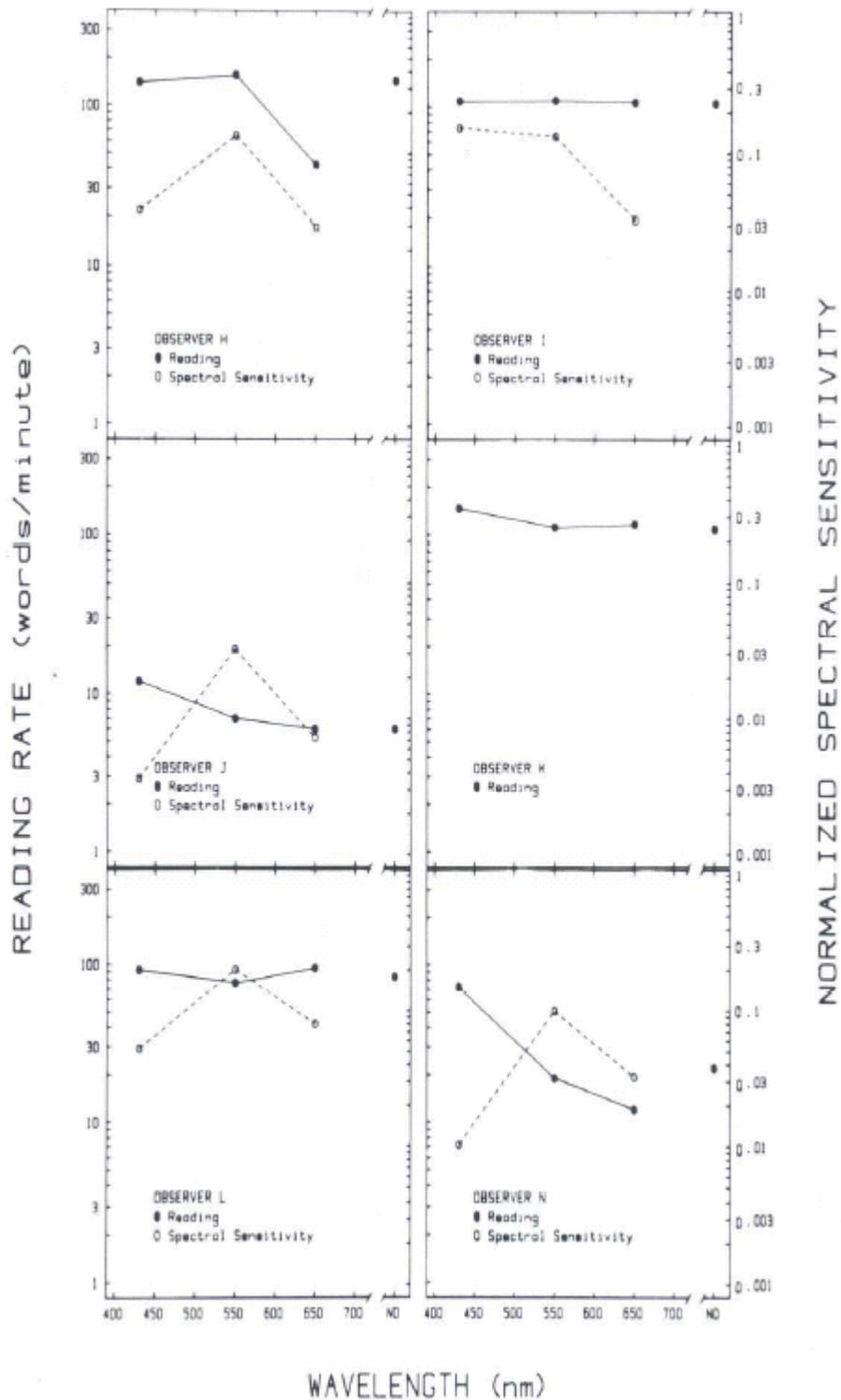
Figure 6. Reading rate and spectral sensitivity versus wavelength for observers with photoreceptor disorders. Each panel is devoted to one observer; see Table 1. Filled symbols, reading rates, left ordinate; open symbols, normalized spectral sensitivities, right ordinate. The spectral sensitivities are reciprocals of increment thresholds for the detection of 2.3 ° diameter circular spots viewed through interference filters on a 14 cd/m^2 white background. The data have been normalized with respect to average spectral sensitivities of three normal subjects. Therefore a value of 1.0 on the right ordinate refers to normal spectral sensitivity.

The panels of Fig. 6 show data for six subjects with degenerative disorders of the photoreceptors. Subjects H and I suffer from cone-rod degeneration, and subjects J, K, L, and N suffer from RP. The filled symbols show the reading rate (left ordinate) as a function of wavelength.   For these subjects, reading performance is more dependent on wavelength than for subjects with cloudy media. For four of the six subjects, performance drops from the blue to the red. This trend is reminiscent of the more rapid performance decline in the red for normal subjects when luminance is decreased (Fig. 3). In that case, we attributed the decline to a shift from photopic to scotopic vision. It is possible that wavelength dependence in Fig. 6 reflects an abnormal reliance on rod vision for the performance of the reading task. Such an abnormal shift to rodlike function in pathological cases has been termed "scotopization" (Pokorny *et al.*, 1979).

We asked whether the scotopization of the reading data would be reflected by the shape of photopic spectral-sensitivity functions. We measured increment thresholds for 2.3° diameter, narrow-band disks superimposed upon a white adapting field of luminance 14 cd/m^2 (see Method). The results are shown as triangles in Fig. 6. Spectral sensitivity (right ordinate) has been normalized by average values obtained from three normal subjects.[2] Accordingly, a value of 1.0 represents normal spectral sensitivity. (Subject K was unable to return for spectral-sensitivity measurements.) First, note that there is a correlation between the overall heights of the reading curves and the spectral-sensitivity curves; subjects with low spectral sensitivities read more slowly. Correlation coefficients for log values of reading rate and spectral sensitivity at 430, 550, and 650 nm are 0.83, 0.83, and 0.77, respectively.   However, only one of the five spectral-sensitivity functions shows scotopization. Subject I's normalized spectral sensitivity dropped from about 0.15 in the blue and the green to 0.035 in the red. The remaining four spectral-sensitivity functions exhibit peaks at 550 nm. In each case, there is a decline in sensitivity from 550 nm to 650 nm as expected from scotopization, but there is a sharp decline in the blue as well. Verriest and Uvijls (1977), have also observed a decline in the blue for photopic increment thresholds for some of their RP patients (they use the term pigmentary retinopathy). We may speculate that the decline in the blue is associated with early and rapid degeneration of the blue cones. As mentioned in the Introduction, loss of the blue cones might not matter for a pattern-analyzing task such as reading.

From the data in Fig. 6, we conclude that subjects with advanced forms of photoreceptor degeneration commonly read better in the blue or the green than in the red. Nevertheless, their spectral sensitivities tend to be highest in the green. Presumably, this complex pattern of results represents the different degrees to which rods and cones contribute in the visual tasks of reading and increment detection.

We comment briefly on a subject for whom we have incomplete data, subject M in Table 1. We believe that he is a congenital rod monochromat. He showed no effect of wavelength in the reading task. Assuming that he relies only on rods, we would have expected a strong scotopization effect. The fact that we did not find it is puzzling.

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[2] The average spectral sensitivities of our three normal subjects (in arbitrary energy units) were 100 (430 nm), 204 (500nm), and 105 (650 nm). It is difficult to compare our increment thresholds with those of previous studies since our background was a P-4 phosphor, not a standard white background. In addition, we measured spectral thesholds using targets that were continuously present rather than the usual brief flash or flickering targets used in other studies.

Observers with Central- or Peripheral-Field Loss

Figure 7 shows data for five eyes with central-field loss, and Fig. 8 shows data for six eyes with peripheral-field loss.

Although most of these subjects have retinal disorders (Table 1), disease is not specific to the photoreceptors. The sets of data in the two figures show remarkably little effect of wavelength. Although the subjects with central-field loss must rely on peripheral vision to read, there is no evidence for the predicted advantage of blue over red (Fig. 7). From these results, we conclude that central- versus peripheral field loss per se is not associated with any clear wavelength-specific effects in reading.

Relation to Color-Vision Test Results

The rightmost column in Table 1 gives the results for the enlarged D-15 color-vision test. Are these results related to the presence or the absence of wavelength effects in reading? We may classify the results of the D-15 as normal or abnormal. Normal means that the subject made no more than two minor errors or one major error in the ordering of the color caps (Pokorny and Smith, 1979 Chap. 5). Abnormal refers to all subjects who exceeded these limits. Similarly, we classified reading performance as wavelength dependent or wavelength independent on the basis of one-way analyses of variance. A subject was classified as wavelength dependent if there was a significant effect of color on his/her reading performance. Wavelength-dependent subjects are indicated by asterisks following their letter designations in Table 1.[3] Table 2 shows the number of eyes in the four resulting categories.

A chi-square test indicates that the rows and the columns are not independent [$\lambda^2_{(1)} = 8.8$, $p < 0.005$]. This means that subjects who have abnormal color vision according to the D-15 test are significantly more likely to demonstrate wavelength effects in reading than subjects who are normal by the D-15 test.

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[3] Two subjects, designated as B and T in Table 1, were classified as wavelength dependent on the basis of the analysis of variance, even though there was less than a 5% difference between maximum and minimum reading rates across the four wavelength conditions. Although the wavelength effect was statistically significant because of the extremely small variability in their reading rates at each wavelength, it is of little practical significance to these two observers. The significance of the subsequent chi-square test is unaffected by whether these two subjects are included in the wavelength-dependent or wavelength-independent categories.
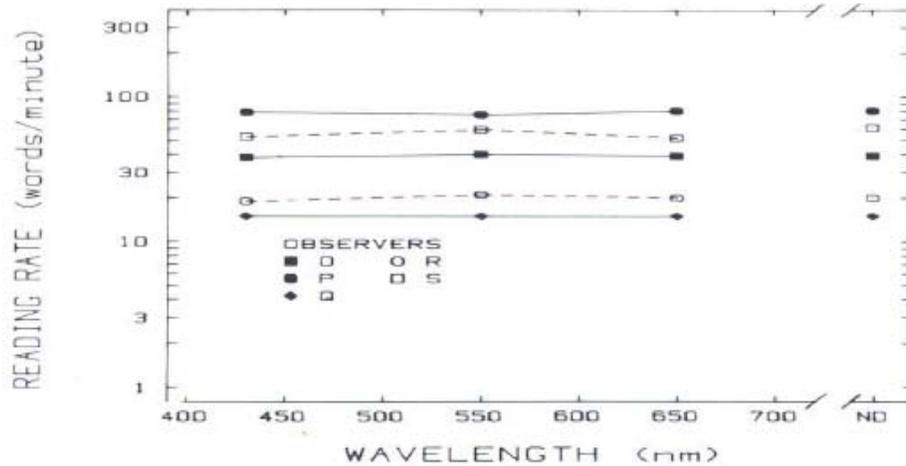
Figure 7. Reading rate versus wavelength for two observers with central-field loss. O, P, Q, R, and S refer to the individual observers described in Table 1.
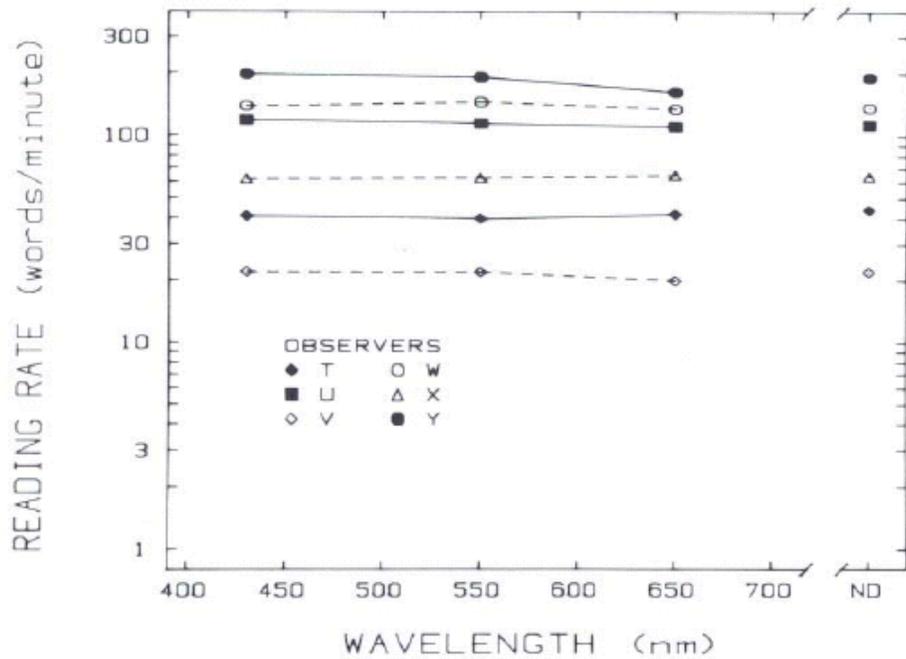

Figure 8. Reading rate versus wavelength for observers with peripheral-field loss. T, U, V, W, X, and Y refer to the individual observers described in Table 1.

SUMMARY

We have asked whether wavelength affects reading performance. We have found that, with the possible exception of letters near the acuity limit, the reading performance of normal subjects under photopic conditions is independent of wavelength. Our deuteranope behaved normally, but our protanope exhibited a reduced reading rate in the red. This reduction can be accounted for by the protanope's reduced photopic spectral sensitivity in the red.

Table 2. Relation of wavelength effects in reading to color vision test results for low-vision subjects[a].

	Normal Color Vision	Abnormal Color Vision
Wavelength-dependent reading	2	5
Wavelength-independent reading	16	2

[a] The cells show the number of low-vision subjects in each of the four categories. Subjects were classified as having abnormal color vision if they failed the D-15 test. They were classified as having wavelength-dependent reading if their reading rates showed a significant dependence on wavelength in a one-way analysis of variance ($p < 0.05$). The table reveals a significant interaction between status of color vision and wavelength specificity of reading [$x^2_{(1)} = 8.8, p < 0.005$].

Most of our low-vision subjects with cloudy ocular media showed no effect of wavelength. Although light scatter has adverse effects in such eyes, it is apparently not wavelength specific. Subject A, who has severe corneal vascularization, showed depressed performance in the blue. We traced this effect to wavelength-selective absorption. Although absorption may sometimes be wavelength-specific in eyes with cloudy media, (e.g., cataract) the effect will rarely be as extreme as for subject A and will not often produce wavelength-selective effects in reading.

Our subjects with degenerative diseases of the photoreceptors showed the most pronounced effects of wavelength. They tended to read better in the blue than in the red. This scotopization may reflect a role played by rods in the reading process.

Finally, the presence of central- or peripheral-field loss per se is not predictive of wavelength effects in reading.

The scatter plot in Fig. 9 summarizes our findings. Each point plots one subject's minimum reading rate against his or her maximum reading rate. The symbol shape represents the color for which the minimum rate was measured. Filled symbols refer to our four normal observers and two dichromats, and open symbols refer to low-vision observers. The data are for 6° characters. Points lying on or near the diagonal line refer to subjects for whom maximum and minimum reading rates differed very little across wavelengths.

The most important feature of Fig. 9 is that the data cluster near the diagonal. Departures are usually small. Among subjects with high reading rates (mostly subjects with normal vision), there is only one point that departs substantially from the diagonal. It is the filled square representing the protanope's performance in the red. The points that lie substantially below the diagonal at lower reading rates represent effects of wavelength on the reading performance of some low-vision subjects. Most of these subjects had photoreceptor degeneration. For the seven low-vision subjects who showed a significant wavelength effect, three read slowest with red text, two read slowest with blue, and one each read slowest with green and gray.
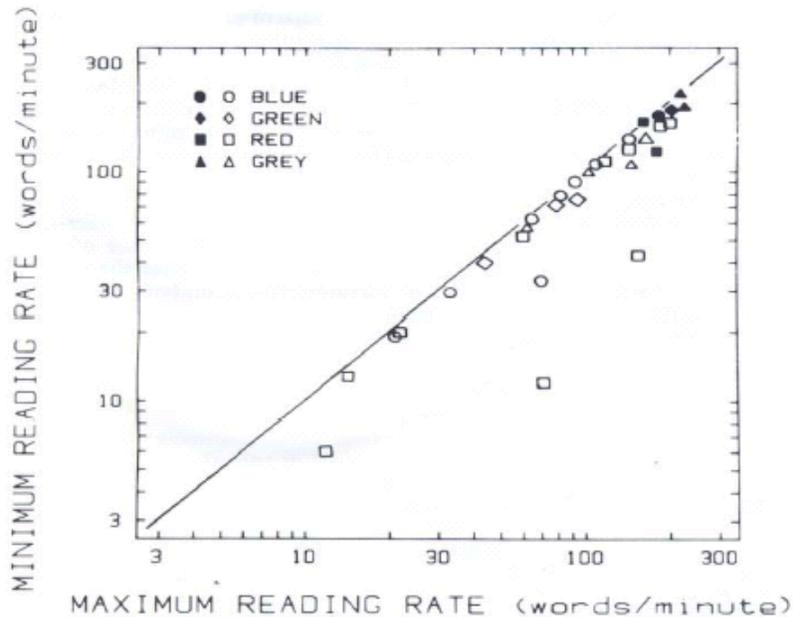
Figure 9. Scatter plot of minimum reading rate versus maximum reading rate. Each point represents one observer's minimum and maximum reading rates. The shape of the symbol refers to the color of text for which the minimum rate was obtained. Open symbols refer to low-vision subjects and filled symbols to normal subjects (including dichromats). Points near the diagonal refer to subjects for whom the minimum and the maximum reading rates were almost the same and for whom the effects of wavelength were negligible. Points lying substantially below the diagonal refer to subjects for whom the reading rate is substantially reduced for text having the indicated color.

Figure 9 indicates that minimum reading rates occurred more frequently for red and blue text than for green and gray. On the whole, green and gray are the colors for which subjects showed the least departure from maximum performance. The implication is that these are the colors best suited for the design of reading displays for subjects with normal or low vision.

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