Psychophysics of reading. XI. Comparing color contrast and luminance contrast

Gordon E. Legge, David H. Parish, Andrew Luebker, and Lee H. Wurm

Minnesota Laboratory for Low-Vision Research, University of Minnesota, 75 East River Road, Minneapolis, Minnesota 55455

Received January 11, 1990; accepted June 8, 1990

Text can be depicted by luminance contrast (i.e., differences in luminance between characters and background) or by color contrast (i.e., differences in chromaticity). We used a psychophysical method to measure the reading speeds of eight normal and ten low-vision subjects for text displayed on a color monitor. Reading speed was measured as a function of luminance contrast, color contrast (derived from mixtures of red and green), and combinations of the two. When color contrast is high, normal subjects can read as rapidly as with high luminance contrast (>300 words/min). Curves of reading speed versus contrast have the same shape for the two forms of contrast and are superimposed when contrast is measured in multiples of a threshold value. When both color and luminance contrast are present, there is no sign of additive interaction, and performance is determined by the form of contrast yielding the highest reading rate. Our findings suggest that color contrast and luminance contrast are coded in similar ways in the visual system but that the neural signals used in letter recognition are carried by different pathways for color and luminance. We found no advantages of color contrast for low-vision reading. For text composed of 6° characters, all low-vision subjects read better with luminance contrast than with color contrast.

INTRODUCTION

In our culture, reading is one of the most important everyday visual tasks. In a series of studies in our laboratory, we have used psychophysical methods to examine visual factors in reading. This series has two major goals: understanding of the roles played by sensor and perceptual mechanisms in reading and understanding of how visual impairment affects reading.

Low vision refers to any chronic visual condition, not correctable by spectacles or contact lenses, that impairs everyday function. A Snellen acuity of 20/70 is often taken as a criterion for low vision. Approximately 1.5 million Americans fall into this category, and most of them are handicapped in reading.

How does color affect reading? Reading rates have been measured for luminance-matched stimuli differing in color[1] (colored letters on black backgrounds or black letters on colored backgrounds). Normally sighted subjects showed no effect of color on reading under photopic conditions, except near the acuity limit. Only 7 of 25 low-vision subjects, mostly those with advanced photoreceptor disorders such as retinitis pigmentosa, showed wavelength-specific effects in reading. This study showed that wavelength *per se* only occasionally affects reading.

Usually, letters on a background are made visible by luminance contrast (dark letters on a white background), but color contrast may play a similar role (e.g., red letters on a green background). In the present paper we ask whether color contrast can support rapid reading and how it compares with luminance contrast in its effects on reading. For reasons discussed below, it is possible that color contrast may be preferable to luminance contrast for some types of low-vision reading or that color contrast in combination with luminance contrast may be beneficial.

Tinker and Paterson[2] measured reading speeds for 11 combinations of colored text printed on colored backgrounds. Rates were highest in their black-on-white condition. They recognized a distinction between color contrast and brightness contrast, but they did not try to quantify it. However, they believed that reading speed was governed by brightness contrast.

We have already studied the effects of luminance contrast on reading.[3,4] Normally sighted readers are tolerant to losses in contrast; reading rate decreases by approximately a factor of 2 when text contrast decreases from 100% to 10%. However, below 10%, reading rate slows down much more rapidly. (Curves of reading rate versus luminance contrast can be found in Figs. 3 and 5 below.) It was also found that plots of reading rate versus contrast were superimposed for different character sizes when contrast was scaled in units of threshold contrast,[3] indicating that character-size effects are due simply to differences in contrast sensitivity. These luminance-contrast findings raise three issues concerning color contrast and reading.

The first issue is whether the dependence of reading rate on color contrast is qualitatively, or even quantitatively, similar to its dependence on luminance contrast. Specifically, can color contrast support reading rates as high as those observed with luminance contrast? Do rate-versus-contrast curves have the same shapes for color and luminance? Does the threshold-scaling principle extend to color contrast?

These questions immediately raise the problem of finding a metric for comparing luminance and color contrast. We constructed text by adding together red and green images, each of which had the same luminance contrast. As illustrated in Fig. 1, the red- and green-component images were superimposed in two ways. In register [Fig. 1(A)], they

0740-3232/90/102002-09$02.00

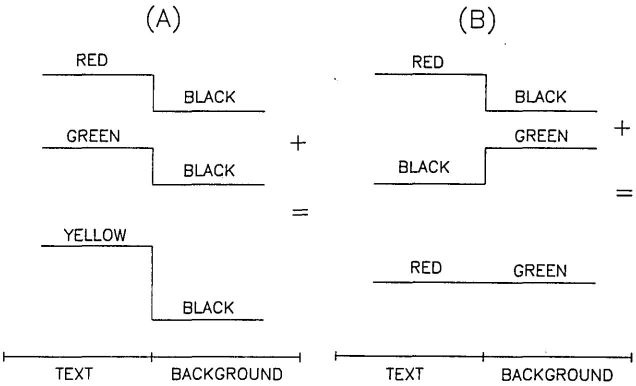

Fig. 1. Luminance profiles of red and green images are summed to produce stimuli with either luminance or color contrast. In (A) the bright portions of both the red and green images fall on the text and the dark portions fall on the background. When the profiles are summed, the background remains dark and the text becomes yellow—there is no chromatic difference between the text and background. In (B) the bright portion of the red image falls on the text, whereas the bright portion of the green image falls on the background. When the profiles are summed, there is a chromatic difference between the text and background but no luminance difference.

yielded yellow text, in which the letters and background differed in luminance. Out of register [Fig. 1(B)], they yielded red-on-green text, in which the letters and the background differed in chromaticity but had the same luminance. When the red- and green-component images were reduced in contrast, the in-register superposition yielded yellow text of lower luminance contrast. In the out-of-register superposition, the lower-contrast-component images combined to yield equiluminant text in which both red and green were mixed in the letters and the background. Instead of red text on a green background (high color contrast), there was orange text on a greenish-yellow background (lower color contrast). We can define the contrast of either the in-register or the out-of-register superposition as equal to the Michelson contrast of the component red or green images:

$$C = (L_{\max} - L_{\min})/(L_{\max} + L_{\min}),$$

where $L_{\max}$ and $L_{\min}$ are the maximum and minimum luminances, respectively. The chromatic contrast of sine-wave gratings has been defined in this way.[5,6] This definition of color contrast is problematic because the end point of the scale (i.e., 100% Michelson contrast) is determined by the particular chromaticities of the component images (in our case, the chromaticities of our red and green cathode-ray-tube phosphors). We dealt with the arbitrariness of the Michelson definition for color contrast by relating it to the contrasts seen by the long- and medium-wavelength-sensitive cones (see the Methods section below) and by expressing both luminance contrast and color contrast as multiples of a threshold value (see the Results and Discussion section).

A second issue is the possibility that color contrast may enhance reading for text composed of large characters. This possibility derives from the crossover in chromatic and luminance contrast-sensitivity functions at low spatial frequencies demonstrated by Mullen.[6] She found that chromatic contrast sensitivities are greater than luminance contrast sensitivities below 0.3 cycle/degree (c/deg), differing by a factor of 3 at 0.1 c/deg. (It should be noted that comparisons of Mullen's chromatic and luminance contrast sensitivities are in terms of Michelson contrast having the aforementioned limitations.) It has been argued[3] that contrast sensitivities can help to explain character-size effects in reading, with spatial frequencies near a character's "fundamental frequency"[7] playing a major role. Large characters are of prime importance in low vision, with maximum reading rates usually occurring for characters subtending 3° or more.[10] Mullen's crossover point of ~0.3 c/deg corresponds to the "fundamental frequency" of 3° letters. It would be of both theoretical and practical value to know whether text composed of letters larger than 3° can be read as well or better when conveyed by color contrast.

The third issue concerns color- and luminance-contrast additivity. Once we know how reading rate depends on either attribute alone, we can ask how it depends on their combination. One possibility is that letter recognition can be based on either a color- or a luminance-contrast channel, but the reader must choose between the two. If this is the case, the reading rate should be determined by whichever attribute—color or luminance—yields the better performance. To the extent that color and luminance contrast in reading are processed in independent parallel pathways, there should be no additive interactions.

There is a single-channel alternative. It has been argued that spatiotemporal contrast-sensitivity functions for color and luminance contrast can be explained by the filtering properties of color-opponent center-surround receptive fields of cells early in the visual pathway.[5,11,12] If chromatic and luminance signals in reading are passed through the same set of early filters, we might expect to find a threshold-scaling property like the one described above for different character sizes. If so, once contrast sensitivity is taken into account reading should show the same dependence on color and luminance contrast. The single-channel model would also predict additive interaction of color and luminance contrast.

If it exists, additivity could be useful in some forms of low vision. Some low-vision subjects can be characterized as "contrast attenuators."[4] When stimulus contrast is 100%, they function as if the contrast were much lower. The luminance contrast of text cannot be increased beyond 100% to aid these readers, but, if additivity holds, some combination of color contrast and luminance contrast might enhance the effective neural-signal strength.

Knoblauch *et al.* have studied some forms of color- and luminance-contrast interactions in reading.[13,14] They showed that color contrast can support rapid reading for text that is nearly equiluminant (no more than 1% luminance contrast). When luminance contrast was high enough to support rapid reading, the addition of color contrast had no systematic effect on reading rate. Knoblauch *et al.* did not study additivity over the range of low-luminance contrasts where small changes in contrast have major effects on reading speed.

Finally, a comment on terminology. By "luminance contrast" we mean isochromatic modulation, that is, modulation of a color involving only a change in intensity. By "color contrast" we mean purely chromatic modulation, that is, chromatic modulation at constant luminance.

METHODS

Subjects

Eight subjects with normal vision participated: four in the additivity test and four in the other experiments. All had corrected acuity of 20/20 or better, and all had normal color vision (FM-100 test).

Ten subjects with low vision participated. They were selected from our roster of low-vision research subjects based on two primary criteria: (1) All but one had normal color vision[15] (D-15 enlarged blocks test), and (2) they had relatively high maximum rates so that a decline with reduced contrast would be measurable. Many people with low vision have acquired color defects,[16] but we chose to defer consideration of this complication to future research. Characteristics of the low-vision subjects are listed in Table 1. Clarity of the ocular media and presence/absence of central-field loss are indicated because these are variables known to play an important role in reading.[10] All testing was monocular, and the entries in Table 1 pertain to the eye tested for low-vision subjects.

Heterochromatic flicker photometry[17] was used to find luminance matches for each subject for the red and green primaries used in the reading experiments. Subjects viewed a square white patch, 2° on a side, that alternated at 30 Hz with a colored (red or green) test patch of the same size. Subjects adjusted the luminance of the white patch by pressing keys until the flicker "seemed to disappear" or "reached its slowest point." The mean of five such trials established the equiluminant white and was taken as the effective luminance of the colored patch. This procedure was repeated for a number of intensities of the colored patch, and the resulting graph—luminance of white patch at match versus luminance of colored patch—was used to define equiluminance.

Apparatus and Stimuli

The stimuli were produced on a Conrac 7241 color monitor. The red, green, and blue guns of the monitor were connected to three Imaging Technology Inc. FG-100 frame buffers in an IBM PC-AT computer. Each frame buffer had resolution of 512 × 480 pixels and 256 gray levels. The CIE chromaticity coordinates of the three phosphors, measured with a Minolta CS-100 chroma meter, were (0.617, 0.352) for red, (0.281, 0.602) for green, and (0.146, 0.053) for blue. The spectral-energy distributions of the three phosphors were measured with an EG&G Gamma Scientific photometer.

The character font was fixed width with serifs, similar to Courier. The characters were 20-pixel-wide by 32-pixel-high binary images (i.e., two gray levels).

Text was constructed as outlined in Fig. 1. To create luminance contrast, identical texts were created in the red and green frame buffers (bright letters on dark backgrounds) and displayed simultaneously. At maximum contrast, the subject saw bright yellow (12-cd/m^2) letters on a dark (0.01-cd/m^2) background. Contrast was reduced by contracting the luminance difference between letters and surround toward 6 cd/m^2, using the look-up tables.

For color contrast, one frame buffer produced a red image composed of dark letters on a brighter background. A second frame buffer produced the same text in green, but in opposite polarity (bright letters on a darker background). The high and low luminances of the red image were matched by flicker photometry to the high and low luminances of the green image. The luminance contrasts of the red and green images were always equal. We varied color contrast of the text by varying the luminance contrast of the red and green images. Reducing the luminance contrast of the red and green images has the effect of moving the chromaticity coordinates of letters and background toward one another along the line that joins the chromaticity coordinates of the monitor's red and green phosphors. When the image contrasts reach zero, a uniform green field is added to a uniform red field, producing a yellow field with zero color contrast.

As described in the Introduction, the Michelson definition of chromatic contrast is unsatisfactory because it is tied to the particular choice of stimulus primaries. Instead, we can compute the contrast seen by the L and M cones, providing a scale for chromatic contrast that is not tied to the stimulus primaries. Moreover, cone-contrast signals may provide the input to color-opponent and luminance channels.[18] When the red and green component images are added in register, the cone contrasts are identical to the Michelson contrast of the stimulus. However, for an equiluminant stimulus the cone contrasts are different from the Michelson contrast of the stimulus. We computed cone contrasts as follows. The luminance and CIE chromaticity coordinates of each phosphor were transformed into tristimulus values. These values were used in a method based on equations by MacLeod and Boynton[19] (their footnote 2) to estimate levels of cone excitation. [These equations relate cone spectral sensitiv-

Table 1. Low-Vision Subjects

Subject	Age	Decimal Acuity	Media	Central Loss	Diagnosis
LCJ	42	0.10	Cloudy	No	Congenital cataracts/nystagmus
SLS	40	0.167	Cloudy	No	Congenital cataracts
GJH	63	0.05	Cloudy	Yes	Diabetic retinopathy/cataracts
PAW	39	0.17	Clear	Yes	Optic nerve hypoplasia
LLE	49	0.083	Clear	Yes	Retinopathic lesioning
MJH	34	0.063	Clear	Yes	Retrolental fibroplasia
MJS	36	0.10	Clear	No	Macular pucker
SSS	26	0.25	Clear	No	Congenital glaucoma
KG	74	0.05	Clear	Yes	Macular degeneration
MAS	30	0.05	Clear	Yes	Macular degeneration

ities to CIE spectral sensitivities. We did not include Judd's correction of the $V(\lambda)$ curve because our red and green phosphors had little energy below 460 nm.] For the L and M cones separately, we computed cone contrast from the excitations due to text and background using the Michelson definition. The resulting cone contrasts are proportional to the Michelson contrast of the component red and green images. For an observer for whom 6 cd/m^2 red and green phosphors are equiluminant, the L- and M-cone contrasts corresponding to a Michelson contrast of 1.0 are 0.14 and 0.35, respectively. In fact, our subjects' equiluminant matches deviated slightly from photometric equality, so slightly different scaling factors are required, and these are given in the caption to Fig. 3 below. These values can be used to convert the Michelson contrast of chromatic stimuli to L- and M-cone contrasts.

Viewing distance was changed to vary angular character size. Subjects with normal vision were tested with 1° (at 69 cm) and 6° (at 11.5 cm) characters. (Character size is defined as the center-to-center spacing of the letters in text.) Low-vision subjects were tested only with 6° characters.

We did not attempt to correct for the eye's chromatic aberration by using an achromatizing lens. The large field sizes required for our reading stimulus and the need for scanning eye movements made this impractical. It is therefore likely that small luminance artifacts were present in our high color-contrast equiluminant stimuli. Two empirical results suggest that chromatic aberration had little effect. First, we used a laser optometer[20] to measure the dioptric difference in focus between red-on-black and green-on-black text.[21] The measured difference was only ~0.1 D. Second, as described in the Results and Discussion section, luminance contrast and color contrast have independent effects on reading rate; there is no evidence for additivity. If equiluminant reading were actually due to luminance artifacts in the stimulus, we would expect additivity. Knoblauch *et al.*, using a reduced model of the eye, have computed the size of luminance artifacts associated with lateral chromatic aberration for equiluminant text.[14] According to their calculations, these artifacts, occurring along vertical but not horizontal chromatic borders, should be detectable, but their relevance to reading has yet to be determined.

Procedure

Reading speed was measured with the MNread procedure.[22] Briefly, subjects were required to read aloud a single sentence of text, termed a flash card, displayed on the monitor. Figure 2 shows a typical flash card. There were 170 sentences available for presentation. Each sentence had thirteen characters, including spaces, on each of four lines. Sentences were constructed from high-frequency, nontechnical words and were declarative in nature.

Subjects were instructed to read each flash card aloud as fast as possible without skipping words. The presentation time was reduced until subjects could no longer read the entire sentence. Reading rate was computed for each sentence as the number of words correctly read divided by the stimulus duration. Recent data indicate that silent and oral reading rates obtained with this method are almost identical.[22]

The data points in the figures are the means of four measurements. Standard errors for normal subjects ranged

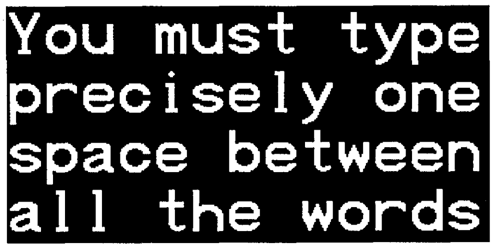

Fig. 2. Sample flash card stimulus shown with full luminance contrast.

from 6% to 16% of the mean. Only "good" trials were included in the means. For a trial to be considered good, more than half of the words had to be read correctly. This condition prevented the inclusion of trials in which a subject stumbled on the first word or two and gave up on the rest of the sentence. Such "bad" trials occurred between 5% and 10% of the time.

Conditions were blocked by contrast (color or luminance) and character size. After data for one character size were gathered, subjects were tested with the second character size. A 6-cd/m^2 gray field appeared on the screen between trials.

RESULTS AND DISCUSSION

Comparing Reading Rates for Color and Luminance Contrast

Figure 3 shows reading rate, in words/minute, as a function of Michelson contrast for four normal subjects. Open symbols are for luminance contrast and closed symbols for color contrast. The figure caption gives conversion factors for computing L- and M-cone contrasts for the equiluminant stimuli. The character size was 1°, in the range yielding maximum reading rates for normal subjects.[8,22] Maximum rates for both color and luminance contrast were 340 words/min or more for each subject. The color- and luminance-contrast functions are qualitatively similar: there is a flat region for some range of high contrasts and a sharp decline in reading rate for lower contrasts. Subject AJW was unusual in that his rates increased over a wider range of contrasts, reaching a value of 670 words/min.

Two aspects of the data in Fig. 3 stand out. First, high color contrast can support reading rates that are as fast as those for luminance contrast. It is likely that sensory signals carrying information about equiluminant text are transmitted by the parvocellular pathway. Because this pathway is said to be temporally sluggish,[23] it may be surprising that reading rates in excess of 340 words/min can be achieved for equiluminant text. However, a dominant temporal frequency in reading is ~4 Hz (corresponding to approximately 4 saccades/sec), and this is well within the temporal-resolution limit of the parvocellular pathway.[24]

Second, the decline in reading rate occurs at a higher Michelson contrast for color than for luminance, but the arbitrariness of the Michelson definition of color contrast makes this comparison of dubious value. A better comparison can be made by expressing contrast—color or luminance—as multiples of a threshold value. Following earlier work,[3] we defined the threshold contrast for reading as the

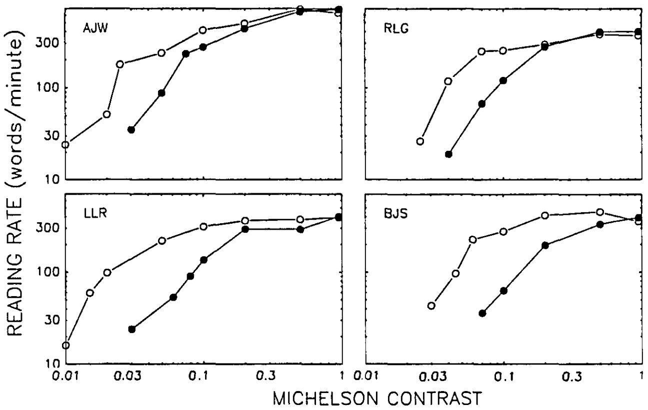

Fig. 3. Data are shown for four subjects with normal vision. Reading rate is plotted as a function of luminance contrast (open circles) and color contrast (filled circles), using characters that subtend 1° of visual angle. Cone contrasts can be found (see the Methods section) for the color-contrast text by multiplying the corresponding Michelson contrasts by the following factors for L and M cones, respectively: AJW, 0.128, 0.364; LLR, 0.103, 0.385; RLG, 0.180, 0.317; BJS, 0.096, 0.391.

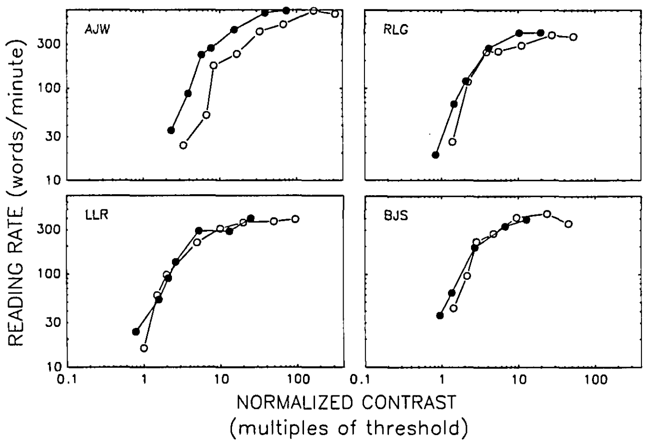

Fig. 4. Data from Fig. 3 replotted with contrast expressed as multiples of a threshold value (i.e., the contrast required to read 35 words/min). In these units, plots of reading rate versus luminance contrast and color contrast are nearly superimposed.

contrast yielding a rate of 35 words/min. In the present case, we estimated the threshold contrasts from bilinear fits[25] to the rate-versus-contrast curves in Fig. 3. Figure 4 shows the data of Fig. 3 with contrast normalized by these threshold values. It can be seen that the curves for color and luminance contrast are very nearly superimposed for three subjects and are not far off for the fourth. According to the bilinear fits, maximum reading rates require at least six times the threshold contrast, i.e., six times the contrast to read 35 words/min.

The superposition of curves in Fig. 4 indicates that a contrast-scaling principle accounts for differences between reading rates for color and luminance contrast. Once differences in contrast sensitivity are accounted for, rate-versus-contrast curves are the same in the two cases.

Switkes *et al.* discovered a similar scaling principle relating color and luminance.[26] They found that contrast-discrimination functions for luminance-contrast and color-contrast sine-wave gratings were almost exactly superimposed when contrast was expressed as multiples of a threshold value.

These scaling results suggest that the processing of color- and luminance-contrast signals is quite similar, apart from an early filtering stage that determines sensitivity. This is consistent with the single-channel model proposed by Kelly.[5]

Character-Size Effects

Figure 5 plots reading rate versus Michelson contrast (lower scale) and normalized contrast (upper scale) for text composed of 6° characters. Data are shown for four normal subjects. As in the 1° data shown in Fig. 3, there is a steep rise at low contrast followed by a flattening at high contrast. While the maximum reading rates achieved at 6° (200–400 words/min) are roughly the same for luminance and color contrast, they are lower than maximum rates for 1° characters (340–670 words/min). This is consistent with previous results[8] of Legge *et al.*, who showed that reading rate declines for text characters larger than 2°. As in Fig. 3, subject AJW is unusual in his high rates and in the low contrasts at which he can read.

A striking difference between 1° data and the 6° data is that the color and luminance curves for 6° are nearly super-

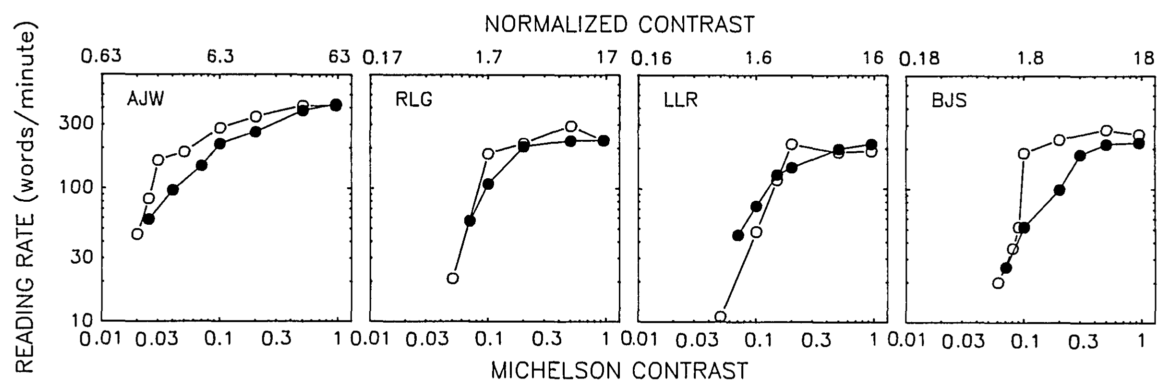

Fig. 5. Data are shown for four subjects with normal vision. Reading rate is plotted as a function of luminance contrast (open circles) and color contrast (filled circles), using characters that subtend 6° of visual angle. The lower horizontal axis shows Michelson contrast, and the upper horizontal axis shows the corresponding normalized values (multiples of threshold). Cone contrasts for the chromatic stimuli can be calculated by multiplying the Michelson contrast values by the constants given in the caption to Fig. 3.

imposed without any contrast scaling. While the cone contrasts are equal to the Michelson contrasts for the luminance case, they are much lower for the chromatic text (approximately 14% and 35% for the L and M cones, respectively). This means that much lower cone contrasts support equivalent reading performance for chromatic- versus luminance-defined text. This result is consistent with the finding that contrast thresholds for chromatic increments can be much lower than for luminance increments.[18]

In the Introduction we asked whether character-size effects could be accounted for by differences in contrast sensitivity. From previous work[3] we argued that contrast sensitivities at twice the fundamental frequencies of the characters should play the dominant role—0.33 c/deg for 6° characters and 2 c/deg for 1° characters. We can refer to the red–green chromatic and luminance sine-wave contrast-sensitivity functions measured by Mullen (her Fig. 8, p. 391).[6] At 2 c/deg, her luminance-contrast sensitivity was ~3.8 times the color-contrast sensitivity. This specific value depends on the stimulus-specific Michelson definition for color contrast. However, to the extent that our red and green primaries were similar to Mullen's,[27] we would predict the 1° reading curves for color and luminance contrast in Fig. 3 to differ by the same contrast-scaling factor. The actual shift factors used in constructing Fig. 4 (i.e., ratios of contrast thresholds for reading) were 2.7, 3.5, 3.8, and 4.3, quite close to the prediction. At 0.3 c/deg, Mullen's color and luminance contrast sensitivities were almost the same. The near superposition of the luminance and color reading curves at 6° (Fig. 5) is consistent with this near equality. These comparisons corroborate the view that character-size differences for luminance and color contrast are due to differences in contrast sensitivity.

A practical finding is that, even for text composed of 6° characters, reading with color contrast is no faster than reading with luminance contrast. It is possible that, had we used characters substantially larger than 6°, we might have found an advantage for color contrast. However, such large character sizes are fairly rare in normal- and low-vision reading.

Are Color Contrast and Luminance Contrast Additive?

Suppose that a subject requires four multiples of threshold contrast (color or luminance) in order to read 150 words/min for 6° characters. What will happen in a mixed case in which letters and background differ in both luminance and chromaticity? For example, suppose that we construct text in which the luminance contrast between letters and background is twice the luminance threshold contrast and the chromaticities are also twice their threshold. Will color contrast and luminance contrast sum in their effects to produce a reading rate of 150 words/min?

We conducted an experiment of this sort with a criterion reading rate of either 100 or 150 words/min, depending on the subject's maximum reading speed. For each of the four normal subjects tested, we verified that this value was on the rising portion of the rate-versus-contrast curve. (A criterion rate on the flat part of the curve would be uninformative because additive interactions would not be reflected by changes in reading rate.) Color contrasts[28] were fixed at a series of values that yielded reading rates less than the criterion rate. For each such color-contrast value, luminance contrast was varied, and reading rate was measured until the

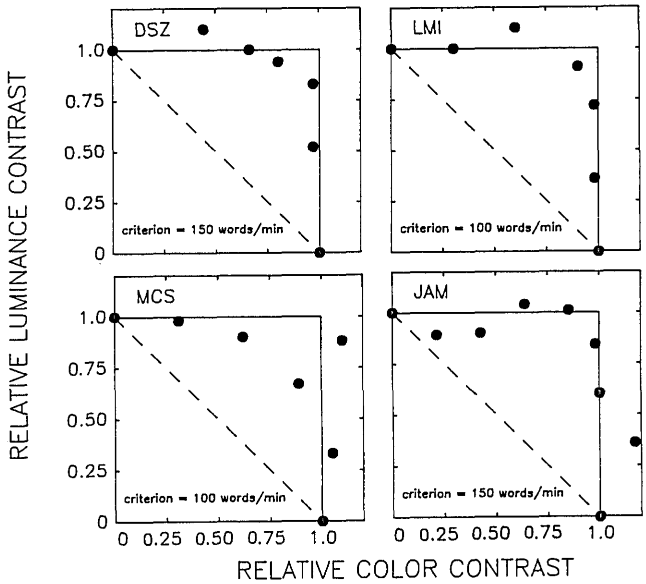

Fig. 6. Data are shown for four subjects in which text and background varied in both color contrast and luminance contrast. The circles show the relative color and luminance contrasts that combined to yield a criterion reading rate of 100 or 150 words/minute. A relative contrast of 1.0 refers to the contrast of a single attribute, color or luminance, needed for reading at the criterion rate. The solid lines in each panel show the prediction of an independent channel model, and the dashed lines show the prediction of a linear summation model.

rate bracketed the 150-words/min criterion. The amount of luminance contrast needed to achieve the criterion rate, in combination with the fixed color contrast, was then obtained by interpolation. The same procedure was used with fixed values of luminance contrast to find the additional color contrast required to achieve the criterion.

Figure 6 shows data for four normal subjects, with relative color contrast plotted against relative luminance contrast. A scale value of 1.0 represents the amount of pure contrast—color or luminance—required for reading at the criterion rate. The solid lines show the predictions of an independence model in which reading rate is determined by the attribute that yields highest performance and is unaffected by the other. The diagonal dashed lines show the predictions of a linear-summation model.

It is clear from the data that color contrast and luminance contrast act independently in their effects on reading. For all four subjects, the data lie close to the independence prediction and far from the linear-summation model.

Of necessity, this test of independence was conducted at quite low contrasts (typically <0.10) to avoid ceiling effects. Our finding of independence therefore applies only to low contrasts. The previous discussion of contrast scaling and character size suggested that differential effects of color contrast and luminance contrast arise at an early sensory stage. But the lack of additivity suggests that these signals are processed in independent parallel pathways. However, if these pathways are independent, it appears that they have similar contrast coding and filtering properties.

Other investigators have observed a similar pattern. Cole *et al.*[29] found that contrast-discrimination curves for chromatic increments on chromatic pedestals have the same

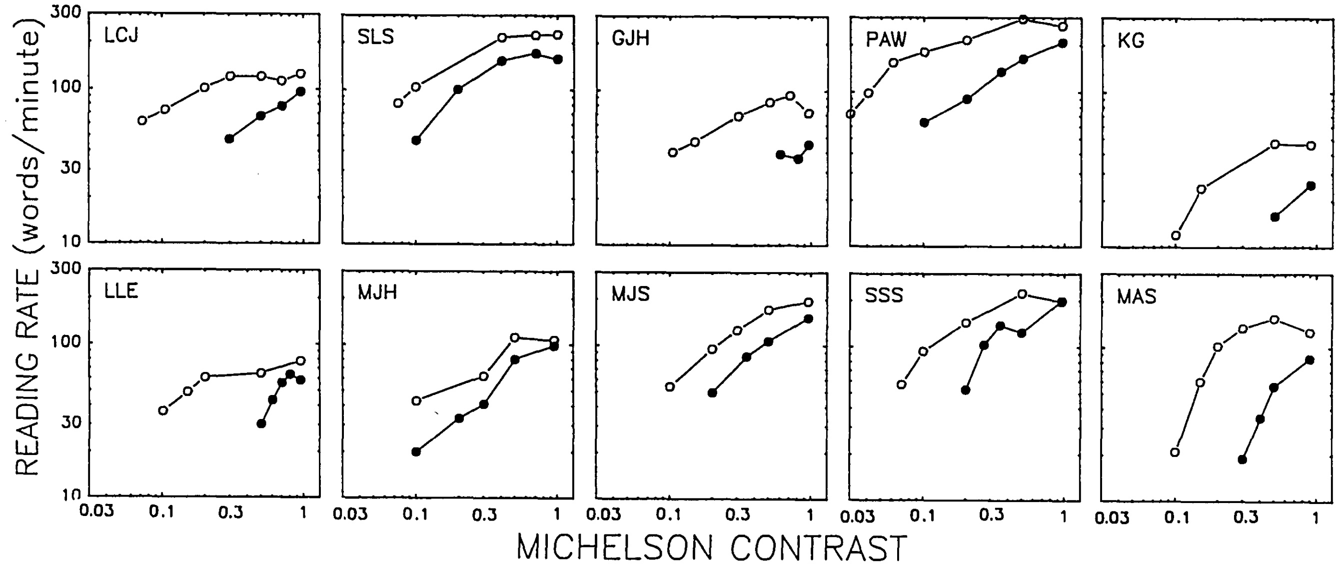

Fig. 7. Data for ten low-vision subjects (Table 1) that show reading rate as a function of luminance contrast (open circles) and color contrast (filled circles), using characters that subtend 6° of visual angle.

form as contrast-discrimination curves for luminance increments on luminance pedestals. However, they observed no cross masking between chromatic and luminance stimuli but rather only a small facilitation effect. Similarly, Gegenfurtner and Kiper[30] found that chromatic noise has no effect on luminance-contrast detection and that luminance noise has no effect on chromatic-contrast detection. But Switkes *et al.* found asymmetric masking interactions between sine-wave gratings defined by color contrast and luminance contrast.[26] Luminance masks did not elevate thresholds for chromatic gratings at any spatial frequency (although facilitation effects were noted for a substantial range of luminance contrast). Chromatic masking gratings did elevate thresholds for luminance gratings, but the effects were reduced at low spatial frequencies. While the cross-masking results are weaker than the luminance-on-luminance and color-on-color effects, they provide evidence for some interaction.

As a practical matter, the lack of additivity in reading found for normal subjects makes it unlikely that a hybrid text composed of color contrast and luminance contrast would be beneficial to people with low vision.

Low Vision

Figure 7 shows reading rate as a function of luminance and color contrast for ten low-vision subjects. The data are for 6° characters. We chose this size for two reasons: (1) because it is usually close to the size yielding highest reading rates for people with low vision and (2) to study the possible advantage of color contrast for large characters.

The low-vision data differ in two important ways from the 6° data for normal subjects (Fig. 5). First, although a few of the low-vision curves flatten out at high contrast, most continue to climb throughout the entire range. This is particularly true for color contrast. This extends to color contrast the finding of Rubin and Legge that low-vision reading is usually sensitive to any reduction from maximum contrast.[4]

Second, unlike the normal data for 6°, the low-vision reading rates for color and luminance contrast are not superimposed. With the exception of a single data point from subject SSS, low-vision reading rates are lower for color contrast than for luminance contrast. This was true at maximum contrast but increasingly so at lower contrasts. Relative to normal subjects, low-vision reading is hampered, not enhanced, by color contrast.

Why should color contrast be more deleterious to low-vision reading than to normal reading? Some of our low-vision subjects complained of glare when reading the color-contrast text. In our past work, we have shown that subjects with cloudy media read white-on-black text faster than conventional black-on-white text because of the extra light scattered from the page in the latter case.[10,31] A similar explanation might account for depressed reading of equiluminant text. In this case, light can be scattered from both letters and background to dilute retinal-image contrast. This glare explanation applies to subjects LCJ, GJH, and SLS with cloudy media (Fig. 7). The first two of these certainly did show substantial differences between color and luminance contrast. But even subjects with clear media showed depressed reading with color contrast, especially subject PAW. However, it was previously shown that glare effects in low vision are not restricted to subjects with cloudy media but are found widely in subjects with clear media and central-field loss.[32] Whatever the neural explanation in such cases, glare may play a role in explaining depressed reading with color contrast.

SUMMARY

For normally sighted subjects, reading rates for high color contrast are as fast as those for high luminance contrast, more than 300 words/min. Even though equiluminant contours in text may be processed by the parvocellular pathway, information processing is rapid.

Plots of reading rate versus color contrast and luminance contrast have the same shape in log–log coordinates and differ only by a horizontal translation (i.e., a contrast scale factor). When contrast is expressed in multiples of a threshold (where threshold is the contrast required for reading 35 words/min), the rate-versus-contrast curves for color and luminance coincide. This suggests that the coding of color and luminance contrast is closely similar.

Although rate-versus-contrast curves for color and luminance differ by a scale factor for 1° characters, they can be superimposed without any scaling for 6° characters. This character-size effect can be explained by differences in color- and luminance-contrast sensitivity for low and medium spatial frequencies. It appears that differences in reading performance for color and luminance contrast, and for big and small characters, can be traced to differences in sensitivity at an early stage of spatial filtering.

Despite their similarity in coding, color and luminance contrast do not interact in their effects on reading speed. Our data indicate that readers rely on information conveyed by color contrast or luminance contrast, whichever yields the best performance. Hybrid texts in which letters and background differ in both luminance and color do not offer any advantages for reading.

People with low vision usually require high magnification in order to read. Studies of contrast sensitivity indicated that color contrast might be as good or better than luminance contrast for the recognition of large characters. However, all our low-vision subjects read text composed of 6° characters faster with luminance contrast than color contrast. It remains possible that better performance would be found with color contrast for a larger character size.

Many people with low vision are sensitive to any loss in text contrast. For these people, the addition of color and luminance contrast might enhance reading. Unfortunately, our additivity test with normal subjects makes this unlikely.

ACKNOWLEDGMENTS

We thank Charles Stromeyer, Rea Eskew, and Jeff Mulligan for helpful comments and discussion. We thank Paul Beckmann for help in calculating cone contrasts, Ken Knoblauch for discussion of transverse chromatic aberration, and Steve Saxe for help with spectral calibration of our display. This research was supported by National Institutes of Health grant EY02934 to Gordon E. Legge. Some of the findings that appear in this paper were presented at the 1989 meeting of the Association for Research in Vision and Ophthalmology.

REFERENCES AND NOTES

1. G. E. Legge and G. S. Rubin, "Psychophysics of reading. IV. Wavelength effects in normal and low vision," J. Opt. Soc. Am. A **3**, 40–51 (1986).
2. M. A. Tinker and D. G. Paterson, "Studies of typographical factors influencing speed of reading. VII. Variations in color of print and background," J. Appl. Psychol. **15**, 471–479 (1931).
3. G. E. Legge, G. S. Rubin, and A. Luebker, "Psychophysics of reading. V. The role of contrast in normal vision," Vision Res. **27**, 1165–1177 (1987).
4. G. S. Rubin and G. E. Legge, "Psychophysics of reading. VI. The role of contrast in low vision," Vision Res. **29**, 79–91 (1989).
5. D. H. Kelly, "Spatiotemporal variation of chromatic and achromatic contrast thresholds," J. Opt. Soc. Am. **73**, 742–750 (1983).
6. K. T. Mullen, "The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings," J. Physiol. **359**, 381–400 (1985).
7. A letter's fundamental frequency is equal to the reciprocal of its angular subtense (e.g., for 2 deg letters, the fundamental frequency is 0.5 c/deg). Critical information for letter recognition seems to lie in a band extending 1 octave up from the fundamental frequency.[8,9]
8. G. E. Legge, D. G. Pelli, G. S. Rubin, and M. M. Schleske, "Psychophysics of reading: I. Normal vision," Vision Res. **25**, 239–252 (1985).
9. D. H. Parish and G. Sperling, "Object spatial frequencies, retinal spatial frequencies, and the efficiency of letter discrimination," Vision Res. (to be published).
10. G. E. Legge, G. S. Rubin, D. G. Pelli, and M. M. Schleske, "Psychophysics of reading: II. Low vision," Vision Res. **25**, 253–266 (1985).
11. C. R. Ingling, Jr., and E. Martinez-Uriegas, "The spatiotemporal properties of the r-g X-cell channel," Vision Res. **25**, 33–38 (1985).
12. A. M. Rohaly and G. Buchsbaum, "Inference of global spatiochromatic mechanisms from contrast sensitivity functions," J. Opt. Soc. Am. A **5**, 572–576 (1988).
13. K. Knoblauch, A. Arditi, and J. Szlyk, "Reading rate depends on luminance contrast but not chromatic contrast," Invest. Ophthalmol. Vis. Sci. Suppl. **29**, 44 (1988).
14. K. Knoblauch, A. Arditi, and J. Szlyk, "Effects of chromatic and luminance contrast on reading," submitted to J. Opt. Soc. Am. A (under review).
15. One subject, KG, showed four significant block displacements (i.e., greater than 2 places) in the enlarged block D15 test, indicating a significant color defect. Her data, however, were not qualitatively different from those of other low-vision subjects.
16. J. Pokorny, V. C. Smith, G. Verriest, and A. J. L. G. Pinkers, *Congenital and Acquired Color Vision Defects* (Grune & Stratton, New York, 1979), Chap. 8.
17. G. Wagner and R. M. Boynton, "Comparison of four methods of heterochromatic photometry," J. Opt. Soc. Am. **62**, 1508–1515 (1972).
18. C. F. Stromeyer III, G. R. Cole, and R. E. Kronauer, "Second-site adaptation in the red-green chromatic pathways," Vision Res. **25**, 219–237 (1985).
19. D. I. A. MacLeod and R. M. Boynton, "Chromaticity diagram showing cone excitation by stimuli of equal luminance," J. Opt. Soc. Am. **69**, 1183–1186 (1979).
20. Y. Gu and G. E. Legge, "Accommodation to stimuli in peripheral vision," J. Opt. Soc. Am. A **4**, 1681–1687 (1987).
21. The subjects focused on the same text used in reading trials. For red-on-black and green-on-black text, each subject made five laser-optometer settings. For DHP, the mean chromatic difference in focus was 0.11 D, and for LW it was 0.07 D.
22. G. E. Legge, J. A. Ross, A. Luebker, and J. M. LaMay, "Psychophysics of reading. VIII. The Minnesota low-vision reading test," Optom. Vision Sci. **66**, 843–853 (1989).
23. M. Livingstone and D. Hubel, "Segregation of form, color, movement, and depth: anatomy, physiology, and perception," Science **240**, 740–749 (1988).
24. A. Derrington and P. Lennie, "Spatial and temporal contrast sensitivities of neurones in lateral-geniculate nucleus of macaque," J. Physiol. (London) **357**, 219–240 (1984).
25. The bilinear fit was constrained to a flat horizontal line and a rising straight line in log–log coordinates. The best, least-squares error fit was found through an iterative computer search.
26. E. Switkes, A. Bradley, and K. K. De Valois, "Contrast dependence and mechanisms of masking interactions among chromatic and luminance gratings," J. Opt. Soc. Am. A **5**, 1149–1162 (1988).
27. One way of comparing Mullen's chromatic stimuli with ours is to compare the cone contrasts. Using the chromaticity coordinates associated with her 520- and 602-nm spectral primaries, we computed her maximum L- and M-cone contrasts as described in the Methods section. For an observer whose equiluminant red–green match corresponds to photometric equality, her maximum L- and M-cone contrasts are 0.19 and 0.41, respectively. These values are greater than ours by 34% (L cones)

and 18% (M cones). It may be the case that the shift factor of 3.8 discussed in the text underestimates the appropriate value by 18% to 34%.

28. To produce text in which letters and background differed in both luminance and color, we could no longer retain the constraint that the red and green images in the two frame buffers have the same Michelson contrast. Since Michelson contrast scales linearly with distance in CIE color space for our equiluminant conditions, we similarly define nonequiluminant color contrast to be the distance between the two chromaticities of the text and background, divided by the distance between the chromaticities of the red and green phosphors.

29. F. R. Cole, C. F. Stromeyer III, and R. Kronauer, "Visual interactions with luminance and chromatic stimuli," J. Opt. Soc. Am. A **7**, 128–140 (1990).
30. K. Gegenfurtner and D. Kiper, "Contrast detection in luminance and chromatic noise," Invest. Ophthalmol. Vis. Sci. Suppl. **31**, 110 (1990).
31. G. E. Legge, G. S. Rubin, and M. M. Schleske, "Contrast-polarity effects in low-vision reading," in *Low Vision: Principles and Applications*, G. C. Woo, ed. (Springer-Verlag, New York, 1986), pp. 288–307.
32. G. S. Rubin, G. E. Legge, and M. M. Schleske, "Glare effects in normal and low vision," presented at the Optical Society of America Topical Meeting on Noninvasive Assessment of the Visual System, Monterey, California, March 23–26, 1986.