



**Cone-Specific Measures of Human  
Color Vision  
(Reprint)**

**By**

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**Aircrew Health and Performance Division**

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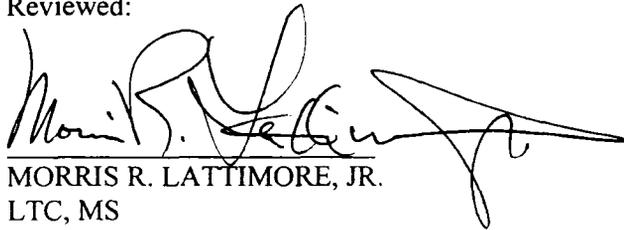
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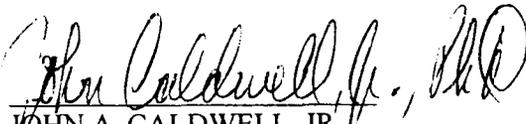
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<b>19. ABSTRACT (Continue on reverse if necessary and identify by block number)</b> Purpose. To describe a new test of color vision (cone-specific contrast sensitivity) and to evaluate its sensitivity in comparison to standard clinical tests. Methods. Cone-specific colored letter charts were generated by computer and displayed on a color monitor. Each chart consists of colored letters that are most visible at the top but that gradually fade into a gray background. Cone contrast varies systematically on each chart so that the letters are visible to only one cone type (L, M, or S cone). Cone-specific letter contrast sensitivity was measured in 30 color normals and 13 subjects with hereditary color deficiency. Values were compared to standard measures of color vision. Results. In color normals, mean log contrast sensitivity was approximately the same on L-cone (1.84 +/- 0.08 log contrast sensitivity) and M-cone (1.87 +/- 0.08) tests but was reduced on the S-cone test (0.89 +/- 0.15) because of the fewer number of S cones in the human retina. Subjects with red color deficiency showed significantly reduced contrast sensitivity on the L-cone test but normal performance on M- and S-cone tests. Subjects with green color deficiency showed decreased contrast sensitivity limited to the M-cone test. When standardized relative to variability, cone contrast sensitivity (Continued)												
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identified color deficiency unequivocally in all subjects, whereas FM 100 hue error scores detected 9 of 13 subjects with color deficiency.

Conclusions. Cone-specific contrast sensitivity provides a quantitative measure **of** normal color vision and indicates both type and severity of color deficiency. It is useful for diagnosing hereditary color deficiency and for monitoring early color vision loss in ocular and systemic disease.

## Cone-Specific Measures of Human Color Vision

Jeff Rabin

**Purpose.** To describe a new test of color vision (cone-specific contrast sensitivity) and to evaluate its sensitivity in comparison to standard clinical tests.

**Methods.** Cone-specific colored letter charts were generated by computer and displayed on a color monitor. Each chart consists of colored letters that are most visible at the top but that gradually fade into a gray background. Cone contrast varies systematically on each chart so that letters are visible to only one cone type (L, M, or S cone). Conespecific letter contrast sensitivity was measured in 30 color normals and 13 subjects with hereditary color deficiency. Values were compared to standard measures of color vision.

**Results.** In color normals, mean log contrast sensitivity was approximately the same on L-cone ( $1.84 \pm 0.08$  log contrast sensitivity) and M-cone ( $1.87 \pm 0.08$ ) tests but was reduced on the S-cone test ( $0.89 \pm 0.15$ ) because of the fewer number of S cones in the human retina. Subjects with red color deficiency showed significantly reduced contrast sensitivity on the L-cone test but normal performance on M- and S-cone tests. Subjects with green color deficiency showed decreased contrast sensitivity limited to the M-cone

test. When standardized relative to variability, cone contrast sensitivity identified color deficiency unequivocally in all subjects, whereas FM 100 hue error scores detected 9 of 13 subjects with color deficiency.

**Conclusions.** Cone-specific contrast sensitivity provides a quantitative measure of normal color vision and indicates both type and severity of color deficiency. It is useful for diagnosing hereditary color deficiency and for monitoring early color vision loss in ocular and systemic disease. Invest Ophthalmol Vis Sci. 1996;37:2771-2774.

Most persons can discern small differences in color, but 8% of males and 0.5% of females are born with some degree of red or green color deficiency. This condition is nonprogressive, hereditary (sex-linked recessive), and attributed to a decreased number of long wavelength- (L or red) or middle wavelength- (M or green) sensitive cone photoreceptors or to a shift in the peak absorption of L or M photopigments.<sup>1,2</sup> Persons with color deficiency have difficulty judging differences in hue and confuse colors that appear distinct to color normal persons. Although blue (S-cone) hereditary defects are rare (0.001% to 0.007%), color deficiency can be acquired with ocular or systemic disease, and S-cone defects occur early in the course of these diseases.<sup>3-5</sup> Despite numerous methods for detecting the presence of color anomalies, relatively few clinical tests readily indicate type (L, M, or S) and severity of color deficiency. We describe a new approach, suitable for rapid clinical testing, based on the photopigments of normal color vision. Letters visible to only one cone type (L, M, or S) are presented in graded steps of cone contrast to determine the

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threshold for letter recognition. This test provides a quantitative measure of color vision in normals and indicates type and severity of color deficiency.

**METHODS.** Cone-specific colored letter charts were generated with a 486 computer equipped with a high-resolution video controller (24 bits per pixel, 16.7 million colors) and displayed on an NEC MultiSynch 5FG 15" color monitor (NEC Corp., Tokyo, Japan). As noted in previous studies<sup>6,7</sup> and as specified in subsequent sections for our letter recognition stimulus, the resolution of this system (8 bits per color channel) has proven adequate for measuring thresholds in normals and subjects who are color defective. Separate charts, each comprised of colored letters that fade into a gray, achromatic background, were generated for each cone type (L, M, and S). By using specific combinations of the monitor red (R), green (G), and blue (B) guns relative to the gray background, a single cone mechanism was stimulated without detectable stimulation of the other two cone types. The R, G, and B relative intensities needed to isolate each cone type were determined by measuring monitor luminance and CIE  $x, y$  chromaticity (Minolta CS-100 chroma meter) and by transforming these values to cone excitations based on psychophysically derived cone spectral sensitivities.<sup>8</sup> Equations found in Wyzecki and Stiles<sup>9</sup> and stated explicitly by Cole and Hine<sup>10</sup> were used to transform luminance and chromaticity values into cone excitations:

$$L \text{ excitation} = \text{Lum}[0.15514x/y + 0.54312 - 0.03286(1-x-y)/y]$$

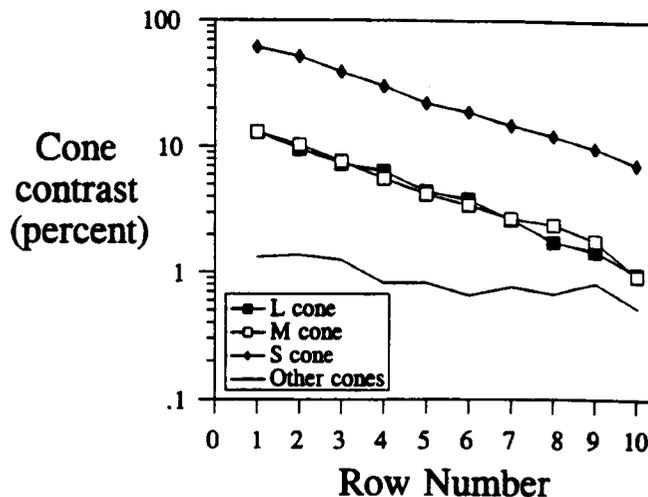
$$M \text{ excitation} = \text{Lum}[-0.15514x/y + 0.45684 + 0.03286(1-x-y)/y]$$

$$S \text{ excitation} = \text{Lum}[0.00801 \times (1-x-y)/y]$$

Cone contrast was computed from the amount of cone excitation ( $E$ ) in a colored letter relative to the gray background ( $17.5 \text{ cd/m}^2$ ,  $x = 0.293$ ,  $y = 0.335$ ) and expressed as a percentage:

$$\left( \frac{E_{\text{letter}} - E_{\text{background}}}{E_{\text{background}}} \right) \times 100.$$

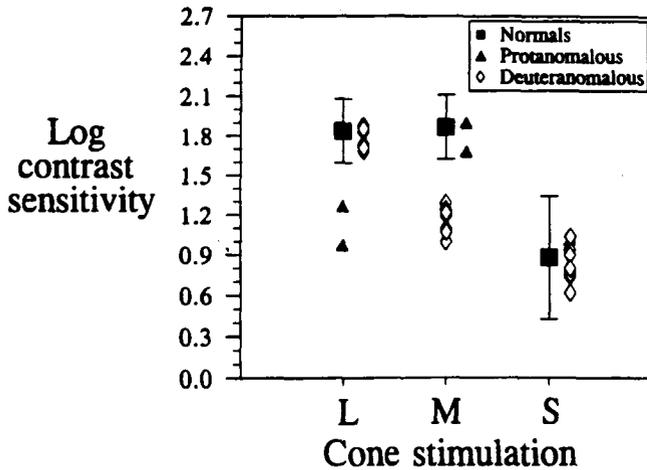
Each contrast sensitivity chart (L, M, and S cone) consists of 10 rows of letters that are most visible at the top but that gradually fade into the gray background, from top to bottom, in steps of 0.1 log cone contrast per row. There are five letters per 0.1 log contrast row, and credit is given for each letter read correctly (0.02 log units per letter).<sup>11</sup> Because chromatic aberration causes a difference in focus between colored letters and background, large letters are used (20/316; stroke width = 1.9 cyc/deg), which are less susceptible to defocus,<sup>12</sup> particularly at threshold color



**FIGURE 1.** Cone contrast is plotted against row number for each cone-contrast sensitivity chart (L, M, and S cone). The bottom solid line is the mean contrast to the other two cone types not stimulated systematically on each chart.

contrasts where chromatic (i.e., wavelength) differences in focus are minimal. Figure 1 shows the systematic change in cone contrast with row number on L-, M-, and S-cone contrast-sensitivity charts. The L-cone chart has reddish letters, the M-cone chart has greenish letters, and the S-cone chart has violet letters that become less detectable from the gray background as one progresses from the top (row 1) to the bottom (row 10) of each chart. It is clear from the colorimetrically derived data plotted in Figure 1 that cone contrast decreases in 0.1 log steps per row. The contention that each chart stimulates only one cone type is indicated by the solid line in Figure 1, showing mean contrast to the two cone types that are not stimulated systematically on each chart. These contrasts are generally below threshold for letter recognition, making each chart visible to only one cone type. The S-cone function is shifted upward relative to L and M because there are far fewer S cones in the human retina,<sup>13</sup> making it necessary to use higher cone contrasts to achieve letter recognition. Although the S cone test is equiluminant (i.e., letters and background have same luminance), both L- and M-cone tests have low amounts of luminance contrast (0.7% to 8%; letters higher in luminance than background), but only a single cone type (L or M) is stimulated systematically on each test. This approach of selectively stimulating each cone type makes no assumptions about the role postreceptoral mechanisms.

Thirty subjects (mean age,  $30 \pm 9$  years) with normal color vision and 13 subjects with hereditary color deficiency (mean age,  $33 \pm 13$  years) were tested monocularly with cone-specific contrast sensitivity (tested at 94 cm, dark room) and with several clinical color vision tests, including Dvorine (Scientific Publishing, Baltimore, MD) and Richmond Products (Boca Raton,



**FIGURE 2.** Mean ( $\pm 3$  SD) log cone contrast sensitivity for 30 color normal subjects is plotted for L-, M-, and S-cone tests. Individual results for two L-cone-deficient (protanomalous) and M-cone-deficient (deuteranomalous) subjects are shown.

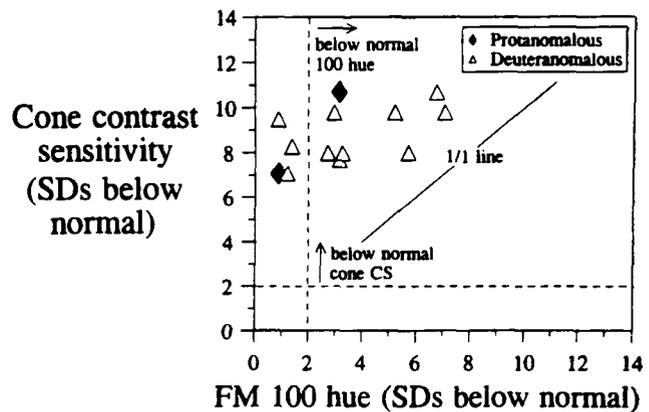
FL) pseudoisochromatic plates, FM 100 hue (both illuminated by a MacBeth [Newburgh, NY] Easel lamp), and Nagel (Schmidt and Haensch, Berlin, Germany) (type I) anomaloscope. All subjects were free of ocular and systemic disease, were corrected to at least 20/20 acuity during testing, and gave their informed consent in accord with the Declaration of Helsinki.

**RESULTS.** Figure 2 shows mean ( $\pm 3$  SD; 99% confidence interval) log contrast sensitivity (log 1/contrast threshold) from 30 color normal subjects (filled squares) plotted separately for each cone type. Although mean L and M cone sensitivities are the approximately the same, S-cone contrast sensitivity is nearly 1 log unit less because of the sparse distribution of S cones in the human retina. Figure 2 also shows individual results from 13 color-deficient subjects: two L-cone deficient (protanomalous) and 11 M-cone deficient (deuteranomalous). The protanomalous subjects show dramatically reduced sensitivity on the L-cone chart but normal performance on the M-cone chart, making the diagnosis of protanomaly unequivocal. Subjects with deuteranomaly show the reverse effect: significantly reduced sensitivity on the M-cone chart but normal sensitivity on the L-cone chart. As expected, performance by subjects with red and green color deficiency is essentially normal on the S-cone chart.

To evaluate the sensitivity of cone-specific contrast sensitivity, performance on this new test was compared to performance on the FM 100 hue cap arrangement test.<sup>14</sup> To facilitate comparison between tests, values were transformed to standard scores by taking the difference between the scores of subjects with color deficiency and the mean values for normals ( $n = 30$ ) and dividing by the standard deviation (SD) for normals. This expresses all scores in common units (i.e., SD from the mean) and allows for direct comparison be-

tween the results of different tests. Figure 3 shows cone contrast sensitivity plotted against FM 100 hue standard scores for 13 subjects with color deficiency. Values to the right of the vertical line are more than 2 SD below normal for FM 100 hue, and those above the horizontal line are more than 2 SD below normal for cone contrast sensitivity. If there was exact agreement between the two tests, data would fall on the 1/1 line. However, results for cone contrast sensitivity fall well above this line, with values ranging from 7 to 11 SD below normal. In contrast, test results for 9 of 13 subjects were below normal on the FM 100 hue test. When this analysis of FM 100 hue scores was repeated using age-controlled means and SD from a more extensive, earlier study,<sup>14</sup> only 4 of 13 subjects tested below normal on the FM 100 hue, which points to greater sensitivity of cone contrast sensitivity.

**DISCUSSION.** These results indicate that normal and anomalous color vision can be quantified using the familiar task of letter recognition, provided the letters are presented in systematic steps of cone contrast. This approach gives a cone-specific measure of color vision in normals and can indicate both type and severity of color deficiency. In addition to hereditary anomalies, cone-specific contrast sensitivity should prove useful for monitoring the course of acquired color deficiency that can occur early in the course of ocular and systemic disease (e.g., glaucoma and diabetes).<sup>3-5</sup> Although recent studies of color vision have emphasized equiluminant stimuli to discriminate between color and luminance processing,<sup>15,16</sup> we take a more fundamental approach of stimulating individual cone mechanisms based on psychophysically derived spectral sensitivities. Our approach is comparable to the (now out of print) American Optical H-R-R plates and a computer-based test developed by



**FIGURE 3.** Cone contrast sensitivity is plotted against FM 100 hue scores for 13 subjects with color deficiency. Values are expressed as standard deviations below the mean for normal subjects. See Results for further details.

Mollon and coworkers,<sup>6,7</sup> both of which use cone-isolating stimuli to identify type and severity of color deficiency. Although the H-R-R and Mollon tests use spatial and luminance noise to insure detection by chromatic mechanisms, cone contrast sensitivity uses systematic steps in cone contrast and *by-letter* scoring developed by Bailey and coworkers<sup>11</sup> to quantify human color vision. Unlike classical studies of cone sensitivity<sup>5,8,9,17</sup> in which stimuli are superimposed on intense backgrounds to desensitize one or more class of receptors while sparing those being tested, we used a common, achromatic background for all stimuli, thereby ensuring a constant state of visual adaptation.

### Key Words

color vision, cone contrast, cones, contrast sensitivity

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### References

1. Krill AE. In: Krill AR, Archer DB, eds. *Krill's Hereditary Retinal and Choroidal Diseases. Vol II: Clinical Characteristics*. New York: Harper & Row; 1977:335-390.
2. Pokorny J, Smith VC, Verriest G, eds. *Congenital and Acquired Color Defects*. New York: Grune & Stratton; 1979.
3. Adams AJ. Chromatic and luminosity processing in retinal disease. *Am J Optom Physiol Opt*. 1982;59:954-960.
4. Adams AJ, Rodic R, Husted R, Stamper R. Spectral sensitivity and color discrimination changes in glaucoma and glaucoma-suspect patients. *Invest Ophthalmol Vis Sci*. 1982;23:516-524.
5. Greenstein VC, Hood DC, Ritch R, Steinberger D, Carr RE. S (blue) cone pathway vulnerability in retinitis pigmentosa, diabetes and glaucoma. *Invest Ophthalmol Vis Sci*. 1989;30:1732-1737.
6. Mollon JD, Reffin JP. A computer-controlled colour vision test that combines the principles of Chibret and Stilling. *J Physiol*. 1989;414:5P.
7. Regan BC, Reffin JP, Mollon JD. Luminance noise and the rapid determination of discrimination ellipses in colour deficiency. *Vision Res*. 1994;34:1279-1299.
8. Smith VC, Pokorny J. Spectral sensitivity of the foveal cone pigments between 400 and 500 nm. *Vision Res*. 1975;15:161-171.
9. Wyszecki G, Stiles WS. *Color Science: Concepts and Methods, Quantitative Data and Formulae*. New York: Wiley-Interscience; 1982.
10. Cole GR, Hine T. Computation of cone contrasts for color vision research. *Behavior Research Methods, Instruments and Computers*. 1992;24:22-27.
11. Bailey IL, Bullimore MA, Raasch TW, Taylor HR. Clinical grading and the effects of scaling. *Invest Ophthalmol Vis Sci*. 1991;32:422-432.
12. Bradley A, Hook J, Haeseker J. A comparison of clinical acuity and contrast sensitivity charts: effect of uncorrected myopia. *Ophthalmic Physiol Opt*. 1991;11:218-26.
13. Marc R, Sperling HG. Chromatic organization of primate cones. *Science*. 1977;196:454-456.
14. Verriest G, Laethem JV, Uvijls A. A new assessment of the normal ranges of the Farnsworth-Munsell 100-hue test scores. *Am J Ophthalmol*. 1982;93:635-642.
15. Krauskopf J, Williams DR, Heeley DW. Cardinal directions of color space. *Vision Res*. 1982;22:1123-1131.
16. Livingstone MS, Hubel DH. Segregation of form, color movement and depth: Anatomy, physiology and perception. *Science*. 1988;240:740-749.
17. Stiles WS. *Mechanisms of Colour Vision*. London: Academic; 1978.