Rapid Quantification of Color Vision: The Cone Contrast Test

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Purpose. To describe the design, specificity, and sensitivity of the cone contrast test (CCT), a computer-based, cone-specific (L, M, S) contrast sensitivity test for diagnosing type and severity of color vision deficiency (CVD).

Methods. The CCT presents a randomized series of colored letters visible only to L, M or S cones in decreasing steps of cone contrast to determine L, M, and S letter-recognition thresholds. Sensitivity and specificity were determined by retrospective comparison of CCT scores to anomaloscope and pseudoisochromatic plate (PIP) results in 1446 applicants for pilot training.

Results. CVD was detected in 49 (3.4%) of 1446 applicants with hereditary red-green (protan or deutan) CVD detected in 47 (3.5%) of 1359 men and blue-yellow (tritan) in 2 of 1446. In agreement with the anomaloscope, the CCT showed 100% sensitivity for detection and categorization of CVD (40 deutan, 7 protan, 2 tritan). PIP testing showed lower sensitivity (80% detected; 20% missed) due in part to the applicant's prior experience and/or pretest preparation. CCT specificity for confirming normal color vision was 100% for L and M cone tests and 99.8% for S cones.

Conclusions. The CCT has sensitivity and specificity comparable to anomaloscope testing and exceeds PIP sensitivity in practiced observers. The CCT provides a rapid (6 minutes), clinically expedient, measure of color vision for quantifying normal color performance, diagnosing type and severity of hereditary deficiency, and detection of acquired sensitivity loss due to ocular, neurologic, and/or systemic disease, as well as injury and physiological stressors, such as altitude and fatigue. (*Invest Ophthalmol Vis Sci.* 2011;52:816–820) DOI:10.1167/iovs.10-6283

Human trichromatic vision enables detection of more than two million surface colors, wavelength discrimination with precision <1 nm, and the unique capacity to exploit color information for multiple applications in myriad settings.[1] This formative ability is predicated on a normal complement of L, M, and S cones. Hereditary color vision deficiency (CVD; 8% of males, 0.5% females) derives from a lack of L cones (protanopia 1%) or M cones (deuteranopia 1%); or from a cone spectral sensitivity shift (protanomaly: L shifted toward M in 1%; deuteranomaly: M shifted toward L in 5%).[2,3] Most color vision tests (e.g., pseudoisochromatic plates; PIPs) detect the *presence* of CVD, but few quantify *type* or *severity*, vital for predicting performance and improving safety when color is used for critical discriminations.[4,5] Previous studies reported that letter contrast sensitivity specific for L, M, and S cones readily identifies type and severity of hereditary CVD and reveals acquired CVD in eye disease.[6,7] We describe the design, specificity and sensitivity of a new cone contrast sensitivity test (cone contrast test; CCT) successfully used for rapid diagnosis of CVD in a population of applicants for pilot training.

Methods

The CCT presents a randomized series of colored letters visible to a single cone type (L, M, or S) in decreasing steps of cone contrast to determine the threshold for letter recognition. Figure 1 illustrates CCT design principles in letter chart format with scoring, contrast levels, and categorization of color vision. In the current computer-generated CCT, a single letter appears briefly centered in the display (Trinitron Multiscan G420 CRT; Sony, Tokyo, Japan; Celeron 1.7 GHz with Extreme Graphics Controller; Intel, Santa Clara, CA) and the subject is required to report the letter aloud (forced-choice letter-recognition task). The test is conducted monocularly in a dark room at 1 m; distance correction is worn with a +1 D ADD if improved visibility of demonstration letters is reported. After instructions and demonstration of L, M, and S letter appearance and central location on the display, the test begins with a random series of 20 reddish letters (L), followed by greenish letters (M), and then violet letters (S) progressing from most visible (Fig. 1, top row) down to least visible (bottom row; lowest contrast). The program randomly selects letters from the British Standards Institution letters having equal legibility and used on the Bailey-Lovie ETDRS visual acuity chart[8] (H, N, V, R, U, E, D, F, P, Z; Arial bold font; L and M cone: 20/330; S cone 20/440; approximate spatial frequency 1.8 and 1.4 cyc/deg, respectively, based on 2.5 cycles/letter). On each trial the program presents a colored letter centered within a crosshairs on a gray background (21.5 cd/m^2, $x = 0.299$, $y = 0.300$). The letter appears for a duration of 1.0 to 1.6 seconds (duration increases as contrast decreases), followed by an intertrial interval (gray field) of equal duration. During this time, the subject is required to read the letter aloud, and the program then advances to the next trial. As indicated in Figure 1, the letters decrease from a clearly visible cone contrast down to a threshold level (L and M: 27.5%–1%; S: 173%–7%) in 0.16 logarithmic steps (two letters per step; 0.08 log contrast units per letter). The letters read correctly and those missed are carefully recorded by a technician using a preprinted score sheet with the unique (random) letter sequence for the subject being tested. For each test (L, M, S; right and left eyes), the number of errors (of 20 letters) is entered into the CCT program which stores and prints the L, M, and S cone scores. To facilitate clinical application, the log contrast sensitivity scores are normalized to an intuitive 100-point scale such that each letter that is read correctly counts as five points, making the maximum score 100 (all 20 read correctly; L and M contrast threshold = 1%, S threshold = 7%) and the minimum score 0. Subjects are required to read all letters or reply "no" if a letter is not detectable. The CCT time is 3 minutes per eye.

As described previously,[6,7] cone-specific contrast is based on measurement of display luminance and CIE chromaticity and converting

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Distribution Statement A: Approved for public release; distribution is unlimited. 311 ABG/PA No. 10-309, 5 AUG 10.

Submitted for publication July 27, 2010; revised September 2 and 10, 2010; accepted September 17, 2010.

Disclosure: **J. Rabin**, None; **J. Gooch**, None; **D. Ivan**, None

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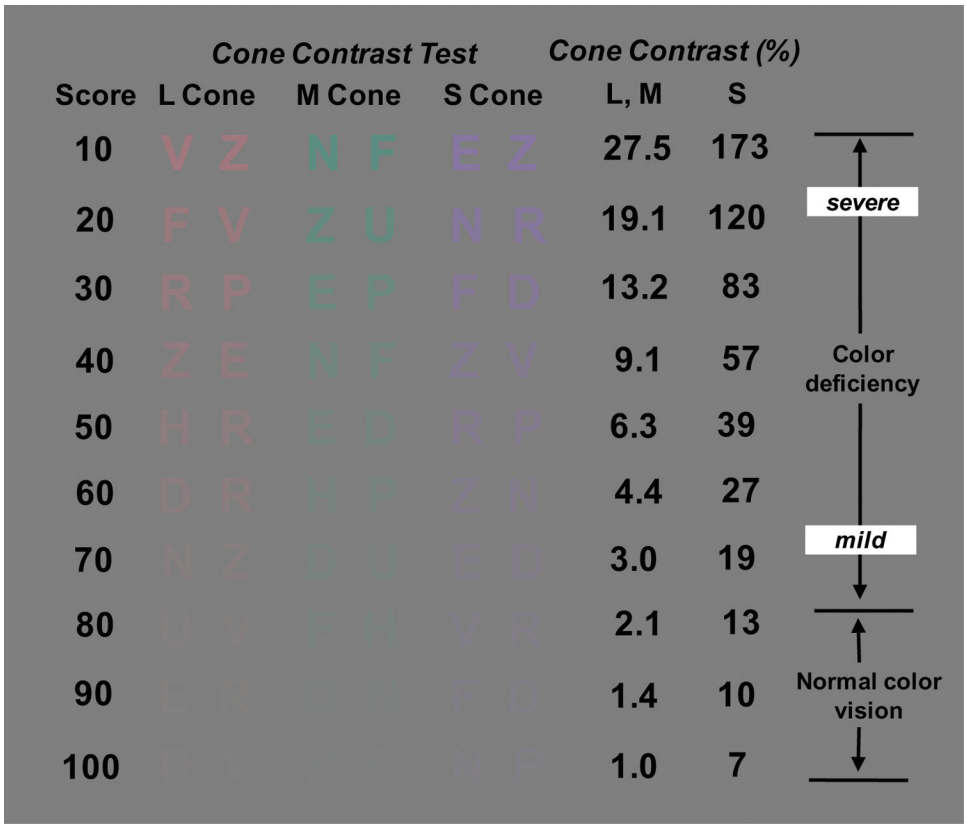

FIGURE 1. Cone contrast test design principles are shown in letter chart format with 100-point numerical score, cone contrasts, and qualitative categorization of color vision.

these values to cone excitations[9,10] (E) based on psychophysically derived cone sensitivities[11]:

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

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

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

Cone contrast is computed as a Weber contrast; difference between letter and background divided by background multiplied by 100:

$$\text{Cone contrast (\%)} = [(E_{\text{letter}} - E_{\text{background}})/E_{\text{background}}]100$$

Display (letter and background) luminance and chromaticity were measured with a colorimeter (ColorCAL; Cambridge Research Systems) and converted to cone contrast with custom-designed programs to determine the RGB phosphor intensities required for each cone contrast level; measurements were repeated quarterly to confirm the values. In L, M, and S CCTs, a single cone type is stimulated systematically while stimulation of the other two cone types is maintained at a subthreshold level (<1% cone contrast). This is achieved by ensuring that the amount of cone excitation in letter and background is essentially *equal* for the two (unstimulated) cones (hence *zero contrast* in the equation above).[6,7] Due to overlap of the cone functions, it is not possible to limit stimulation to a single cone type, but by keeping the amount of stimulation in letter and background equal (undetectable) for two cone types while systematically stimulating the third, the letter is detectable only by a single class of cones. Moreover, the photopic display luminance (21.5 cd/m^2) is beyond the detection range of rod photoreceptors, making it unlikely that rods participate in the letter-recognition task. The relatively large letter size (L, M: 20/330; S: 20/440) is optimal for stimulation of chromatic mechanisms and minimally affected by defocus.[6]

A total of 1446 pilot applicants (1359 men, 87 women; mean age ± SD, 24.3 ± 3.2 years) presumed to have normal color vision (CVN) based on a military entrance physical examination underwent comprehensive color assessment as part of standard entry requirements for pilot training. Color testing included the Dvorine PIP: 14 red-green plates, passing score 12/14 correct in each eye; Standard Pseudoisochromatic Plates Part 2 (SPP2): 10 red-green and blue-yellow (tritan) plates, passing score 9/10 correct in each eye; Farnsworth F2 plate: single PIP plate with two overlapping squares, one R-G, one B-Y, passing score in each eye: perception of two squares in the correct locations; and the CCT, passing score: ≥75 in each eye on L, M, and S tests; 75 = 2 SD below normal mean on the S CCT. Any applicant who failed any portion of this battery of tests underwent further diagnostic testing with Rayleigh and Moreland Heidelberg Multi-Color anomaloscopes (Heidelberg Multi Color [HMC]; Oculus, St. Louis, MO) using a forced-choice iterative method to determine matching range and midpoint. CCT specificity was based on comparison of CCT scores to anomaloscope scores in 92 CVN applicants; time constraints precluded anomaloscope testing of all applicants. In accordance with the Declaration of Helsinki, this retrospective study was authorized by an exempt protocol approved by our Institutional Review Board. A Cooperative Research and Development Agreement has been established to improve the CCT (paperless automated scoring, response-driven rapid staircase to threshold, choice of letter or numeric characters) and ensure widespread availability.

RESULTS

L, M, and S CCT specificity (percentage of CVN confirmed to be CVN), based on the concordance between passing scores on the CCT (≥75) and passing scores on Rayleigh and Moreland anomaloscope and PIP tests, was 100% in 92 applicants assessed on all tests. All applicants determined to be CVN on PIP tests (n = 1397) achieved normal L and M CCT scores

TABLE 1. Color Vision Test Sensitivity in Color Deficiency

Dvorine	SPP2	F2	Combined PIP Battery*	CCT
58	40	68	80	100

Data are the percentage of color vision–deficient subjects detected with each test.

* Failed Dvorine, SPP2, and/or F2.

(≥75), but three showed slightly reduced S cone scores (65–70) without additional evidence of color deficiency or eye disease at the time of testing, and thus categorized as false-positive results. Table 1 shows test sensitivity: percentage of CVD identified correctly as CVD based on agreement with anomaloscope testing. A total of 49 (3.4%) of 1446 were identified with CVD. All were men, with 47 of the 1359 men detected with hereditary protan or deutan CVD (3.5% of the men). Sensitivity of individual PIP tests (Dvorine, SPP2, and F2) for detecting CVD ranged from 40% to 68% (Table 1), whereas the combined PIP battery detected CVD in at least one eye in 40 (80%) of 49. In comparison, the CCT detected CVD in 100% of applicants as confirmed by anomaloscope testing. One applicant (1 [0.07%] of 1446) who showed a symmetrical bilateral tritan defect on the Moreland anomaloscope and S CCT (detected in one eye with the SPP2) was presumed to be hereditary in origin, since additional ophthalmic and electrophysiological testing revealed no evidence of disease or an acquired basis for the tritan defect. Another individual who showed decreased color vision in one eye on multiple tests with greatest loss on the S CCT was presumed to have an acquired defect, possibly due to a subclinical optic nerve or retinal condition not fully manifest at the time of testing.

Figure 2 shows CCT scores, right eyes plotted against left eyes, for CVD (n = 49) with L, M, and S CCT means (±2 SD) for the CVN population shown for comparison. CVD scores are clearly reduced below normal limits with a range of CVD severity. Most red cone (protan) CVDs show greater decrease (higher thresholds) than green cone (deutan) CVDs, consistent with results of Barbur et al.,[12] who used a color-contrast threshold test. By assuming that interocular (right versus left eye) differences in CVNs mainly reflect test–retest variability, it was possible to estimate CCT repeatability. The SD of CCT interocular differences was multiplied by two to calculate the coefficient of repeatability (COR; 95% confidence interval for change).[13,14] This yielded L, M, and S CORs of 15 points; hence, scores that differ by ≥15 points, when measured in the same subject over time or when comparing right and left eyes are considered outside normal limits.

Figure 3 shows CCT L and M scores plotted against the midpoint of the Rayleigh anomaloscope matching range. Individual results are shown for hereditary protan and deutan CVDs (n = 47; 94 eyes) with means and ranges illustrated for CVN. It is clear that the midpoint of the anomaloscope matching range shifted toward green in most of the deutans (more green needed in the red+green metameric match to yellow) and is shifted toward red in the protans (more red needed to achieve the match). Consistent with this benchmark result, deutan CVDs showed significantly decreased M cone CCT scores (two-sample t-test, unequal variance, t = 18.4; $P < 0.0001$), whereas the protans showed decreased L cone CCTs (t = 9.0; $P < 0.0002$), making categorization of CVD unequivocal. However, the protans and deutans tended to score less than the CVNs on M and L CCTs, respectively, but the scores were rarely outside normal limits, and were significantly higher than the selective decrease on the affected CCT test (paired t-test, t = 11.9; $P < 0.0001$). The majority of the protan and deutan CVDs show Rayleigh anomaloscope matches shifted toward red or green, respectively, but relatively few (7/47, 15%) showed expanded matching ranges, indicative of decreased ability to perceive discrete hues for various combinations of red and green. With expansion of anomaloscope matching range midpoint regresses toward the center, making the degree of midpoint shift less meaningful as an index of color deficiency. There was no correlation between the CCT and anomaloscope midpoint shift (r = 0.12; $P > 0.26$) but a mild correlation between CCT scores and matching range (r = 0.25; $P < 0.02$). It is of interest that one applicant classified as deutan showed a normal midpoint and matching range in one eye with a slightly expanded range in the fellow eye, whereas green CCT scores were mildly reduced below normal (65 and 70; two filled diamond symbols, top center, Fig. 2). This applicant passed the standard PIP battery (Dvorine, SPP2, and F2) but failed a follow-up Ishihara test (7/14

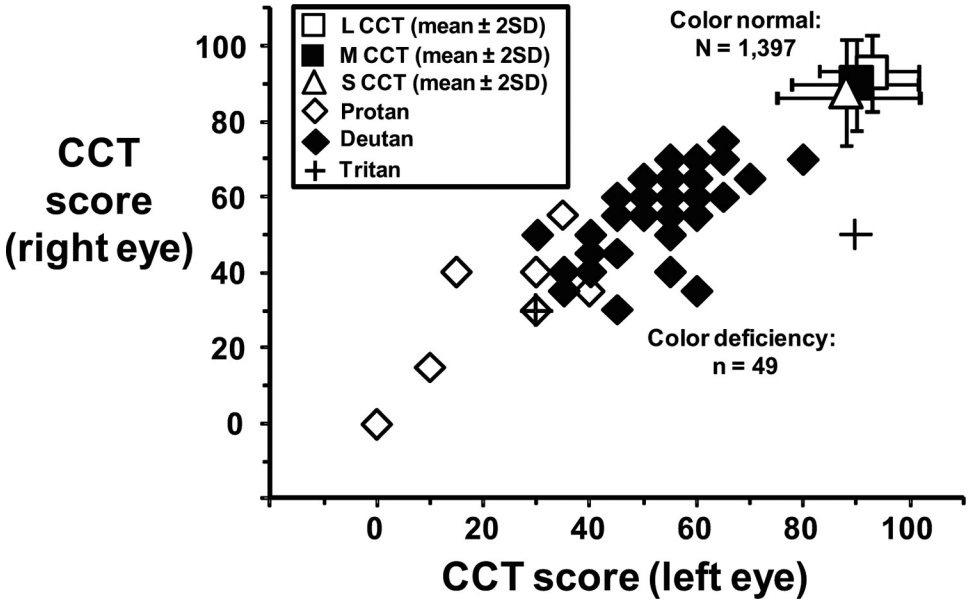

FIGURE 2. CCT scores from the right eyes are plotted against corresponding scores from the left eyes of CVD applicants with mean (±2 SD) L, M, and S values shown for the CVN population.

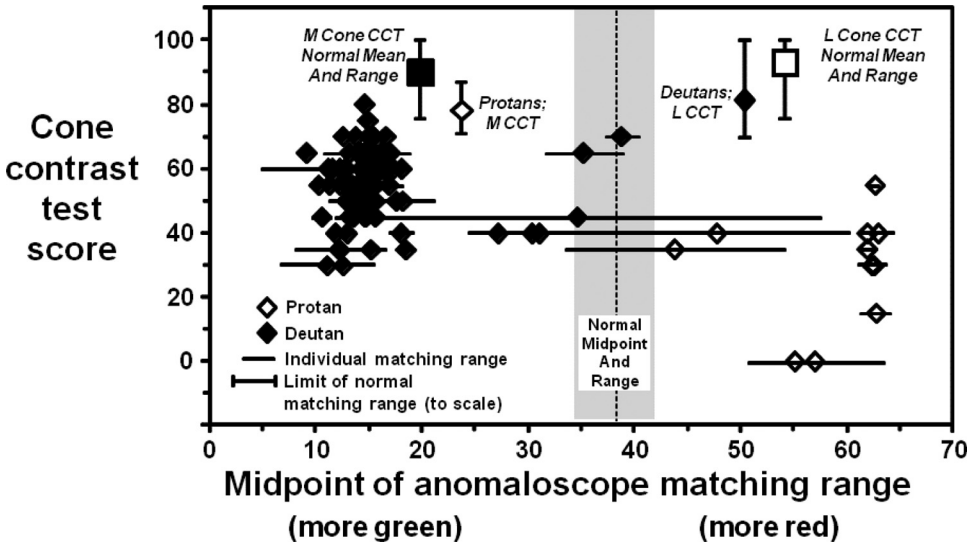

FIGURE 3. Cone contrast test scores are plotted against the midpoint of the anomaloscope matching range. The boxes and error bars show the mean and total range of CCT scores for CVNs (n = 1397). Individual data (right and left eyes) for protan and deutan CVDs (n = 47) are plotted for L and M cone tests with CVD means and ranges plotted for the unaffected cone test. The *central broken line* and *shaded region* are the mean and total range of anomaloscope midpoints for CVN. Horizontal bars represent the anomaloscope matching range for each CVD.

correct) confirming the presence of deuteranomaly detected with the CCT.

DISCUSSION

The CCT provides a quantitative index of color ability specific for L, M, and S cone–mediated vision. Hereditary CVD is readily detected, categorized (protan, deutan, or tritan), and graded in terms of severity. Unlike most PIP tests that determine pass-fail performance, the CCT yields a threshold sensitivity score applicable to CVD and CVN as well. This approach can also reveal acquired CVD in diseases spanning levels of the visual system.[7]

A total of 3.5% of the male pilot applicants were found to have CVD; lower than in the general population (8%) and presumably because of prior screening on military entrance examinations. Comprehensive PIP testing was 80% effective in detecting CVD but missed 20% of applicants. Prior experience with PIP tests and/or test preparation in highly motivated applicants can probably explain this result. In agreement with anomaloscope testing, the CCT showed 100% sensitivity for detection of CVD in the applicant population, attributable to CCT specificity for each cone type (L, M, and S), threshold quantification, and importantly, randomization of target sequence before each test administration. Consistent with the superiority of the CCT compared with PIP testing reported herein, the CCT technique was shown to be more sensitive than the FM 100 Hue test for detection of hereditary CVD.[6]

While the Rayleigh anomaloscope match remains the benchmark gold standard for detection of hereditary protan and deutan CVD, atypical or normal-appearing Rayleigh matches occasionally occur in CVD, despite evidence of reduced chromatic sensitivity on alternate testing.[15,16] In addition, anomaloscope indices of CVD severity (degree of midpoint shift and extent of the matching range) can be difficult to interpret because of (1) the limited range of midpoint shift in CVD (0.25 log units in Fig. 3; most deutan midpoints are near setting 15; protans near setting 62), (2) the tendency for matching range to be normal despite a definitive midpoint shift, and (3) regression of the CVD matching midpoint toward the normal midpoint with expansion of the matching range. In comparison, the CCT shows a range of contrast threshold scores in CVDs having comparable anomaloscope midpoint shifts (Fig. 3). The range of values revealed with the CCT may reflect inter-subject differences in photopigment optical density and/or variability in the peak wavelength of the anomalous photopigment which are not readily disclosed by anomaloscope testing. Other factors related to the threshold nature of the CCT task (low contrast letter recognition), including effort level, attention, and/or physiological status, may influence CCT score, and its predictive value for performance on real-world color tasks remains uncertain.

In conclusion, the CCT offers an intuitive, robust index of color vision that accurately detects type of CVD and is capable of grading severity of CVD as well as color ability in the CVN population. The rapid, threshold letter-recognition task is well-suited for clinical application.

Acknowledgments

The authors thank Kennith Stevens, Steve Linnemeyer, and Michael Foxworth for their invaluable assistance in multiple aspects of this research.

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