A Comparison Between Three Computer-Based Cone Specific Color Vision Tests

Julie Lovell; Jeff Rabin

INTRODUCTION: Computerized color contrast sensitivity (CS) tests that aim to determine presence, type, and severity of color vision deficiency have been developed and are available, but data on agreement between tests is lacking. The purpose of the present study was to determine data agreement between three computerized color vision tests.

METHODS: A total of 50 subjects, 25 color vision normal (CVN) and 25 color vision deficient (CVD), were tested with the Konan CCT-HD®, NCI, and a modified version of the Innova CCT. Sensitivity and specificity were compared across systems as well as differences in log CS values and how these relate to standards used to classify occupational performance.

RESULTS: Each test showed 100% sensitivity for detection of hereditary red-green CVDs as well as type (protan vs. deutan). Each test showed 100% specificity for confirming normal red-green color vision in CVNs. Innova CCT and NCI showed 100% specificity in CVNs and CVDs for S cone CS. Konan CCT-HD® showed 96% specificity in CVNs and 92% in CVDs for S cone CS.

DISCUSSION: These findings indicate that each test reliably identifies hereditary CVD and confirms normal color vision. However, the three tests differ slightly in log CS values used to determine pass/fail scores of red-green color vision using a 100-point scale, and all show that protans consistently score lower than deutans on cone CS. Hence, depending on the criterion used in occupational settings, a single score may not prove equitable for individuals who have a protan deficiency.

KEYWORDS: color vision, Innova cone contrast test, pilot color vision standards, Konan Medical cone contrast test, Nordstrom cone contrast test.

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A number of computerized color vision tests have been developed over the last 25 yr which seek to identify both type (protan, deutan, or tritan) and severity of color vision deficiency (CVD). These tests are also used to confirm normal color vision (CVN). The Cambridge Color Test uses computer generated Landolt-Cs embedded in luminance noise to determine thresholds based on orientation of the gap and expressed as color ellipses in a specified chromatic space.[1] It has proven highly sensitive and efficacious for hereditary and acquired testing.[7,17] The Color Assessment and Diagnosis (CAD) test uses dynamic luminance noise as well. The task is a forced-choice identification of the direction of a moving box of different chromaticity than the background, but isoluminant relative to the mean luminance of the background.[4] The CAD has been highly successful for hereditary, acquired, and occupational applications using a standard score CAD unit metric based on standard deviations from well-established normal means.[4] In cone specific contrast sensitivity (CS), letters seen only by red (L), green (M), or blue (S) cones are presented in graded steps of cone contrast using a rapid response-driven staircase.[12–16] For example, L cone letter contrast is computed as a positive Weber contrast:

$$\left(\frac{L_{stimulation\ in\ letter} - L_{stimulation\ in\ grey\ background}}{L_{stimulation\ in\ grey\ background}} \right) * 100$$

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It is crucial to comprehend that the L cone letters yield subthreshold contrasts to M and S cones, and the same applies when M cone CS is determined (the letter contrast for both the L and S cones is subthreshold), and when S cones are tested (the letter contrast for both the L and M cones is subthreshold). Additionally, as in the Cambridge and CAD tests, the display luminances are too high to stimulate rods. The first commercial version of the Rabin Cone Contrast Test was developed by Innova Systems, Inc., in collaboration with the U.S. Air Force (USAF). Since then, several additional versions have been designed using Landolt-C targets and all have been refined since the original test fielded by the USAF. Since cone CS, as described herein, is used in the United States for clinical applications and occupational standards by the Department of Defense (DoD) and Federal Aviation Administration (FAA), we chose to compare the sensitivity and specificity of three similar cone CS tests as well as differences in contrast steps, character sizes, and other factors which may impact test efficacy. Hence, in addition to preliminary CVD identification using pseudoisochromatic plate tests and anomaloscope testing, our purpose was to determine data agreement between the Innova Cone Contrast Test[3] (Innova CCT, version 19.7.1.4), Konan CCT High-Definition[5] (Konan CCT-HD®, version 1.0.70), and Nordstrom Consulting, Inc., CCT[9] (NCI, version 14). The stimuli of the three tests are displayed in **Fig. 1**. Throughout the rest of the paper, they will be referred to as the Innova CCT, Konan CCT-HD®, and NCI, respectively.

METHODS

Subjects

We recruited 50 subjects (mean age 27 ± 9 SD; 34 men and 16 women) from the local community to participate in the study. Exclusion criteria included history of ocular disease or trauma, neurological disease, or systemic disease not controlled medically. Subjects' color vision status was confirmed by the 24-plate Ishihara PIP[8] and the HMC-Anomaloscope,[6] which is the gold standard for diagnosing protan vs. deutan CVD and discriminating between dichromacy and anomalous trichromacy. Subjects were divided into two groups, CVN ($N = 25$, mean age 24 ± 3; 10 men and 15 women) and CVD ($N = 25$, mean age 30 ± 12; 24 men, 1 woman; 7 protanomalous, 18 deuteranomalous). There were no dichromats in the subject pool. Each subject provided written informed consent in accord with our IRB-approved protocol.

Equipment and Procedures

Subjects were first administered the 24-plate Ishihara as an initial screening tool. The test was illuminated by the Daylight Illuminator (illuminant C, Precision Vision, Inc.) with room lights off at a distance of 60 cm. Subjects were identified as CVN if they identified at least 12 of the first 14 testable plates correctly, the same criterion used by the DoD. After subjects were classified as CVN or CVD by the Ishihara, the classification was confirmed by anomaloscope testing. The Konan CCT-HD®,

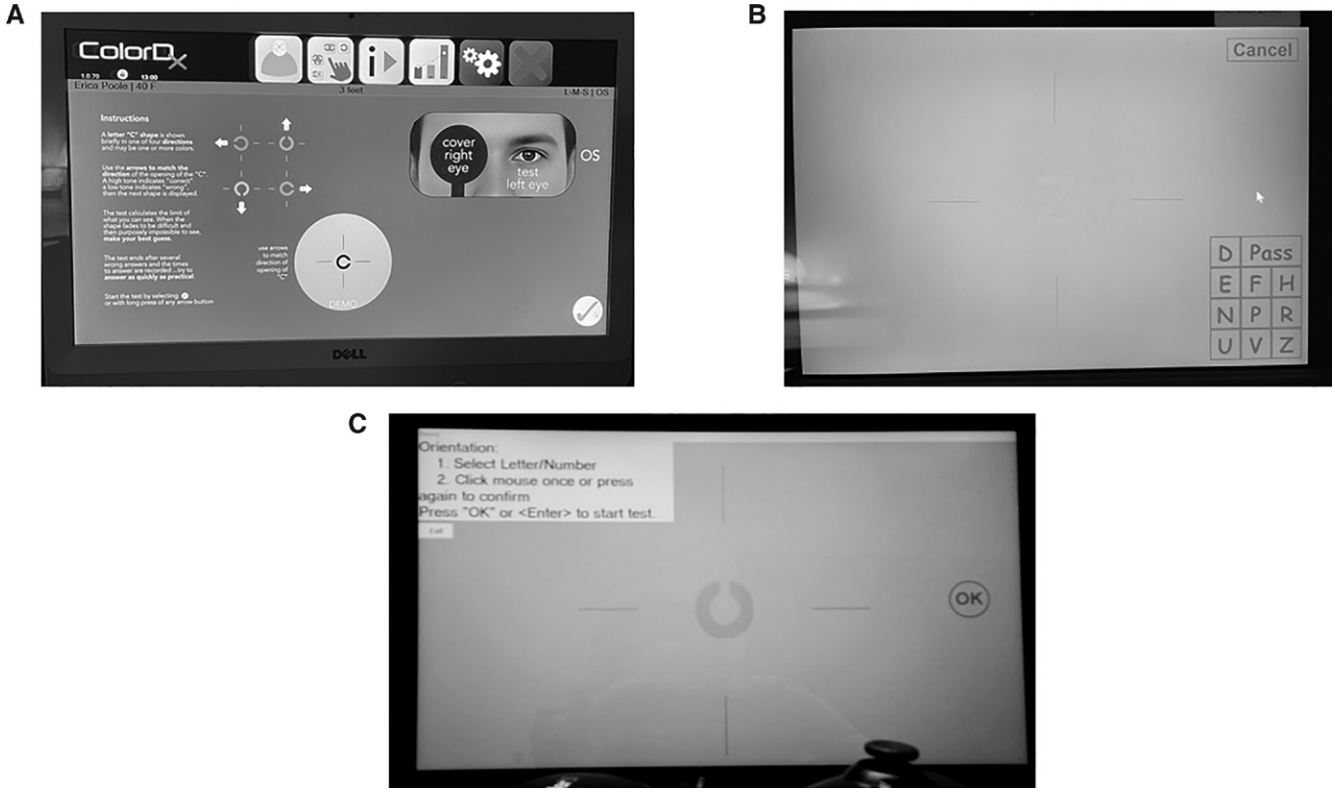

Fig. 1. Picture of computerized color contrast sensitivity tests: A) Konan CCT-HD®; B) Innova CCT; C) NCI.

NCI, and Innova CCT were performed separately for right and left eyes according to manufacturer's instructions. Testing was conducted monocularly at the specified viewing distance (3 ft; 91.44 cm) in an otherwise dark room with habitual correction and added power as needed for presbyopic subjects. No subjects were allowed to wear tinted spectacle or contact lenses. Cone CS test order and which eye was tested first were randomized across subjects.

The Innova CCT also presents letters (20/330 visible only to L and M cone, 20/440 letters visible only to S cones) at progressively lower cone contrasts using a response driven rapid staircase to determine L , M, and S cone letter recognition thresholds. The letter appears briefly (5 s) in the center of the display and the subject uses a mouse to select the letter seen from an adjacent matching display. The version used in this study was adjusted to slightly lower cone contrasts (0.8–16% for L and M cones and 8–128% for S cones) on a Microsoft Surface Display to enable threshold CCT measures comparable the original CRT-based system.[11,14]

The Konan CCT-HD® isolates cone types using the same luminance and chromaticity approach to present a 20/330 Landolt C with a gap in one of four orientations and a four-alternative forced choice response-driven PSI algorithm allowing subjects to use a keypad to identify the correct gap orientation (up, down, left, or right).[10] This system uses a finer contrast scale to achieve more exact thresholds. The NCI CCT also uses a Landolt C in a manner similar to the CCT-HD, but does not include as extensive a contrast range. In addition, The NCI has a ceiling effect for the S cone stimulus scores.

Statistical Analysis

While all three tests use a 100-point scale based on logarithmic steps in cone contrast and hence cone CS, we converted all 100-point values to log cone CS based on our measures and values specified by each test manufacturer. Specifically, the 100-point scores were converted to log cone CS based on the cone contrasts of each threshold. For example, a Konan 100-point scale score of 98 for the L cone equates to a log CS of 1.88. For the Innova, a 100-point scale score of 90 for the L cone equates to a log CS of 1.89. **Table I** shows examples of the conversion for each test and L and M cone type. This does not lessen the importance of an intuitive 100-point scale for technicians, clinicians, and scientists alike, but is more exacting and accurate to compare tests based on actual contrast levels.

Two-way nested ANOVA with replication was used to determine if there was a difference in log CS between right and left eyes and assess differences between the three tests. Post hoc paired *t*-tests with Bonferroni correction for multiple comparisons was used to determine cone-specific differences within and between tests. Since no difference was found between right and left eyes across tests [CVNs, $F(2,1) = 0.05$, $P = 0.82$; CVDs, $F(2,1) = 0.51$, $P = 0.48$], the higher log CS of the two eyes was used for analyses of each cone stimulus for both CVN and CVDs since we considered this to be the subject's best effort for that given cone mechanism. Further analysis was conducted to determine if there were differences between test results of normal and anomalous trichromats.

Table I. Examples of 100-Point Scores Converted Log CS Values for L and M Cones.

100-POINT SCORE	CONE TYPE	KONAN CCT-HD® LOG CS	INNOVA CCT LOG CS	NCI LOG CS
75	L	1.67	1.65	1.63
55	L	1.47	1.35	1.30
75	M	1.65	1.65	1.63
55	M	1.45	1.35	1.30

RESULTS

There was a significant difference in CCT log CS between tests [$F(2,2) = 2181.45$, $P < 0.001$]. **Fig. 2A** shows CVN means (± 2 SE) for L and M cone tests, all of which are well within normal limits using log CS values equivalent to ≥75, and differences were relatively small. Konan L and M cone CS was higher than the Innova and NCI scores ($P < 0.001$), while Innova S cone CS was higher than Konan and NCI scores ($P < 0.03$).

Fig. 2B shows results for protanomalous CVDs on the L cone test and results for deuteranomalous CVDs on the M cone test. All values are at least 5 standard deviations below the normal mean for the abnormal cone for each test (Fig. 2A). This result is below the equivalent 75 cutoff score for the CVDs abnormal cone. As CVNs, CVDs also showed a difference between the three cone CS tests [$F = 585$ (2,2), $P < 0.001$]. Konan cone CS for CVD cone types was higher than the Innova and NCI scores ($P < 0.001$), while their normal cone types were not different ($P > 0.23$).

Each test showed 100% sensitivity for detection of hereditary red-green CVDs as well as type (protan vs. deutan). Each test showed 100% specificity for confirming normal red-green color vision in CVNs.

With CVNs all tests showed 100% specificity for confirming normal L and M cone CS, but Konan CCT-HD® showed 96% specificity in CVNs and 92% in CVDs for S cone CS. That is, regardless of color vision status, the Konan test mis-identifies some observers as tritan deficient, most likely due to the smaller character size used compared to the original CCT and Innova system, which use larger letter sizes for S cone testing near the peak of S cone and L/M cone contrast sensitivity function.[11,14] More importantly, protanomalous CVDs showed significantly lower scores on all three L cone tests compared to M cone scores for the deuteranomalous CVDs on all three M cone tests ($P < 0.001$). If a passing score of <75 is applied equally for protan and deutan CVDs, then this may prove inequitable in occupational and related scenarios.

DISCUSSION

Our findings indicate no significant differences between sensitivity of the three computer-based tests to detect the presence and type of CVD. Using the 100-point scale, all CVDs showed

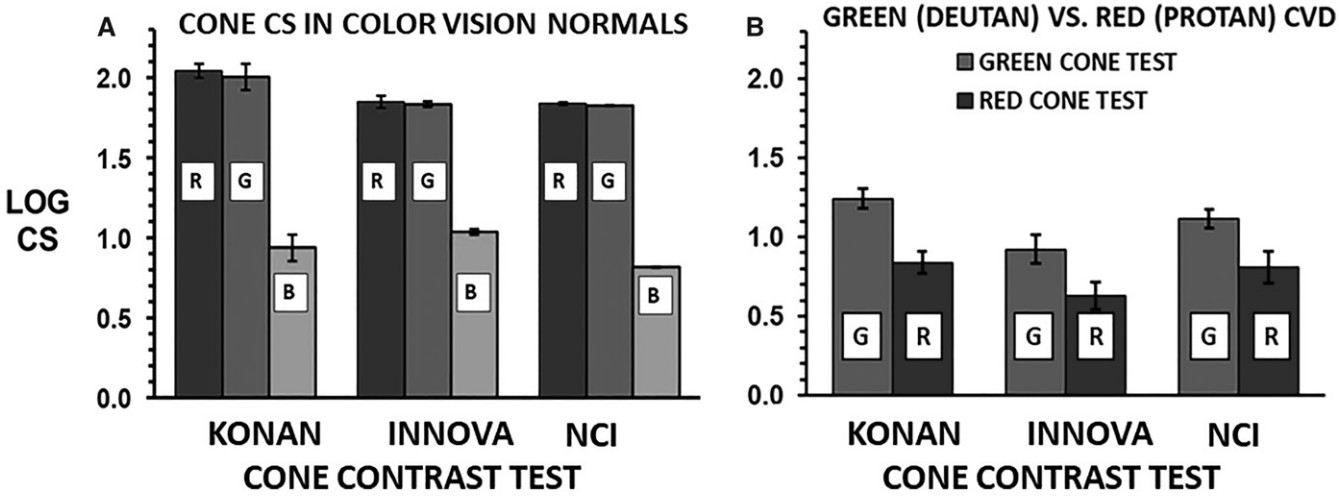

Fig. 2. A) Mean Log CS (± 2 SE) by cone type. The Konan CCT-HD® yields higher log CS for the L and M cones. The NCI yields the lowest threshold for the S cone. B) Comparison of deutan and protan mean log CS (± 2 SE). Across tests, protans scored lower than deutans.

scores <75 in each eye for their anomalous cone type on all three tests, indicating 100% sensitivity. All three tests identified normal red-green color vision in CVN subjects (>75 on L and M cone tests). Based on these criteria, all three tests are suitable for occupational application for detection of hereditary CVD if administered appropriately. For example, inadvertent testing at incorrect distances or selecting a 'distance' setting on the test rather than the 'near' setting would produce larger letters and provide incorrect results.

The Konan CCT-HD® system yielded higher values for L and M cone CS, likely due to its finer gradation in contrast steps and lower contrasts achieved than either the modified Innova CCT or NCI.[10] The version we tested has a larger display and higher luminance (100 cd · m^{-2}) than both the Innova Surface Pro and NCI displays (30–50 cd · m^{-2}). Since the Konan CCT-HD® uses a 4-alternative forced choice discrimination task vs. a 10-alternative forced letter recognition task, improved scores could derive from guessing, but the superior algorithm for threshold determination in the Konan-CCT likely circumvents this. It is conceivable that fatigue and effort level may have influenced our results; however, since all three tests were conducted in one session in random order this is most likely not an issue and would have been revealed as significant differences in CVNs and CVDs, which were not detected. In addition, practice or transference effects are possible, but unlikely given the agreement between sensitivity and specificity, lower protan than deutan scores across all three tests, and the dissimilarity in exact testing procedures. From an operational perspective, the age range used in this study is in line with other studies using subjects of suitable military occupational training age.[18] However, caution should be applied for generalizing the results for a clinical setting due to the young mean age of the study participants.[2]

Overall, each test provides reliable classification of CVN and CVD status with acceptable test repeatability indicated by lack of significant differences between right and left eyes, and excellent sensitivity and specificity with a cutoff which reliably distinguishes between CVDs and CVNs. An important finding of this study is, regardless of test, the lower L cone scores in protan CVDs vs. deutan CVDs. Hence pass/fail criteria which allow for CVDs may be enhanced by using separate cutoffs for protans and deutans.

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