

Simulating Color Vision Deficiencies on Clinical Tests with a Blue Light

Jeffery K. Hovis, OD, PhD, FAAO

Alex Muntz, MSc

Abstract

Teaching color vision testing can be challenging when all (or nearly all) of the students in the class have normal color vision. Colored filters or computer simulation can be used to simulate color vision deficiencies, but both have some drawbacks. As an alternative, we used a blue compact fluorescent lamp to illuminate various clinical color vision tests. The results from 20 students showed that the illumination produced typical responses made by individuals with congenital red-green defects on the Ishihara, Standard Pseudoisochromatic Part 1, Standard Pseudoisochromatic Part 2, and Ishihara Compatible color vision plate tests. Although the majority of errors on the other plate tests were along the red-green axis, some blue-yellow and scotopic errors also occurred. The results on the arrangement tests were more variable with deutan-scotopic defects as the most common patterns. Even though the blue light illumination did not produce responses that are typical of individuals with red-green color vision defects on all color vision tests evaluated, it did provide students a reasonable approximation of their responses and the experience of making decisions based on minimal differences in color.

Key Words: *simulated color vision defects, pseudoisochromatic plate tests, arrangement color vision tests*

Introduction

One of the challenges in teaching clinical techniques is exposing students to both normal and abnormal patient encounters so they have a better appreciation of the nuances and hurdles involved in performing the techniques and interpreting the results prior to entering the clinic. Their experience can be enhanced further if they can actually experience abnormality through simulation. A few examples of simulation techniques are using sector Fresnel prisms mounted on spectacles to simulate noncomitant deviations,¹ goggles designed to simulate various low vision conditions in order to teach empathy for patients,² and training individuals to simulate various medical conditions as part of a practical assessment.³ The general consensus of students participating in the low vision and binocular vision simulations was that the simulations provided a greater understanding of the difficulties faced by patients with these conditions.^{1,2} In addition to greater empathy, the majority of students in the low vision simulation saw the need to offer more comprehensive care for their low vision patients. Students using the noncomitant simulations believed that the learning experience was more effective than performing the procedures on their healthy classmates. Simulating patients for practical examinations was also judged as effective because only one student was able to distinguish between the simulated and actual patients.

Exposing students to patients who have congenital color vision deficiencies in a preclinic course where the students serve as both patient and clinician is difficult. There may be no one in the class who has a color vision defect, or there may be only one student and he or she may not be willing to serve as a demonstration patient for the others. The deficiencies could be simulated using an image processing algorithm such as VisCheck (www.vischeck.com), but this would require one to scan the pages of a given test booklet. Arrangement tests would require one to scan each cap, alter the color, print and then verify that the printed color matched the color on the computer

Dr. Hovis is an Associate Professor at the University of Waterloo School of Optometry and Vision Science in Waterloo, Ontario, Canada. He lectures in visual perception courses, is a clinical instructor in the primary care and binocular vision clinics, and has been working in the area of human color perception for the past 30 years.

Alex Muntz is enrolled in the vision sciences PhD program at the University of Waterloo. His research interests include corneal physiology and contact lenses.

monitor. This would be tedious if the arrangement test was the Farnsworth-Munsell 100 Hue. It is possible to use a colored filter to alter the appearance of the test in order to simulate congenital defects. This technique has been used to simulate color vision changes with aging.^{4,5} Informal conversations with other instructors indicate that they do use filters to simulate color vision defects, but usually restrict the demonstration to one or two tests because both red-green and blue-yellow errors are often produced. We did some preliminary observations with the individual red, blue and green filters from the red/green and red/blue glasses used for binocular vision testing. Although the vanishing test numbers in the Ishihara test did disappear, the transformation numbers were also invisible when viewed through the filters. With other tests, such as the Standard Pseudoisochromatic Part 2 or the Hardy, Rand, Rittler color vision test, it was difficult to see both red-green and blue-yellow test figures, which would result in an indeterminate diagnosis as to the nature of the defect.

Rather than continue to search for a suitable filter, we elected to try a blue light for illuminating the tests in an attempt to find a technique that would simulate primarily red-green defective responses on a variety of tests. This approach was based on Schmidt's report that color-normals make more errors on the pseudoisochromatic plates when the illumination on the test is bluer than the recommended light source.⁶ This report summarizes how effective the blue illumination was in rendering the test colors so that the responses matched the results from a person with a red-green color vision defect. We are unaware of any systematic evaluation of any technique to simulate color vision deficiencies across a variety of tests.

Methods

The criteria for selecting the lamp were that the lamp was readily available in home improvement or hardware stores, relatively inexpensive, could fit into an incandescent lamp desk and did not generate a substantial amount of heat. The latter requirement eliminated the more common filtered incandescent

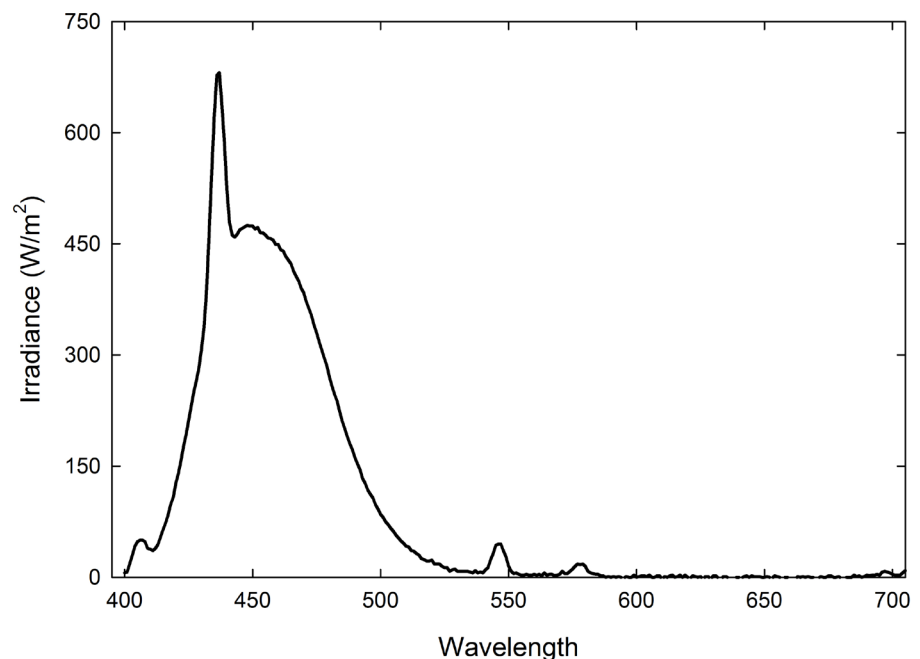
lamps. The bulb selected was a 13-watt blue twisted compact fluorescent light bulb (BPESL 13T/B/CAN, manufactured by Feit Electric, Pico Rivera, Calif.). This lamp is available from a number of suppliers in our area and appears to be easy to obtain in the United States based on a Web search. **Figure 1** shows the spectral irradiance of the lamp in the visible spectrum. The measurements were made using a LI-COR LI-1800 Spectroradiometer (Lincoln NB) with the lamp placed 50 cm straight above the detector. The illumination on the plane 50 cm below the lamp was 36 lux.

The light source was used as part of a teaching laboratory in administering color vision tests. Optometry students administered five different pseudoisochromatic plate tests and three different arrangements tests to each other. The pseudoisochromatic plate tests were the 38-plate edition of the Ishihara

test (Kanehara & Co, Tokyo) (the first 21 screening plates and 4 diagnostic plates), Standard Pseudoisochromatic Part 1 (SPP1) and Part 2 (SPP2) (Igaku-Shoin, Tokyo), the 3rd edition of the Hardy, Rand, Rittler Color Vision Test (HRR) (Richmond Products, Albuquerque, N.M.), and the Pseudoisochromatic Plates Ishihara Compatible (PIPC) (T.L. Waggoner, Gulf Breeze, Fla.). The arrangement tests were the Farnsworth-Munsell D-15 (D15), Lanthony Desaturated D-15 (Desat D15), and the Farnsworth-Munsell 100 Hue (FM100).

The tests were administered using both a daylight lamp (Richmond Products, Albuquerque, N.M.) and the blue lamp, with the daylight condition performed first. Results from 20 individuals will be presented for each test; however, the 20 individuals were not the same across the various tests. All subjects had normal color vision.

Figure 1
Spectral Irradiance of the Blue Compact Fluorescent Light Bulb



Results

Figures 2 and 3 show photographs taken with a Sony Digital Camera (DSC-W270, Fluorescent Day white balance and Auto metering settings) of an Ishihara transformation plate and a D15 arrangement under the blue light.

Table 1 summarizes the results of the plate tests performed under the blue light. All subjects passed the tests under daylight illumination. Nearly all the red-green screening figures were missed on all the tests. More importantly, the majority of students gave the expected response of a person with a red-green color vision defect on both the Ishihara and SPP1 tests under the blue light. These responses included the expected red-green defective responses on the transformation and hidden figures. The other error on these tests was that no figure was visible. Two SPP1 demonstration plates can screen for blue-yellow defects,⁷ but neither of these figures was missed by any student under the blue illumination. Nevertheless, the SPP2, HRR and PIPC test results show that students did miss other blue-yellow or scotopic test figures under the blue lamp. In all three cases, the average number of blue-yellow errors was small, but nearly everyone missed the same SPP2 figure on plate 4 (the second test plate) and one of the figures on the second HRR blue-yellow screening plate. The blue-yellow figures on the PIPC test were least susceptible to errors. The six (30%) individuals who missed at least one of the HRR blue-yellow diagnostic plates also missed one of the blue-yellow screening figures. The four individuals (25%) who missed one of the SPP2 scotopic figures also made at least one error on the blue-yellow test figures along with numerous errors on the red-green figures.

The Ishihara and SPP1 diagnostic plates were more likely to classify the person as a deutan. Most individuals saw the last SPP2 red-green test figure, which would also be suggestive of a deutan defect.⁸ In contrast, the HRR classification was more likely to result in a protan defect if none of the tritan diagnostic plates was missed. Seeing both diagnostic figures was the primary reason for the unclassified results for the Ishihara, SPP1 and PIPC tests, whereas an equal number of protan and deutan

Figure 2
Pictures of an Ishihara Transformation Plate Under the Blue Light and Daylight

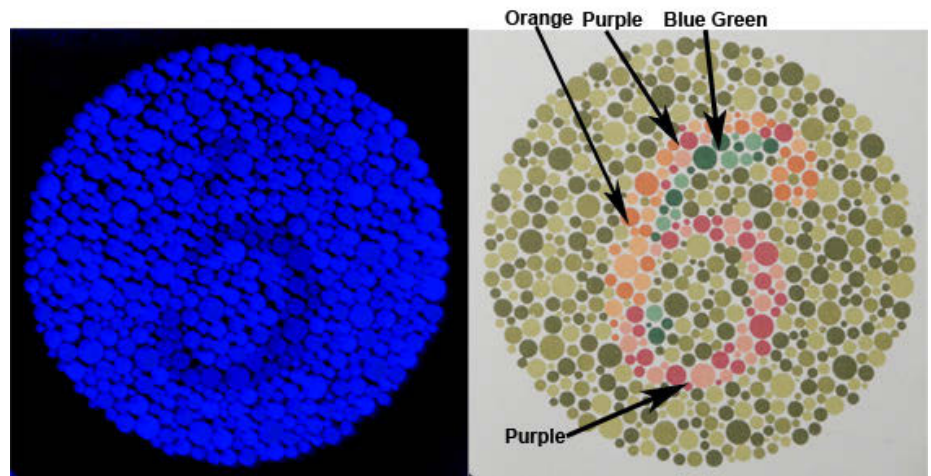


Figure 3
Arrangement of the D15 Under the Blue Light and the Same Arrangement Under Daylight



Table 1
Mean Errors and Classification on the Various Pseudoisochromatic Plate Tests when Performed Under the Blue Light (The percentages in the parentheses represent the number of students who made at least one of the blue-yellow or scotopic errors. None of the students passed the red-green screening portion of any test.)

Test	Mean Red-Green Screening Errors	Percentage Who Gave the Expected Error on the Majority of Transformation or Hidden Plates	Mean Blue-Yellow Screening Errors	Mean Scotopic Screening Errors	Classification Plates
Ishihara	18/21	75%	NA	NA	40% Deutan 5% Protan 35% Unclassified
SPP1	8.35/10	75%	0/2	NA	85% Deutan 5% Protan 10% Unclassified
SPP2	4.9/6	NA	1.25/10 (85%)	0.3/2 (25%)	NA
HRR	5.4/6	NA	1.5/4 (85%)	NA	15% Deutan 40% Protan 30% Mixed Tritan-Red-Green 15% Unclassified
PIPC	14.5/15	NA	0.05/2 (1%)	NA	40% Deutan 60% Unclassified

figures was missed in the unclassified HRR results.

All subjects passed the D15 without error under daylight illumination, whereas visual inspection of the score sheet for the blue light showed a wide range of results. Errors ranged from one minor transposition to six major crossings with an average of 3.2 crossings. The pattern of crossing errors ranged from protan to tritan, with a deutan-scotopic arrangement as the most common pattern. **Figure 4** shows an example of this last arrangement. In order to analyze the nature of the simulated defects quantitatively, the Color Difference Vector Analysis was performed.⁹ The classification of the defect was based on a modification of the red-green dichromats results from Archison et al.¹⁰ **Figure 5** shows the results and the angles used to classify the arrangement. A minor classification indicated that the number of major crossings was <1, which is typically used as the maximum number of major crossings for a pass. The modification to the Archison et al. classification was that the range for the deutan angle extended to -20° instead of -15° . The reason for extending the range to -20° was that the distribution of angles is generally continuous between -3° and 20° with a gap in the distribution between -20° and -25° . The ranges for the scotopic and tritan angles were based on breaks in the data distribution, but the values were consistent with preliminary data from Vingrys and King-Smith and values calculated from Sloan's cases.^{9,11} The arrangement in **Figure 4** is from the subject who had the median angle of the distribution. With the exception of the one result labeled "Other" in **Figure 5**, the S-indices were similar to values found for red-green color defectives and did not fall within the range associated with random arrangements.¹² The one exception had an equal number of red-green and tritan-oriented crossings.

As with the D15, all subjects passed the Desat D15 without error under the daylight illumination, and their results with the blue lamp illumination varied across subjects. Errors ranged from one minor transposition to eight major crossings with an average of 5.4 crossings. **Figure 4** shows the arrangement of the subject who had the median angle

Figure 4
Examples of the Farnsworth and Lanthony D15 Results Under the Blue Light Illumination

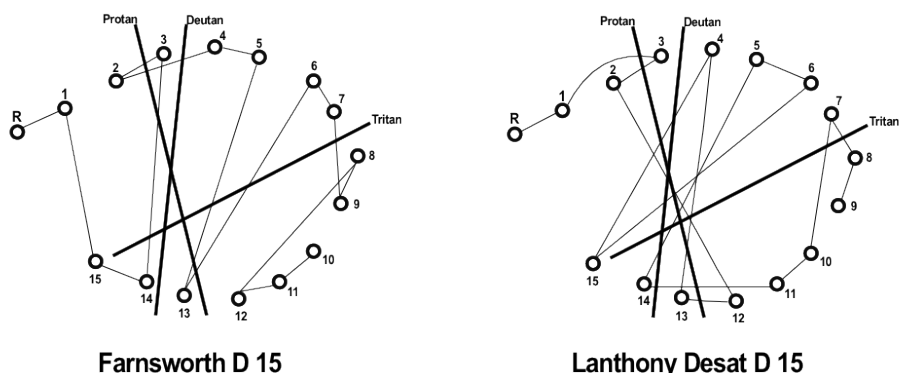
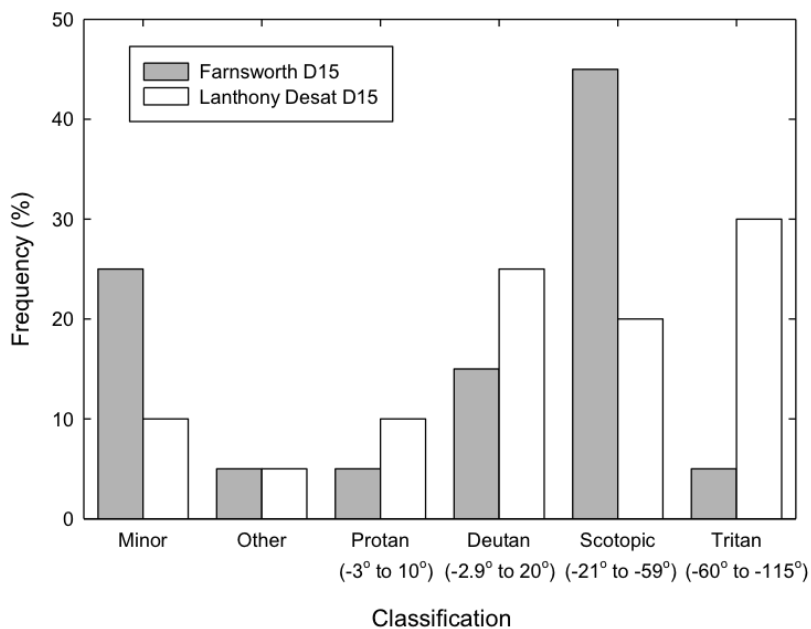


Figure 5
Classification Results for the Farnsworth-Munsell D15 and the Lanthony Desaturated D15 Using the Color Difference Vector Analysis
(The angles in the parentheses are color difference vector values used for the different classifications.)



of the distribution. The Desat D15 was also analyzed with the Color Difference Vector Program using the same range of angles as the D15 for classification purposes. As expected, based on the higher average number of crossings, both the C- and S- indices were higher than the

D15. **Figure 5** shows there was also a slight difference in the distribution of the types of defects, with the majority of angles distributed approximately equally between deutan and tritan instead of a scotopic-deutan pattern.

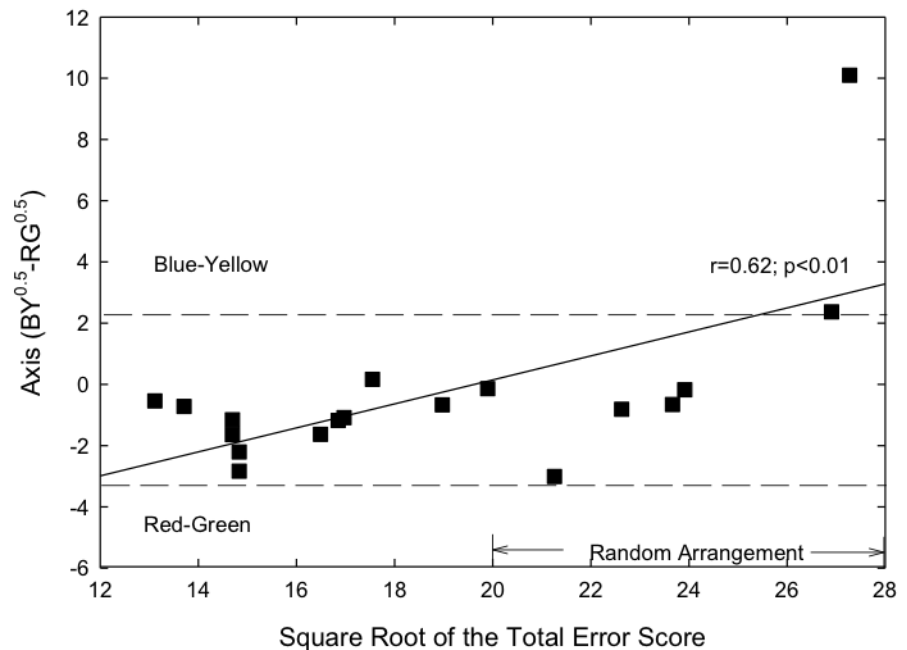
Figure 6 shows the scatter plot of the FM100 square root of the total error score and resulting axis calculated using Smith et al.'s procedure.¹³ The figure includes their tentative criteria for a red-green and blue-yellow defect for patients between age 20 and 29. For comparison, the square root of the total error score under daylight was 4.7 and the error axis was 1.10. Under the blue light, there was an obvious increase in the error score and a shift in the axis for most individuals toward the red-green defect boundary. Nevertheless, the level of difficulty under the blue light was high for some individuals, with 28% of the students having error scores typical of random arrangements.¹⁴ The two extreme error scores also had an error axis indicative of a blue-yellow defect, and these two subjects are primarily responsible for the significant correlation between the error score and axis shown in the plot.

Discussion

The underlying principle of all clinical color vision tests is to incorporate specific color combinations that are near or below threshold for individuals with impaired color discrimination without introducing brightness differences that could be used as secondary information in performing the test. Instead of having a visual system that is unable to distinguish between two different colors, the lamp renders the color difference on the tests so that the difference is below threshold for individuals with normal color vision. Although the color differences could be calculated for each possible color combination and mapped in the respective dichromatic color spaces if the reflective properties of the pigments were known, we can use Figure 2 to illustrate the effect qualitatively.

The background color of the Figure 2 transformation plate is green with a small area of blue-green adjacent to the test figure. The "6" is a combination of purple and orange. For a person with a red-green defect, the green and orange colors appear identical so that the lower left portion of the 6 of would appear broken.¹⁶ For the color-defective person, the purple and blue-green pigments are nearly identical in appearance, but sufficiently different from the green background so that the "broken 6" would appear as the number 5.¹⁶

Figure 6
Relationship Between Farnsworth-Munsell 100 Hue Error Axis and
Square Root of the Total Error Score
(Dashed lines define the color-normal limits for the error axis.)



Under the blue lamp, the difference in color between the orange and green pigments is below threshold, and the purple and blue-green pigments reflect similar amounts of the light but different from the green and orange pigments so that the number 5 is also perceived by a person with normal color vision.

The primary goal of using the blue light was to simulate how difficult color judgments could be on the various clinical tests if the patient has a red-green color vision defect and, at the same time, simulate the type and pattern of errors typical of a person with a red-green color vision defect. This included rendering the transformation and hidden figures as they would be seen by a person with a color vision defect. The blue light used in this demonstration generally meets this goal for several tests. Most of the students gave the expected red-green responses on the Ishihara and SPP1 tests hidden and transformation plates while nearly all the vanishing plates were missed. Nevertheless, the collection of other results demonstrates that the blue lamp would also produce blue-yellow and scotopic errors depending on the test. Most of the blue-

yellow errors occurred on plates where the figure was purple and the background was gray regardless of the test. These types of errors are not surprising because the blue light renders both the gray background and purple test figures nearly the same bluish color because only the short wavelengths are reflected from both pigments. The SPP1 blue-yellow test figures use purple and green as the test and background colors and the Waggoner blue-yellow test plates use a blue-green and green as the test and background colors. Under the blue illumination, the figure colors remained perceptually different from the background for most individuals primarily due to brightness differences so that these plates were rarely missed. The scotopic errors on the SPP2 may reflect individual variability in chromatic discrimination when the color differences are near thresholds for color-normals.

Most of the plate tests classified the defects as deutan, when the classification was possible. This is also expected because the blue light renders the purple figures on the diagnostic plates (missed by deutans) and gray background nearly the same color, whereas the difference

between the pink figures (missed by protans) and the gray background under the blue light remains discernible. The result that both deutan and protan figures were missed or both were seen also occurs in individuals with red-green defects.¹⁵ The result that HRR plates were more likely to give a protan classification is likely related to differences in the pigments used in printing the plates. It would be interesting to determine whether the 4th edition of the HRR, which is visibly different from the 3rd edition, produces similar results.

Both D15 arrangement tests showed a tendency for arrangements in the deutan-scotopic direction with the Desat D15 also showing some tritan arrangements. Although these arrangements do not represent the classical red-green error patterns, they do occur in practice if the number of crossings is less than five on both tests.¹⁰ The higher between-subject variability in the Desat D15 arrangements and corresponding angles calculated using the Color Difference Vector Program has also been reported for congenital red-green color defectives who have less than seven major crossings on the Desat D15.⁹ The FM100 results suggest that the color differences under the blue light may have been too small for the approximately 30% of the students who arranged the caps randomly. For the rest of the individuals who had FM100 error scores below the random range, there was a shift in the error axis toward the red-green direction, but not completely into the red-green color-defective region. The majority of these patterns were oriented in the deutan-scotopic direction, which is between the deutan and tritan error patterns and consistent with the majority of D15 arrangements.

The Ishihara, SPP1, PICP and the D15 worked best with the blue lamp in simulating the responses of individuals with red-green color vision deficiencies. Obviously, the lamp reduces the color difference between the background and figures for the plate tests and the D15 caps. However, the light provides sufficient output in the mid spectral region so that the color difference between the green, blue-green and reds is discernible, whereas the differences between the green and orange colors are not discriminable.

For the D15 caps, the color difference between the blue caps and the purple (cap 15) is reduced more than the color difference with green caps so that the arrangement starts as a deutan pattern for the most individuals. However, the pattern may shift toward a scotopic or tritan arrangement as the student begins to sort the yellow-greens and orange colors. These have a similar hue and brightness to each other under the blue light. This results in a deutan-scotopic arrangement.

Although the blue light does not always give typical red-green results on the D15 tests, the arrangements can be found in practice.¹⁰ The relatively large variability in the patterns was interesting and could arise from at least two factors. The first is the amount of time the students adapted to the blue light illumination. This was not controlled, but it appeared that more than three minutes of adaptation was necessary to minimize the number of blue-yellow errors on the SPP2 and HRR tests and the random arrangements on the FM100. Second, the variability could reflect individual differences in normal color discrimination that become apparent when the color differences are small. Third, it is likely that blue light did produce brightness artifacts and the variability could reflect how the students used this brightness information. This last aspect could also be useful because brightness information is present in everyday tasks for color-defectives and so the testing under the blue light provides students with the experience of performing color-related tasks using brightness information instead of hue. It was interesting to watch the behavior of some of the students as they viewed the tests. Several often tilted the pseudoisochromatic plate booklet back and forth and side to side or held the individual caps close to their eyes in order to help in performing the tests. This type of behavior is sometimes seen with color-defective patients if the testing procedure is not well-controlled.

The demonstration that a blue lamp works reasonably well in simulating red-green defective test results does not preclude using a colored filter instead of a colored light. Figure 1 provides a template for the spectral emittance of a filter-lamp combination that should

produce similar results on the color vision tests. However, the blue lamp eliminates the need for any filter holders on the light fixture or for spectacle-mounted filters. Even without the additional holders, the filter is likely to cost more than the lamp.

One of the issues with either the blue light or filter is that everything in the testing area looks bluish. This is obviously an artificial environment and would not be present in a computer-based simulation. However, the computer simulation will render the colors either yellow or blue, and this raises the issue of whether the test colors actually appear that way to individuals with a red-green defect. The blue light also introduces variability within and across color vision tests without any additional image manipulation. This variability could be an advantage or disadvantage depending on one's perspective in teaching color vision testing. Experience in interpreting less common results can be useful in learning how to evaluate a test.

The blue lamp provides a simple, inexpensive method for simulating color vision deficiencies using common clinical tests. Our data provide some guidance to course instructors as to which tests are more compatible with the blue lamp in simulating typical red-green defective responses and which tests result in atypical and more varied results. Although this illumination does not perfectly simulate red-green color vision deficiencies on all tests, it does provide the students with an appreciation of the small color differences perceived by a person with a congenital red-green defect on the various tests and how they may interpret them. The simulation also provides an appreciation of struggling with a color discrimination task that is so easy for a person with normal color vision to perform.

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