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Comparing Color Vision Testing Using the Farnsworth-Munsell 100-Hue, Ishihara Compatible, and Digital TCV Software

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Abstract

It is crucial that eye care professionals be able to provide quick, accurate, and complete testing of color vision, both to enhance the lives of patients and to satisfy the requirements laid out by industry standards. With the growing popularity of the use of digital equipment in offices, there is a natural progression to digital color vision screening tests, which have the advantage of being fast, inexpensive, and readily portable with automated scoring for greater consistency. Few studies have sought to validate specific digital tests. The aim of this study is to compare two traditionally accepted manual tests for detecting congenital color vision deficiency (CCVD) with analogous digital versions. Thirty-five individuals (11 male, 24 female, mean age 25.1 years) with normal color vision and six individuals (all male, mean age 40.0 years) with congenital red-green deficiency were asked to perform the following four tests for detecting CCVD: Ishihara Compatible Pseudoisochromatic Plate (Ishihara); Waggoner Computerized Color Vision Test by Konan Medical USA (TCV); Farnsworth-Munsell 100-Hue Color Cap Rearrangement Test (100-Hue); and an online version of the Farnworth-Munsell 100-Hue (Online 100-Hue) available for free at color-blindness.com. The administration time for each test was recorded along with test scores. The Ishihara and TCV had sensitivities of 83.3% and 100% and specificities of 100% and 94.3%, respectively. The manual 100-Hue and the online 100-Hue had sensitivities of 66.7% and 83.3% and specificities of 88.6% and 85.7%, respectively. The average test time was 2.3 minutes for the Ishihara and 3.4 minutes for the TCV. The geometric mean completion time for the manual 100-Hue was 15 minutes; for the Online 100-Hue it was 7.5 minutes, thus reducing the test time by 50%. A Bland-Altmann analysis shows that the Online 100-Hue tends to give higher scores than the manual 100-Hue; however, there are several outliers that lead to a wide range and wide variability. Each of the tests included in this study has specific strengths and weaknesses. An understanding of these can aid the clinician in selecting the ideal test for a given situation as well as guide research and development of future digital color vision tests. There are still concerns about consistency and accuracy of digital color tests due to the variations in screens, but so far, results are promising.

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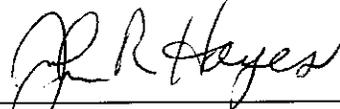
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ABSTRACT

It is crucial that eye care professionals be able to provide quick, accurate, and complete testing of color vision, both to enhance the lives of patients and to satisfy the requirements laid out by industry standards. With the growing popularity of the use of digital equipment in offices, there is a natural progression to digital color vision screening tests, which have the advantage of being fast, inexpensive, and readily portable with automated scoring for greater consistency. Few studies have sought to validate specific digital tests. The aim of this study is to compare two traditionally accepted manual tests for detecting congenital color vision deficiency (CCVD) with analogous digital versions. Thirty-five individuals (11 male, 24 female, mean age 25.1 years) with normal color vision and six individuals (all male, mean age 40.0 years) with congenital red-green deficiency were asked to perform the following four tests for detecting CCVD: Ishihara Compatible Pseudoisochromatic Plate (Ishihara); Waggoner Computerized Color Vision Test by Konan Medical USA (TCV); Farnsworth-Munsell 100-Hue Color Cap Rearrangement Test (100-Hue); and an online version of the Farnworth-Munsell 100-Hue (Online 100-Hue) available for free at color-blindness.com. The administration time for each test was recorded along with test scores. The Ishihara and TCV had sensitivities of 83.3% and 100% and specificities of 100% and 94.3%, respectively. The manual 100-Hue and the online 100-Hue had sensitivities of 66.7% and 83.3% and specificities of 88.6% and 85.7%, respectively. The average test time was 2.3 minutes for the Ishihara and 3.4 minutes for the TCV. The geometric mean completion time for the manual 100-Hue was 15 minutes; for the Online 100-Hue it was 7.5 minutes, thus reducing the test time by 50%. A Bland-Altmann analysis shows that the Online 100-Hue tends to give higher scores than the manual 100-Hue; however, there are several outliers that lead to a wide range and wide variability. Each of the tests included in this study has specific strengths and weaknesses. An understanding of these can aid the clinician in selecting the ideal test for a given situation as well as guide research and development of future digital color vision tests. There are still concerns about consistency and accuracy of digital color tests due to the variations in screens, but so far, results are promising.

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Rachel Murphy

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INTRODUCTION

Congenital color vision deficiency (CCVD) is typically caused by abnormalities of the photopigments within the retina and has the effect of reducing the visibility of part of the spectrum of visible hues. Often colors which appear mismatched to a color-normal individual will look the same to a color deficient individual, causing abnormal color matching and color confusion.[2] Normal color vision is trichromatism, meaning there are three types of

photopigments in the retina. The three types of congenital color vision deficiency (CCVD) indicate how many photoreceptors are abnormally affected: monochromatism, dichromatism, and anomalous trichromatism. CCVD can further be classified by the specific photopigment that is either missing (dichromatism) or deficient (anomalous trichromatism). These classifications are protanopia (L-cone pigment missing), protanomaly (L-cone pigment deficient), deuteranopia (M-cone pigment missing), and deuteranomaly (M-cone pigment deficient). These congenital deficiencies have X-linked inheritance with prevalence as high as 8% of Caucasian males and 0.4% of Caucasian females.[2] A third cone photopigment in the S cone can be deficient or missing, resulting in tritanomaly or tritanopia, but this is extremely rare as a congenital condition and more likely the result of age or pathology, like diabetes.

Image 1.[1] Color spectrums for normal and color deficient individuals.

While CCVD varies in objective severity according to the number of receptors affected, many factors influence subjective severity. This results in overlapping diagnoses, depending on the type and classification, as well as individual differences in gene expression and variations in compensation strategies. Regardless of the true severity, most cope very well, and indeed up to 25% are unaware of their condition until discovered by a routine screening well into adulthood.[3] However, color is becoming an increasingly important aspect to our society with the advent of technology, widespread color offset printing, and the ability to manufacture any color dye very inexpensively. Apart from aesthetics, color is used to convey critical information and provide useful guidance. A few key areas affected by color vision include early learning and education, career options, and workplace safety and performance.[4]

While there does not seem to be an association between presence of abnormal color vision and level of education achieved,[4][5] color is often used in early childhood education. A color deficient child sees their world of color differently than the normal child and this mismatch can lead to frustration and confusion on the part of the color deficient child. In addition, color is one of the earliest concepts taught in school and is often used as an aid in teaching more complex lessons. If this key means of communication is missing for the child, it could appear to be a learning deficiency if the presence of a color deficiency is unknown.[2][6][7]

Career options can also be limited due to CCVD. There are several industries with positions that have stringent requirements for normal color vision such as aviation, maritime, railway, armed services, textile and paint manufacturing, printing and fine art, and electrical

engineering. In these instances, good color vision is critical for safe and efficient operation. Other industries choose screening tests that allow mild color deficient individuals to pass but exclude more severe cases; these include firefighters, police officers, and certain positions in electrical engineering, the armed services, hospital laboratory technicians, and merchant seamen. Other vocations lead to disadvantages but are not officially regulated such as horticulture, cartography, histopathology, and pharmacy.[2] In one study, 30% of people with abnormal color vision said their career choice was affected by their color vision.[3] Domestic life can also be affected by color deficiency in areas such as selecting clothes, picking ripe fruit, choosing decorating materials, and recognizing sunburn.

Road safety has been a large area of debate, both for private and commercial drivers. Ramachandran performed a rather extensive literature review[4] and concluded that CCVD does not appear to be associated with an increased risk of road traffic crashes in a clear majority of studies, although experimental tasks show reduced performance.[8] Reported difficulties with driving are also common. It is speculated that the lack of correspondence between reduced performance in experimental tasks and the incidence of traffic crashes are associated with compensatory behavior.[4]

Unfortunately, despite efforts for well over a century, there remains no universally-accepted treatment for color deficiency. Countless options have been tried, but only a few have shown any promise. In the early 1970's Dr. Zelter[10] [11] designed the X-Chrom lens, a red lens placed over one eye that decreases the amount of light from short and medium wavelengths of the spectrum. This darkens objects that are green and blue for this covered eye to allow for comparison between eyes. A more recent application of filters is the EnChroma lens. These are blue or gray tinted lenses that have a type of "notch filter" to absorb the wavelengths most confusing to color-deficient individuals, allowing for greater separation and discrimination between colors. These filters, whether the X-Chrom or the EnChroma lenses, do allow the patient to pass many of the color screening tests, but they do not correct the underlying cause. There is also a mixed view of how much they actually help with color discrimination as the lenses do not improve the performance on color sorting tests such as the Farnsworth-Munsell 100-Hue.[12] When worn monocularly as instructed, the X-Chrom also decreases depth perception and induces a Pulfrich effect which can reduce safety in many of the applications for which they would be best suited, such as driving.[13]
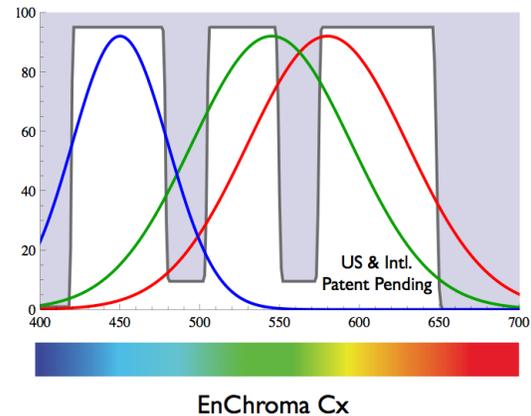
Image 2.[9] Notch filters in the EnChroma lens.

The most recent and promising treatment for color deficiency utilizes gene therapy to replace the missing or abnormal photopigment. In 2009 Drs. Jay and Maureen, scientists at the University of Washington, surgically injected a viral vector and therapeutic transgene into the eyes of color-blind squirrel monkeys. After about 5 months, the monkeys were able to reliably pass a color test.[14] Testing has not yet progressed to humans, but work is underway to develop a vitreal injection that would be safe for use on humans. Human trials are expected in the next couple years according to a 2015 news article on NPR's Shots.[15]

While there are currently no treatments for CCVD, effects can often be minimized with knowledge of the condition.[16] For example, teachers can lessen the reliance on color as a teaching tool. Redundancy can lead to greater safety, and individuals can consciously pay more attention to other non-color cues. It is crucial that eye care professionals be able to provide quick, accurate, and complete testing of color vision, both to enhance the lives of patients and to satisfy the requirements laid out by industry standards.

Traditionally-Accepted Methods for Testing Color Vision

There are three main categories of color vision tests. Pseudoisochromatic plates utilize pass/fail test plates to detect and quantify a color defect. Color cap arrangement tests look at an individual's ability to accurately put a series of color caps in order and analyze the types and quantities of errors that are made. Color matching tests create mixtures of light that will look the same to color deficient individuals but different to color normal individuals. Several tests within each type are currently in use, but this paper specifically addresses the Ishihara pseudoisochromatic plate test and the Farnsworth-Munsell 100-Hue test. The Nagel Anomaloscope, a color matching test, will be discussed briefly.

The Ishihara pseudoisochromatic (PIC) plates is widely considered to be the most effective test for detecting CCVD and is the most commonly used.[2][17] Pseudoisochromatic plate tests are designed using Stilling's principle, which breaks the target and field into small patches and varies the reflectance of the patches so that the luminance difference between the target and field is masked. Thus, color is the only cue available for distinguishing the target from the background. The target and background colors lie on the dichromatic confusion lines, which are the series of colors that a color deficient subject will have difficulty distinguishing.[2] This test requires the use of standardized lighting, typically the C.I.E. standard illuminant C (about 6800 K) in order to maintain these principles.[2][18] This test is best used to detect abnormal color vision, as it has high sensitivity and specificity for this purpose, but it is less reliable for determining type and cannot identify severity. Also, the booklet of plates can wear out over time and the light adds additional expense, as they utilize office space and require maintenance and replacement.
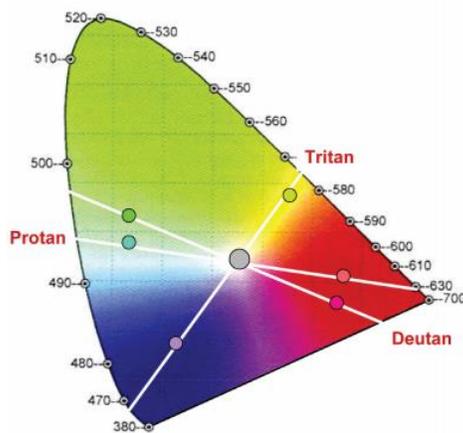
Image 3.[19] Trichromatic Confusion Lines.

The Farnsworth-Munsell 100-Hue (100-Hue) is a color rearrangement test consisting of 85 color caps representing a complete hue circle divided into four 21- or 22-cap sets. The subject is instructed to start with the marked cap and arrange the rest in order according to their color for each of the boxes. The test is scored by calculating and graphing an error score using the numbers on the back of the caps. The error score can divide subjects into groups of superior, average, and poor hue discrimination ability. Training can improve the error score as much as 30%.[20] Errors for normal subjects will be randomly distributed around the hue circle, but for color deficient subjects, the errors will cluster on either side of the hue circle creating an axis of confusion where distortions of the chromaticity plane are present. This axis can then be used to classify the type of color deficiency. This test is also capable of detecting acquired color vision deficiency

and is often used to track disease progression. This test measures color discrimination ability rather than presence or absence of a defect, and there can be a wide range of abilities even among color normal individuals. In color deficient individuals, it indicates ability to compensate for a defect. As such, there is no direct correlation between severity of a color defect and the error score on the 100-Hue.[20][21] The main uses of the 100-Hue are to demonstrate excellent color vision for certain vocations and to track the progression of diseases that lead to acquired color vision loss. Performance is influenced by the illumination used and test administration technique, as well as the skill, comprehension, and motivation of the subject.[21] The largest draw-back to the 100-Hue is the time it takes to score the classic analog version of the test and the difficulty in determining an axis of confusion on some of the more ambiguous results.

A third type of color test involves Rayleigh color matching, most commonly in the form of the Nagel or similar anomaloscope. This is rarely used in a clinical setting, but is considered the gold standard for research purposes.[2] The instrument consists of a circle divided into an upper and a lower half. The top half of the circle consists of a mixture of 670 nm red and 549 nm green light with a knob that changes the mixture from 1 to 75 scale units. A reading of 1 is pure green and a reading of 75 is pure red. The lower half of the circle consists of a pure 590 nm yellow light that can be adjusted in brightness with another knob. Using the anomaloscope is a two-step process. First, subjects are asked to make several free matches by turning the knobs for both the upper and the lower halves. Then the full range of possible matches is determined using the free matches as a guide. The examiner changes the upper red-green mixture and the subject is asked if a match can be made by changing the brightness of the yellow. Normal subjects can create a match with the upper field set at 44 ± 2.5 scale units. Matches outside this are considered abnormal. Protans can create a match with a greater amount of red present in the upper field, and deutans can create a match with a greater amount of green.[23] This is the only test discussed in this paper that is capable of quantifiably separating dichromats from anomalous trichromats. The Nagel Anomaloscope requires careful calibration and maintenance and each machine must be calibrated and used under identical conditions, including control of ambient temperature.[24][25] Later models, like the Oculus anomaloscope, may require less maintenance, and allow for testing of blue-yellow (tritan) defects using the Mooreland criterion.
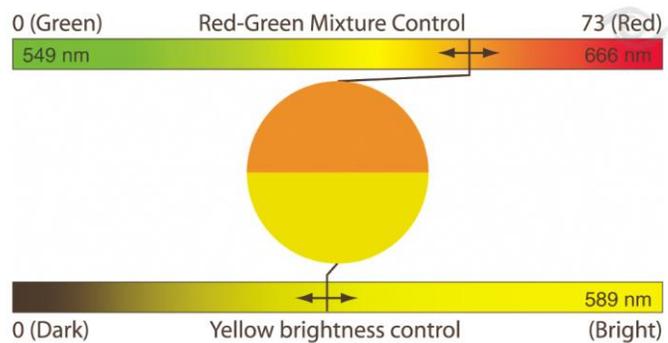
Source: Schiefer, Wilhelm, Hart (Eds.). Clinical Neuro-Ophthalmology - A Practical Guide. Springer, Berlin/Heidelberg/New York, 2007.

Image 4.[22] Target of the Nagel Anomaloscope.

The Ideal Test for Color Vision

A need exists for an efficient diagnostic method for testing color vision to integrate seamlessly with current equipment commonly found in a clinical setting. With the growing popularity of the use of digital equipment in offices, there is a natural progression to the convenience of having a color vision screening test in digital form, as indeed a few companies are already offering.[26][27] Digital color vision tests have the advantage of being fast, inexpensive, and readily portable with automated scoring. Currently, a battery of tests must be used in order to gain a full understanding of an individual's CCVD to include diagnosis and severity.[17] The ideal

color vision test would allow for quick detection, followed by accurate diagnosis, and finally give an indication of severity. It also needs to have universal criterion to reduce variation among clinicians. Digital color tests are perfectly positioned to meet this need.

Electronic methods as a whole have been distrusted due to the variation in brightness and contrast between screens in favor of the well-validated manual tests, but few studies have sought to validate specific tests to either confirm or disprove this general feeling. The aim of this study is to compare two traditionally accepted manual tests for detecting congenital color vision deficiency (CCVD) with analogous digital versions.

METHODS

Subjects

This study was carried out at the Vision Performance Institute at Pacific University. Thirty-five individuals (11 male and 24 female, mean age 25.1 years) with normal color vision and six individuals (all male, mean age 40.0 years) with congenital red-green deficiency were recruited from Pacific University and the surrounding community. Participants had to be over the age of 12. Excluded from this study were individuals with operable cataracts or acquired ocular diseases that may affect color vision (such as diabetic retinopathy or optic neuritis, among other, more rare conditions). These eye diseases can create blue-yellow color vision defects, in the case of diabetic retinopathy or optic neuritis, or otherwise alter color perception. Likewise, participants could not be taking any medications that affect color vision, such as thiazide diuretics for high blood pressure. Appendix C contains a non-exhaustive list of diseases and medications that were excluded. Pregnant women were not excluded, as testing color vision is non-invasive, though no pregnant women participated. None of the subjects had a history of photosensitive epilepsy, and no tinted lenses were permitted. Institutional Review Board approval and informed consent was obtained for all subjects.

Procedure

All the examinations were made by the same examiner using the same procedure and the same viewing conditions. A brief history was collected to include self-reported vision of 20/40 or better at near, absence of exclusionary criteria, previous diagnosis of congenital color vision deficiency (CCVD), and family history of CCVD. Participants were encouraged to wear their habitual near correction. Subjects then performed four tests for detecting CCVD in randomized order in a dark room. All tests were performed binocularly.

A Latin Square was used to determine the randomized order prior to testing. A Samsung Series 5 14" Notebook laptop running Windows 8 was used to administer the two digital tests. Prior to testing, the Display Color Calibration program provided by the computer was used to calibrate the brightness and contrast of the screen. The administration time for each test was recorded along with test scores. Appendix A contains a printout of the exact procedure followed including instructions sets for each test. Appendix B contains the subject recording for used to collect and record all data.

Tests and Scoring

Ishihara Compatible Pseudoisochromatic Plate (24-plate edition)

Image 5.[28] Ishihara Test Plate Number 1.

Plates 1 through 17 were presented sequentially under Richmond Products' Daylight Illuminator (near illuminant C, 6280 K). This test must be administered under specialty lighting to maintain the validity of the test.[2] [18] The subject was instructed to call out the number seen on the plate or to state that they do not see a number; only answers given within three seconds were recorded.
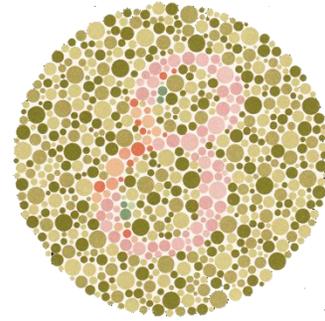
A score of 13 or more correct on plates 1-15 was regarded as normal color vision.[2] For those scoring below 13 out of 15 correct, plates 16 and 17 were used to classify the failed subjects as protan or deutan deficiency as well as to determine moderate (both digits visible on both plates) or strong (only one digit visible on at least one plate). Misreadings, which are common among normal subjects but are not the expected response of a color-deficient subject, were not regarded as mistakes.[29] [30] [31] Based on this criterion, previous studies have found the sensitivity of the Ishihara test to be 99% and the specificity 94%.[29] [32]

Waggoner Computerized Color Vision Test software by Konan Medical USA

The Waggoner Computerized Color Vision Test software (abbreviated TCV for clarity in this paper) adult diagnostic testing program from www.TestingColorVision.com[33] was designed by Terrence L. Waggoner, OD. It is currently available commercially through Konan Medical USA. The TCV is to be used on a color-calibrated monitor illuminated with a 6500 K lighting environment ("Terms-Use"). According to the manufacturer, conditions other than this are most likely to result in false negatives, especially for low-severity color deficiencies; false positives are unlikely. A current color calibration is recommended for optimized results. No studies were found validating this test.

Test plates are programmed to flash for 2 seconds, then replaced by a list of 9 answers from which to select (8 number choices and one "nothing"). There are 30 diagnostic plates presented. If this section is passed, the software ends the testing and presents a simplified scoring certificate with a diagnosis of normal along with the total number of plates correct out of 30 total plates. If this section is not passed, the software immediately begins further tests to quantify the defect. This section consists of three sets: 32 plates for Protan, 32 plates for Deutan, and 12 plates for Tritan. At the end of the test, a score sheet is presented with the number of plates correct out of total plates for each of the four sections (diagnostic, protan,
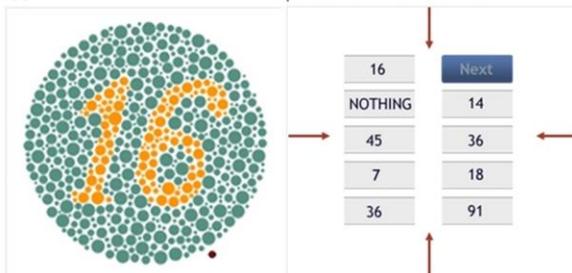
Image 6.[34] Waggoner Computerized Color Vision Test.

deutan, and tritan) with labels of pass, mild, moderate, or severe. The exact algorithm used to determine pass/fail and severity is not known to the authors; however, the cutoff for pass/fail on the diagnostic portion appears to be 25/30 (the lowest pass in our study was 26/30 and the highest fail was 25/30). On several occasions, more than one diagnosis was present; for example, the

software might label a subject as a moderate protan and a severe deutan. In these instances, the most severe diagnosis was used for comparison with the other tests.

Farnsworth-Munsell 100-Hue Color Cap Rearrangement Test

The Farnsworth-Munsell 100-Hue Color Cap Rearrangement Test (100-Hue) was also administered under the Richmond Products' Daylight Illuminator.[36][37] Subjects were instructed to rearrange the color caps in the four boxes in order according to their color. The boxes were always presented in order beginning with box 1 and ending with box 4. No time limit was set.

Cap order was recorded and total error score (TES) was calculated using the excel program "Farnsworth 100 Hue MS-Excel Template for Scoring" published by Richmond Products. Pass/fail was based on a TES outside of the 95th percentile of the age-matched norms found by Kinnear and Sahraie.[38] Failing scores were further classified as protanomaly or deuteranomaly using the axis of the largest cap error.[39][40] Axes falling outside the expected criteria were classified as a tritanomaly.

Image 7.[35] Farnsworth-Munsell 100-Hue.

Online Farnworth-Munsell 100-Hue

An online version of the Farnworth-Munsell 100-Hue (Online 100-Hue), available for free at www.color-blindness.com,[42] was selected as an example of an online version of the 100-Hue. Color-blindness.com is a free informational website hosted by a color deficient individual who wanted to understand his condition better and help others to do the same. The author has created several online versions of color tests. No studies were found validating this test.
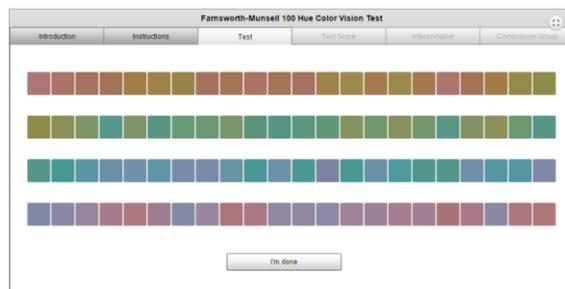
Image 8.[41] Online Farnsworth-Munsell 100-Hue.

The test consists of four rows of colored squares. Subjects were instructed to drag and drop the color squares to arrange them in order according to their color. Squares can only be moved back and forth along their own row, thus mimicking the cap sets of the 100-Hue. When finished, the program gives a total error score and graph of the subject's performance. Categorization was based on the same criteria as the manual 100-Hue rather than relying on the algorithm of the program, as this algorithm was unknown to the authors.

Data Analysis

Completion times for each test were analyzed using Analysis of Variance on SPSS software (Version 19, IBM Inc.). The results of the two digital versions were compared to the results of the manual versions. Sensitivity and specificity for each test were calculated using previous diagnosis of a color deficiency as the standard for comparison. Due to the small sample size, test analysis was based on predictability of the presence of any type of color vision rather than broken down into the specific type and severity.

RESULTS

Each of the 41 subjects performed all four of the color vision tests. Raw data for the six subjects with a previous diagnosis of a color vision deficiency can be seen in Table 1. The Ishihara had no false positives with a specificity of 100%, but it did not fail one color deficient subject resulting in one false negative. The Testing Color Vision program had a sensitivity of 100%, but had two false positives. The Farnsworth-Munsell 100-Hue (100-Hue) had four false positives and two false negatives. The Online 100-Hue had five false positives and one false negative. Table 2 shows the sensitivities and specificities for each of the four tests.

The average test time was 2.3 minutes for the Ishihara and 3.4 minutes for the TCV. The geometric mean completion time for the manual 100-Hue was 15 minutes; for the Online 100-Hue it was 7.5 minutes. Thus, the Online 100-Hue reduced the time of the test by 50%. All times were significantly different from each other with non-overlapping 84% confidence intervals as shown in Figure 1.

A Bland-Altmann analysis was conducted to compare the total error scores of the manual 100-Hue to that of the Online 100-Hue (Figure 2). The chart shows that the Online 100-Hue tends to give higher scores than the manual 100-Hue as scores are clustered between zero and 50. However, there are several outliers that lead to a wide range and wide variability.

To further break down the results of the Testing Color Vision program, Table 3 shows the results of the three diagnostic programs that are triggered once the subject fails the 29-plate screening test. Eight subjects failed the screening test and went on to perform the more in-depth tests.

Based on the performance of the Ishihara, all color deficient subjects were deuteranomalous, which is the most common color deficiency. Of these six subjects, the TCV incorrectly diagnosed three of the known color deficient subjects as protanomalous; the 100-Hue incorrectly diagnosed two subjects as protanomalous; and the Online 100-Hue incorrectly diagnosed one subject as tritanomalous. Tables 4 and 5 compare the diagnostic outcome of the TCV program to the Ishihara and Farnsworth-Munsell 100-Hue respectively. Tables 6 and 7 do the same for the online version of the Farnsworth-Munsell 100-Hue.

DISCUSSION

This study is limited by its use of self-reported data. The anomaloscope is considered the gold standard for color testing in research settings, although this instrument was not included in this study as the authors set out originally to compare clinical methods for color vision testing. The Nagel and similar anomaloscopes are rarely found in use outside of the laboratory. Another test that might have been included is the American Optical Company Hardy, Rand, and Rittler (HRR) pseudoisochromatic plate test. This test includes a severity scale and is capable of testing for tritan defects in addition to protan and deutan defects. In this sense, it is quite similar to the TCV program used in this study.

Another limitation to this study is the small number of color-deficient subjects included in this study. Subjects were recruited from Pacific University College of Optometry and the

surrounding community. The percentage of color-deficient subjects is representative of the prevalence of color deficiency among the Caucasian population, and the authors struggled to recruit larger numbers of color-deficient subjects.

The main object of this study was to determine whether digital versions of testing for color vision are potential options for use in clinic, specifically looking at the TCV program available from www.TestingColorVision.com[43] and the Online 100-Hue available at www.color-blindness.com. Each of the tests included in this study has specific strengths and weaknesses. An understanding of these can aid the clinician in selecting the ideal test for a given situation as well as guide research and development of future digital color vision tests.

The Farnsworth-Munsell 100-Hue is an example of a color cap rearrangement test. The main strength of the 100-Hue is in determining color discrimination ability, whether in a color-normal or a color-deficient individual. Scores can be divided into superior, average, low, and severe. Dichromats tend to be more severe than anomalous trichromats, but performance, especially among anomalous trichromats, can be quite varied. Ultimately, the error score cannot reliably be used to distinguish between dichromats and anomalous trichromats, and up to half of anomalous trichromats may show an error score of less than 100. It is also common to lack an axis of confusion making diagnosis difficult.[21] Vingrys found that the ability to correctly identify deuteranomaly was 26% with 38% being misclassified as protanomalous.[40] This was improved to 71% if the failure criterion was set at a score of 100 with overall misclassifications at 13%. Due to these variables, the 100-hue is not considered to be an accurate screening test for CCVD.[20][40] Additional drawbacks to this test include the time it takes to administer and score and the reliance on attention and motivation of the patient. Currently, the 100-Hue is most often used to prove excellent color vision on a yearly basis for industries that require superior color sensitivity, such as textile, gemology, and paints. Training or a vocation that utilizes continuous color matching can improve the error score by as much as 30%.[20]

The online version of the 100-Hue in this study addresses several of the drawbacks to the manual version. The administration time was cut in half and the scoring instantaneous. While most online versions automatically calculate the axis of confusion, the results of the built-in algorithm for the one used in this study were not relied upon for data analysis. The author's general sense was that doing so would have increased the number of false positives, but exact data were not determined. In addition, many scores were classified as undefined for the built-in algorithm, so these would still have to be manually assessed. It is entirely likely that an accurate algorithm could be created that out-performs even the traditional 100-Hue and improves the accuracy and ease of making a diagnosis. Another advantage is that it takes the subjective interpretation out, which can allow for greater consistency. Unfortunately, the Bland-Altmann comparison of the Online 100-Hue to the manual 100-Hue shows a range as wide as the variability indicating that it is a very poor comparison to the performance on the traditional 100-Hue. As an example, one subject had a perfect score on the manual test and a total error score of 144 on the online version. Another subject had a perfect score on the online version but a score of 120 on the manual version. Neither subject was found to be color deficient by the Ishihara or TCV and neither had a positive family history. This variability is concerning. On the other hand, the variability was reduced considerably when the color deficient subjects were removed from the data (Figure 3). If this test is used to prove excellent color vision rather than to diagnose color deficient patients as the 100-Hue is typically used, an online version might be an acceptable alternative. Under these circumstances, patients are likely to be highly motivated

which may reduce some of the variability. Ultimately, the algorithms may be improved upon, but many of the variables that hinder the manual 100-Hue apply to the online as well, including a large reliance on attention and motivation, a significantly longer administration time than the pseudoisochromatic plates, poor results for use as a screening test, and difficulty determining the best way to score atypical results.

Pseudoisochromatic plates are superior to the 100-Hue as a screening test. The sensitivities and specificities are very high for the Ishihara. The difficulty with scoring and classification inherent in the Farnsworth-Munsell 100-Hue, both manual and digital, are not present, and scoring is not time-consuming. Certain plates are susceptible to misreading, and this must be taken into account when scoring the test,[29][30][31] but otherwise scoring is very straight-forward. The main drawback of the Ishihara is that it does not give a clear indication of severity. Accurately diagnosing protans versus deutans can be unreliable as well, although if patients are asked to compare brightness on the diagnostic plates, accuracy may be as high as 94%.[2] Also, very mild anomalous protans and deutans may pass the Ishihara.[17]

Digital pseudoisochromatic plate tests, such as the TCV software program included in this study, are quite promising. Though the TCV had a statistically significant longer test administration time (p<0.001), the effect size was 1.4 minutes. The greatest advantage of a computerized test is that it is self-run and self-scored once instructions have been given. The Ishihara requires the presence of an administrator throughout the testing period to turn the pages and record the answers, and then the test must be hand scored. Thus, the actual time required of a doctor or technician is quite comparable, if not less for the TCV program. In addition, the Ishihara requires the use of special lighting which adds extra expense, upkeep, and desk space. However, the TCV program has flaws as well. The TCV program gives the number of plates missed and a diagnosis for each category, and most color-deficient individuals missed plates in both the protanomaly and the deuteranomaly categories. Four of the six known color deficient subjects scored were classified as having the same severity rating for both protanomaly and deuteranomaly. The ultimate diagnosis was based on the category that had the most missed plates, but in all color deficient subjects, these numbers were fairly close (average difference of 3 plates between the two categories), making the final diagnosis weak. In the one case that had a difference of 10 plates, the TCV program classified the subjects as a protan when the Ishihara indicated the subject to be a deutan. The TCV software does include a Farnsworth D-15 test, which may aid in the separation of severe protans from deutans, but this was not included in the study. This indicates that the TCV program currently is acceptable as a screening test for color deficiency in general, but needs to be further analyzed to create a larger and more accurate gap between the performances of a protan versus a deutan in order to accurately diagnose the type of deficiency. Further investigation into the reliability of the severity diagnosis is also needed, but was beyond the scope of this study.

Ultimately, digital color vision testing using pseudoisochromatic plates appears to be a potentially valid method for screening as our study showed that those who had a color deficiency did fail the TCV test. It is not recommended for unregistered versions of color vision tests to be used in clinical applications, and any published product needs to be individually tested and validated. There is a commercially available 100-Hue studied by Ghose and associates in 2014[44] that was unknown to the authors at the time of this study that would have been a better option due to the greater likelihood of being consistent and available long-term. Random, free tests are not acceptable for clinical use beyond outside-clinic screening purposes,

but published programs such as the TCV may have a significant role in the coming years with proper validation. As with any diagnostic test, each version must be individually validated and algorithms should be designed and enhanced using performance on each plate to find the best set of plates to present and to further separate the diagnosis of protanomaly versus deuteranomaly. An equivalent of the study by Birch[32] determining the efficiencies of each individual plate in the Ishihara would give greater guidance in altering the test plate sequence for greatest accuracy in the TCV test.

As we move in this direction, a few other concerns for digital color testing must be addressed. What role does the brightness and contrast of screens play in digital color testing? Studies addressing this were performed in the early 1990s,[45] [46] but technology has changed quite a bit in 20 years. Does the calibration of a computer screen change the validity of a test? Is a native color calibration program adequate for setting up the parameters of a screen for use with color testing? In addition to these questions concerning the screen, the screens can create after-images that could potentially interfere with subsequent test plates. These are valid issues and concerns, but ultimately trials must be conducted to determine if they play a role significant enough to discontinue the use of digital color tests or to relegate it to use as an initial screening test only.

CONCLUSION

Digital color vision tests are shorter and easier to administer, allow for automated scoring, and create consistency across testing environments. They are also cheaper to manufacture and maintain, and do not take up as much desk or storage space in the office compared with "hardware" tests and special lighting. With the health industry adapting electronic health records and equipment becoming increasingly digital, it is an economical and logical transition to introduce digital color vision tests. There are still concerns about consistency and accuracy due to the variations in screens, but so far, results are promising. The greatest challenge will be in developing the ideal set of test plates and algorithms to allow for the most ideal test set. This is likely to include more than one type of color test depending upon the application.

Ultimately, the usefulness of a color vision test depends upon the reason for testing, such as the testing of color vision with regards to qualifying for a particular vocation. In these instances, the color vision test must be selected based on a pre-determined industry standard built upon the color vision needs of the particular application. Each of the tests currently used in clinical practice have specific strengths and weaknesses. Understanding these allows the clinician to select a certain test for a specific application. It will also allow for the design of better tests and more accurate algorithms as digital versions become more widespread.

Disclosures
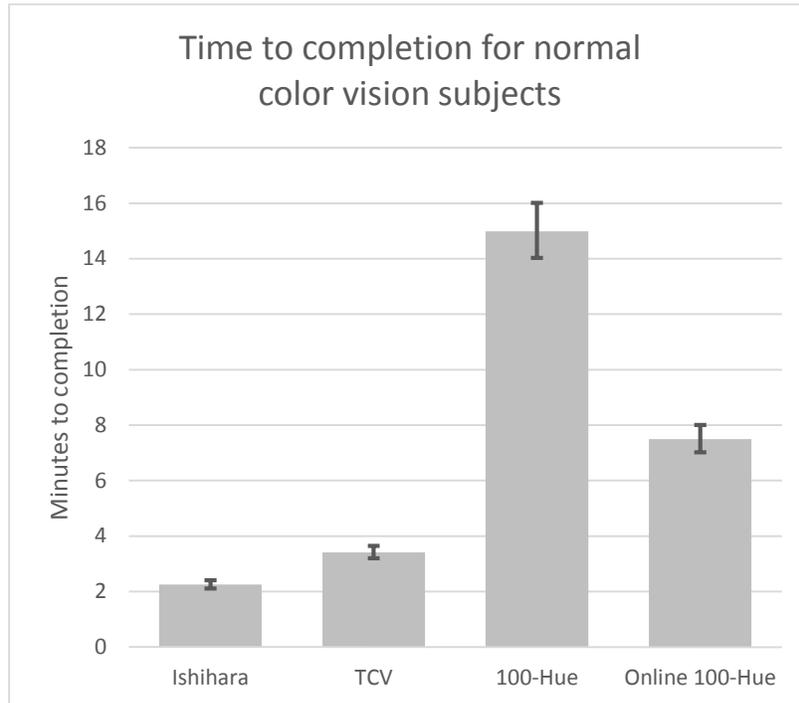
Figure 1. Mean time taken to complete each task for color normal subjects. Error bars show the 84% confidence intervals.
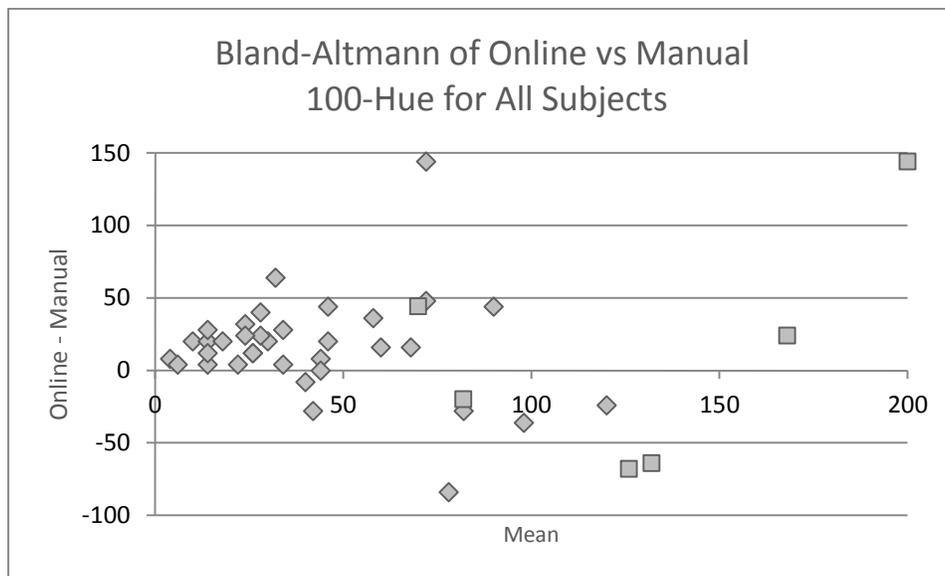
Figure 2. Bland-Altmann comparison of the Online Farnsworth-Munsell 100-Hue total error scores with that of the manual Farnsworth-Munsell 100-Hue for all subjects. Diamonds indicate color normal subjects and squares indicate color deficient subjects.
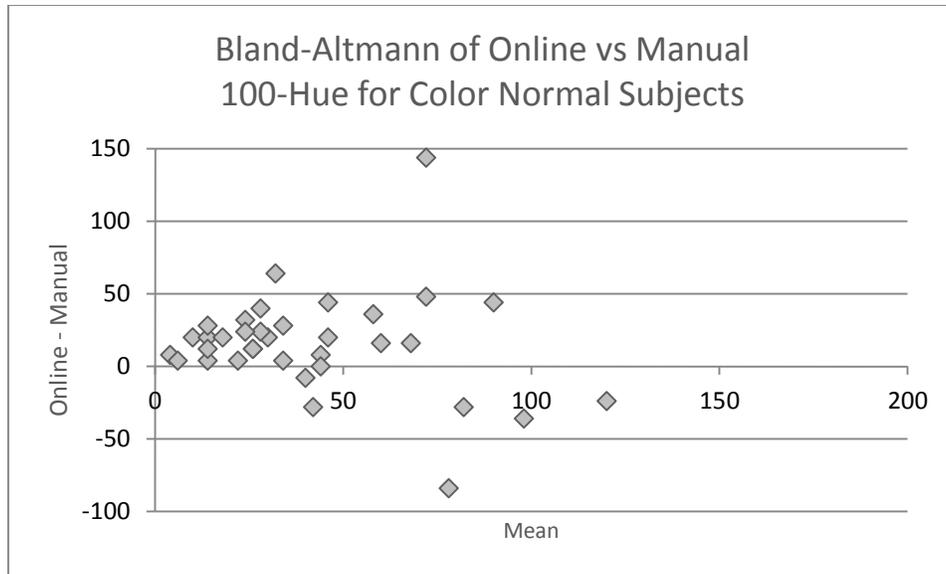
Figure 3. Bland-Altmann comparison of the Online Farnsworth-Munsell 100-Hue total error scores with that of the manual Farnsworth-Munsell 100-Hue for the color normal subjects.

TABLES

Table 1: Raw data for the six male subjects with a previous diagnosis of color vision deficiency.

Subject	Age	Ishihara # Correct (15)	TCV # Correct (29)	100-Hue Error Score	Online 100-Hue Error Score
s09	67	2	2	128	272
s11	49	1	1	92	72
s28	51	1	0	156	180
s31	26	5	2	160	92
s38	16	1	0	48	92
s41	31	13	12	164	100

Table 2: Summary of the results of the 4 color tests when compared to a previous diagnosis of color deficiency.

Test	Sensitivity	Specificity
Ishihara	83.3%	100%
TCV	100%	94.3%
100-Hue	66.7%	88.6%
Online 100-Hue	83.3%	85.7%

Table 3: Raw data for the Testing Color Vision program of subjects who failed the initial screening program. Results show the number of plates correct and severity assigned by the software for each diagnostic set. The total number of plates are shown in parentheses.

Subject	Screening (29)	Protan (32)	Protan Diagnosis	Deutan (32)	Deutan Diagnosis	Tritan (12)	Tritan Diagnosis
s09	2	0	Severe	3	Severe	7	Mild
s11	1	0	Severe	10	Moderate	11	Pass
s16	19	27	Mild	28	Pass	11	Pass
s20	25	27	Mild	26	Mild	12	Pass
s28	0	0	Severe	0	Severe	11	Pass
s31	2	9	Moderate	5	Moderate	12	Pass
s38	0	2	Severe	5	Moderate	12	Pass
s41	12	20	Mild	18	Mild	12	Pass

Table 4: Frequency Distribution of TCV and Ishihara.

Ishihara Results	TCV Results			
	Normal	Protan	Deutan	Tritan
Normal	33	3	2	0
Protan	0	0	0	0
Deutan	0	3	2	0
Tritan	0	0	0	0

Table 6: Frequency Distribution of Online 100-Hue and Ishihara.

Ishihara Results	Online 100-Hue Results			
	Normal	Protan	Deutan	Tritan
Normal	25	0	4	0
Protan	0	0	0	0
Deutan	1	0	4	0
Tritan	0	0	0	0

Table 5: Frequency Distribution of TCV and manual 100-Hue.

100-Hue Results	TCV Results			
	Normal	Protan	Deutan	Tritan
Normal	28	2	3	0
Protan	0	2	1	0
Deutan	2	0	2	0
Tritan	3	0	0	0

Table 7: Frequency Distribution of Online 100-Hue and manual 100-Hue.

100-Hue Results	Online 100-Hue Results			
	Normal	Protan	Deutan	Tritan
Normal	24	0	5	3
Protan	1	0	1	1
Deutan	0	0	3	1
Tritan	1	0	1	1

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APPENDIX A

Examiner Protocol
1. Greet the patient. Fill out paperwork:
    a. Participant Contact Info
    b. Informed Consent
2. Explain the experiment and ask if there are any questions.
3. Seat the subject comfortably and fill out the Subject Recording Form.
    a. Have subject wear habitual correction
4. Determine the patient's testing order and perform each task according to the guidelines below.

Ishihara Compatible Pseudoisochromatic Plate Color Vision Test, 24 plate edition.
1. Seat the subject comfortably in front of a desk.
2. Set the Richmond Products' Daylight Illuminator in front of the subject and turn it on.
    a. The stage should be 30 inches from the subject and tilted so that the plane of the paper is at a right angle to the line of sight.
3. This test should be performed in a dark room for consistency.
4. Explain the test to the subject.

"This task will take about 5-10 minutes. It will be administered under the recommended full-spectrum illumination using this light. The test consists of a book of 17 plates in which you will be asked to identify a number presented on the plate. Some plates may not have a number, and if you do not see a number, please state, "I do not see a number." You must respond within 3 seconds in order to have your answer counted. Do you have any questions?"

4. Note the time.
5. Set the book on the stage and open the front cover to the first example plate.
6. Ask the subject, "Please call out the number you see."
    a. The subject must respond within 3 seconds in order to get credit for the plate.
7. Record the number that the subject said on the "Subject Recording Sheet"
    a. If the subject cannot see a number, or does not respond within 3 seconds, record an "X."
8. Turn the page to the next plate and repeat for all 17 plates.
9. Record the elapsed time for the test on the recording sheet.

Testing Color Vision software version of the Ishihara Pseudoisochromatic Plate Test
1. Seat the subject comfortably in front of a computer at a desk in a dark room.
    a. Ensure a mouse is connected to the computer.
    b. The screen should be 30 inches from the subject and viewed at a 90 degree angle.
2. Click on the icon for TCV (ensure the CD is in the CD drive).
3. Click on Adult Diagnostic Testing
4. Click on Next
5. Enter the Subject Number as the User Name.
6. Explain the test to the subject.

"This task will take about 5-10 minutes. You will see a test plate made up of dots with a number on it. The test plate number will appear for TWO seconds. Next you will see a list of NINE answers to select from. Please click on the number that you saw. If you did not see a number, click "NOTHING." After selecting your answer, click on next to continue to the next test plate. Do you have any questions?"

8. Note the time.
9. Have the subject click the start button when they are ready to begin.
10. Record the subject's score on the Subject Recording Sheet
11. Record the elapsed time on the Subject Recording Sheet.
12. Click Save Certificate and Exit
13. Save results under subject's ID in the desktop folder "TCV"

Farnsworth-Munsell 100-Hue Color Cap Arrangement Test
1. Seat the subject comfortably in front of a desk.
2. Set the Richmond Products' Daylight Illuminator in front of the subject and turn it on.
   a. The stage should be 30 inches from the subject.
   b. Lighting should be from 90 degrees above and viewing angle should be 60 degrees.
3. This test should be performed in a dark room for consistency.
4. Explain the test to the subject.
"This task will take about 15 minutes. The object of the test is to arrange the caps in order according to color. Begin with the cap with a white dot on it. Please use the magnetic wand to drag the caps into place so they form a regular color series beginning with the first cap. It should take you about 2 minutes per tray, but accuracy is more important than speed. There is no time limit. Try to do your best. Do you have any questions?"
5. Note the time.
5. Ensure the first tray is randomized and set it on the stage.
6. Have the patient arrange the caps in color order.
7. Flip the tray over and record the numbers in order on the recording sheet.
8. Repeat for the next 3 trays, in order.
9. Record the elapsed time for the test on the recording sheet.

Online Farnsworth-Munsell 100-Hue Color Cap Arrangement Test
1. Seat the subject comfortably in front of a computer at a desk in a dark room.
   a. Ensure a mouse is connected to the computer.
2. Click on the desktop link to access the Online Farnsworth-Munsell 100-Hue Test.
   http://www.color-blindness.com/fm100hue/FM100Hue.swf
4. Explain the test to the subject.
"This task will take about 15 minutes. The object of the test is to arrange the color tiles in order according to color. The first and last tiles on each row are anchored in place, the rest are mixed randomly within their rows. Please use your mouse to click on a tile, drag, and drop it into place so that they form a regular color series beginning with the first tile. You cannot move a plate from one row to another, just back and forth along its own row. It should take you about 2 minutes per row, but accuracy is more important than speed. There is no time limit, but do not dawdle. Try to do your best. Do you have any questions?"
5. Note the time.
6. Have the subject click start when they are ready to begin.
7. Record the subject's Total Error Score.
8. Take a screen shot of the graph by pressing "Prt Sc." The screen shot will automatically be saved into the "Screenshots" folder on the Desktop. Open the folder and change the file name to the subject's ID.
9. Record the elapsed time for the test on the recording sheet.

Color Vision Testing Subject Recording Form

Subject ID: _____   Gender: M   F

Subject Order: _____   Age: _____

Do you have at least 20/40 vision at near?   Yes   No

Do you have any ocular pathology that may affect color vision? (offer list to subject)   Yes   No

Do you take any medications that may affect color vision? (offer list to subject)   Yes   No

Do you have a history of photosensitive epilepsy?   Yes   No

Have you ever been diagnosed with a color vision deficiency?   Yes   No

At what age?

By whom?

Do you have anyone in your family who has a color deficiency?   Yes   No

Relation:

Age of diagnosis:

Ishihara Pseudoisochromatic Plates

Time Elapsed: _____

Plate #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Stated #																	

TCV Software Program

Time Elapsed: _____

Score: _____   (remember to save the certificate)

F-M 100 Hue

Time Elapsed: _____

Tray Presentation Order: _____

Cap Order Results: Cap Error Score: _____

Tray 1																					
Tray 2																					
Tray 3																					
Tray 4																					

Online F-M 100 Hue

Time Elapsed: _____

Total Error Score: _____   (remember to screen shot results)

APPENDIX C

This is a non-exhausted list of diseases and medications that may affected color vision and were thus excluded from this study.

Exclusionary Diseases
      Alzheimer's disease
      Cataracts
      Diabetes mellitus
      Glaucoma
      Leukemia
      Multiple sclerosis
      Macular degeneration
      Parkinson's disease
      Sickle cell disease
      Thyroid eye disease

Exclusionary Medications
      Chloroquine
      Digoxin
      Ethambutol
      Hydroxychloroquine
      Phenytoin
      Sildenafil
      Tamoxifen

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American Board of Opticianry Certification • #188545 • 2011 – 2014
National Contact Lens Examiners Certification • #188545 • 2011 – 2014

Work Experience:
Vision Performance Institute, Forest Grove, OR　　　　　　　　　　May 2013 – July2013
　　　Research Assistant
　　　　　• Programmed computer activities for research participants using Experiment Builder
　　　　　• Edited macros for collecting data into a single excel sheet

Jackson Eye Care, Fort Collins, CO　　　　　　　　　　February, 2011 – June, 2012
　　　Optometric Technician and Receptionist
　　　　　• Attended to each patient's experience including check-in, pretesting, and payment
　　　　　• Performed contact lens education and handled phone calls and scheduling

Wal-Mart Vision Center, Fort Collins, CO　　　　　　　　　　February, 2011 – June, 2012
　　　Dual Certified Optician (ABO & NCLEC)
　　　　　• Attended to customer's needs to include sales and eyewear adjustments
　　　　　• Worked as a team performing daily tasks to run the vision center

Shades of Jackson Hole, Jackson, WY　　　　　May – August, 2009 & July – November, 2010
　　　Sales Associate/Assistant Manager
　　　　　• Sold and repaired sunglasses, ordered and managed inventory, and used QuickBooks
　　　　　• Communicated professionally with customers and interacted effectively with peers and
　　　　　　superiors

Undergraduate Business & Economics Research Journal, Berry College, GA　September, 2009 – May, 2010
　　　Copy Editor
　　　　　• Corrected APA formatting and language before publishing
　　　　　• Developed excellent written communication skill

Clinical Experience:

Eye Care Associates of Nevada • Dr. Douglas Devries, Sparks, NV	February 22 – May 6, 2016
Koenig & Robertson Optometry • Dr. Gregory Koenig, Fallon, NV	November 16 – February 12, 2016
Veterans Affairs Medical Center • Dr. Kirk Halvorson, Salem WA	August 24 – November 6, 2015
Oak Harbor Naval Hospital • Dr. Kyle Dohm, Oak Harbor, WA	May 18 – August 8, 2015
Pacific EyeClinic • Primary Care • Dr. Susan Littlefield, Cornelius, OR	January 5 – April 24, 2015
Pacific EyeClinic • Vision Therapy • Dr. Hannu Laukkanen, Forest Grove, OR	January 5 – April 24, 2015
Pacific EyeClinic • Primary Care • Dr. Scott Pike, Forest Grove, OR	August 25 – December 16, 2014
Pacific EyeClinic • Ocular Disease • Dr. Ryan Bulson, Portland, OR	August 25 – December 16, 2014
Pacific EyeClinic • Primary Care • Dr. Kirk Halvorson, Hillsboro, OR	May 5 – August 8, 2014
Pacific EyeClinic • Contact Lens • Dr. Scott Overton, Portland, OR	May 5 – August 8, 2014

Research Experience:

Research Assistant, Vision Performance Institute, Forest Grove, OR   May, 2013 – August, 2013
- Conducted human subject research
- Designed and programmed computer activities for testing subjects using Experiment Builder

Biology Research Assistant, Berry College, Mount Berry, GA   January, 2007 – May, 2008
- Conducted online research, collected field data, and processed images using Image J
- Planned, strategized, and implemented research questions; utilized problem solving skills

Research Presentations:

Master's Degree Thesis Defense, Pacific University, Forest Grove, OR   April 23, 2015
- "A New Generation of Color Testing"

Student Research Symposium, Berry College, Mount Berry, GA   April 11, 2008
- "Forest Health, Dogwoods, and the Calcium Connection"

Teaching Experience:

Master's Seminar Tutor, Pacific University, Forest Grove, OR   August, 2013 – May, 2015
- Tutored Master of Science in Vision Science candidates

Chemistry Tutor, Periscope Tutoring, Forest Grove, OR   May, 2013 – August, 2013
- Tutored a high school student preparing for final exams

Biology Tutor, Berry College Biology Department, Mount Berry, GA   August, 2007 – May, 2010
- Helped fellow students develop personal study skills and improved my own teaching skills

Horseback Riding Instructor, Self Employed, Rome, GA   September, 2008 – May, 2010
- Learned to clearly and effectively share my knowledge while maintaining a leadership role

Conferences and Workshops:

Optometry's Meeting, Seattle, WA	June 24-28, 2015
American Academy of Optometry, Denver, CO	November 12-15, 2014
Multifocal Contact Lens Workshop, Forest Grove, OR	November 5, 2014
Valley Contax Workshop, Springfield, OR	July 12, 2014
Toric Soft Lens Workshop, Forest Grove, OR	May 21, 2014
American Academy of Optometry, Seattle, WA	October 23-26, 2013
Great Western Council of Optometry, Portland, OR	September 21, 2013
Northern Rockies Optometric Conference, Jackson, WY	July 25-27, 2013
Optometry's Meeting, San Diego, CA	June 26-29, 2013
Great Western Council of Optometry, Portland, OR	September 29, 2012

Community Vision Screenings:

Harvey Clark Elementary School, Cornelius, OR	February 2, 2015
Project Homeless Connect, Hillsboro, OR	January 30, 2015
Migrant Head Start: Linden, Cornelius, OR	October 31, 2014
Pacific University Baseball Team, Forest Grove, OR	October 15, 2014
Migrant Head Start: Linden, Cornelius, OR	June 18, 2014
Cornelius Elementary School, Cornelius, OR	November 22, 2013
Atlas, Yamhill, OR	September 5, 2013
VSP Mobile Clinic, Virginia Garcia Vision Clinic, Cornelius, OR	January 14, 2013
Tigard Compassion, Tigard, OR	October 13, 2012