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Review of the commonly used colour vision testing methods

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Abstract

Colour is an extremely important component of the information that people gather with their eyes. Most people use colour so automatically that they fail to appreciate how important it is in daily activity. Colour vision is perceived through three types of cones in the retina which are sensitive to red, green and blue colours. The purpose of this paper is to review the available and significant clinical colour vision tests in light of the need in the clinical examination of both congenital and acquired colour vision deficiency (CVD) and colour blindness.

The tests are grouped and described as pseudoisochromatic plates, arrangement or matching tests, the lantern test and the anomaloscope test. The performance of each test type is described. When an individual exhibits CVD, the ability to discriminate cones diminishes under specific circumstances that could involve limitations in career choices, early education, academic, and everyday activities.

Clinicians should test the colour vision of all patients with the Ishihara test. Those shown to have CVD should be evaluated with the Farnsworth D-15 and/or anomaloscope. Although there are many colour vision tests, their performances are difficult to compare. Once the results are obtained, appropriate advice should be given to the patient.

Keywords: anomaloscope, colour vision, colour vision deficiency, Farnsworth D-15 colour test, Ishihara test

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Introduction

The world is blessed with the richness of colours, hence it can be regarded as colourful. However, it is not easy to define colour since it requires the synergistic and harmonic functions of retina, different parts of the thalamus and cerebral cortex. Colour is one perceptual attribute that significantly affects everything we see. The ability to see spatial structured objects, to resolve edges and contours, and to see fine detail requires point by point processing of the amount of light available in the image formed on the retina by the optics of the eyes.[1]

The human retina contains two types of photoreceptors, namely, rods and cones, located on the outer nuclear layer.[2] Rods mediate vision at night and when little light is available. Cones are responsible for colour vision and they mediate vision under light levels encountered in daily life. Colour perception is a function of three classes of photoreceptor cones in the retina, each with its specific sensitivity, namely, short (S) or blue, middle (M) or green, and long (L) or red wavelength sensitive cones, whose peak sensitivities are 414–424 nm, 522–539 nm and 549–570 nm respectively. The sensitivity for each type of cone depends on the type of opsin contained by each cone type. Blue, green and red are the primary colours as any colour can be produced by mixing the appropriate proportion of these three colours.[3,4] Normal individuals require all these colours to match those with the electromagnetic spectrum for normal trichromatic vision. Normal trichromatic colour vision is often required as a condition for employment in demanding occupations.[1,5] Colour vision can be regarded as the ability to detect different wavelengths of light and to distinguish between these different wavelengths and their corresponding colours.

Colour vision deficiency or colour blindness

Human colour vision is normally trichromatic, requiring at least three cone photopigments, one from each of the three well-separated spectral classes.[2,5-11] The three classes of photopigments differ in their relative spectral sensitivity showing peak absorbencies at light wavelengths of 420 nm, 530 nm and 560 nm for short, medium and long wavelengths respectively. Colour vision deficiency or defect (CVD) is the inability to distinguish certain colours due to the absence, malfunction or alteration of one, two or all of the photopigments. CVD occurs when an individual has a restricted colour spectrum that affects their perception of colour. It is characterised

by disturbances of colour perception that occur if the amount of visual pigment per cone is reduced or if one or more of the three cone systems are absent. It occurs due to a genetic disorder in specialised photoreceptors in the retina that distinguish variation in wavelength of colour that enables people to determine the array of contrasting colours.[2] There are two classes of CVD, namely partial and total colour blindness.[9] Partial colour blindness is further classified as red–green and blue–yellow.[4,12] Impairment in colour vision can either be congenital (hereditary) or acquired. In congenital CVD, the congenital visual system is otherwise normal except for the loss of colour discrimination, and the defect remains stable throughout. Congenital red–green CVD can be explained by the absence of one class of cone photopigment. The class of defect characterised by the absence of M or the green cone is called *deutan*, while those defects characterised by the absence of L or the red cone are termed *proton*. S or blue cone defects are called *tritan*. Congenital CVD is an X-linked recessive, autosomal dominant. It is an inherited defect due to the hybrid gene which codes the green and red colours.[8,9] The red–green CVDs are common, affecting more males than females.[10] Acquired CVD is related to an ocular disorder or diseases, and some aspects of the visual function is also affected by the disorder.[7] The defect can progress or regress depending on the underlying disorder.[9] The acquired CVDs are less common in the general population but they are very common in the elderly.[10]

Dichromats are individuals with severe CVD. They usually have non-functional red or L pigment (protanopes) or green M pigment (deuteranopes). Dichromats have dichromatic rather than trichromatic colour vision.[3,4,11-13] CVDs are named on the basis of the cone with the anomalous function, while the depth of the deficiency is named with the -anomaly (partial vision) or -anopia (absence of colour vision) suffixes.[3,4,11-13] The milder forms of red–green colour vision defects are called anomalous trichromacies that parallel the two dicromatic types (protanopes and deuteranopes). Protanopes' or deuteranopes' trichromatic colour vision have their red or green cone photoreceptor pigments missing but replaced by an anomalous or abnormal pigment with altered spectral sensitivity.[8] Their trichromacy is not based on blue, green and red pigments as in those with normal vision.

Colour vision testing assessment

Colour vision can be assessed qualitatively or quantitatively using tests that are grouped as pseudoisochromatic plates, ordering tests, matching tests or arrangement tests. Some of the clinical tests which are utilised for evaluating colour vision are briefly summarised below. However, none of the available tests provide a complete assessment of colour vision.

Pseudoisochromatic plate tests

Pseudoisochromatic means falsely appearing to be of the same colour. The most widely used pseudoisochromatic plate test in daily clinical practice continues to be the Ishihara test (*Figure 1*).[5,11,13-16] The test is based on the plates designed by Stilling (1873). Despite the global scientific and technological developments, the Ishihara is the most widely used test in the clinic, but many tests have been developed for evaluating colour vision.

A symbol or figure (number, letter or geometric figure) composed of coloured spots is placed against a background of differently coloured spots that vary in size and luminance. The Ishihara colour deficiencies test is designed to detect red–green CVD. The test is carried out under daylight illumination with the plates held at a distance of 66–75 cm from the eyes, perpendicular to the light.[5,11,13-16] The test consists of 38 plates and the observer or patient is given four seconds to identify a symbol. The test time is two minutes per eye. An incorrect response to five or more plates is regarded as indicative of defective colour vision. The patient is

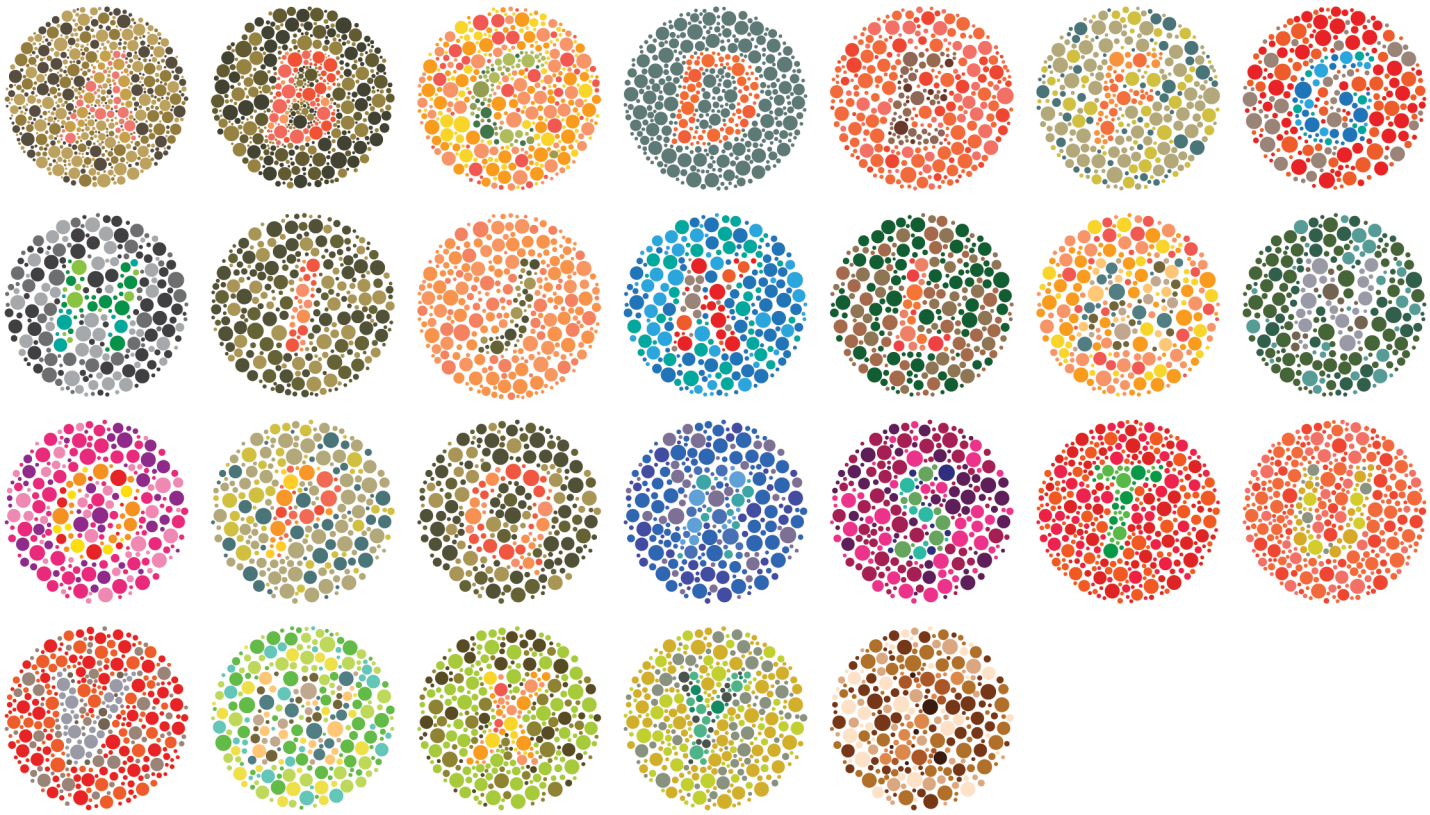


Figure 1. Ishihara plates *Photo credit: Shutterstock.com*

required to identify a number or follow a path observed along each of the plates within four seconds. The Ishihara is widely used to detect or identify CVDs due to its easy administration and its relatively high sensitivity and specificity; however, it is less reliable for assessing the type and severity of the deficiency and does not evaluate the effect on the tritan axis.[12,16]

Other pseudoisochromatic plate tests include Colour Vision Testing Made Easy (CVTME), the Richmond Hardy-Rand-Rittle (HRR) test, Neitz test for colour vision, Cambridge colour test and City University colour vision test.[13-16] All these tests are made up of discrete coloured dots of discs of various sizes and luminance. Individuals with normal trichromatic colour vision can detect the hue difference between figure and background and can easily identify the figure, but individuals with defective colour vision may fail to distinguish between figure and background colours and, hence, fail to identify or read the figure.

Hardy, Rand and Ritter test

Hardy, Rand and Ritter in 1945 divided or characterised the pseudoisochromatic plates into vanishing, hidden, transformation and classification plates, each with its own technique to enable the identification of a specific colour vision-related deficiency.[17,18] The vanishing plates contain a figure or sign that is easily identified by the normal trichromat but not by the colour-defective individual. Only people with good vision can see the figure but colour-blind people will not see anything. The classification plates allow for the differentiation of a protan from a deutan individual, that is, red- and green-blind persons. A person with a protan defect will see a figure only on the right side, while a person with a deutan defect will see it on the left side. In the hidden plates, normal trichromats will not see the figure but the figure will only be seen by those with a red-green colour deficiency. A person with perfect colour vision will not be able to see the figure. In the transformation plate, two figures are embedded in the background, with the appropriate colour and lightness contrast.[17] An individual with a colour deficiency will see a figure that is different from that seen by an individual with normal trichromatic vision.

Colour vision evaluation test

The Colour Vision Evaluation Test (CVET) is based on colour confusion using pseudoisochromatic cards.[19] The test simultaneously analyses two of the three psychophysical parameters of colour, which are the hue and the saturation. It is composed of three elements: an album, a lamp and a software program. The album consists of 72 pseudoisochromatic cards, divided into two groups: the four demonstration and the testing cards. The four demonstration cards are intended to explain the testing methods. They present the image of a stool/chair that can be oriented in four positions: feet oriented up, down, right or left. The 68 testing cards are divided into six series, each corresponding to an axis: monochromatic, protan, deutan, scotopic, tritan and tetartan. The Farnsworth-Munsell 100 Hue test is used as the reference to determine the hue of each axis.[20] Each hue is divided into ten levels of saturation, and each level of saturation into three levels of brightness. The brightest level, forming a confusion image, is seen by the dyschromatic patient. It is the image of a stool oriented differently from that formed by the different colours.

Chromatic vision is measured according to ten levels of saturation. A normal colour perception is noted as 1; the total absence of colour perception as 0. Between 0 and 1 there are nine intermediate values corresponding to different levels of anomalous trichromatism (from 0.9 to 0.1). When performing the test, the child receives a single instruction from the examiner: 'Tell me toward which side of the stool the feet are turned, and place a cardboard stool over the other.' After a demonstration, the testing cards are shown one by one starting with the card with the highest saturation level, then rapidly reducing the saturation using cards with intermediate saturation until the last card that could be read correctly.[19] The test is considered normal (n =1) if the child could read all cards of the album correctly. The intensity of the deficiency is quantified by calculating the six indices:[21]

$$(M + P + D + S + Tr + Te)/6,$$

where M = monochromatic, P = protan, D = deutan, S = scotopic, Tr = tritan and Te = tetartan.

Arrangement or ordering tests

The arrangement or panel tests (Farnsworth D-15 Hue test, Farnsworth D-100 Hue Test and Lanthony 15-Hue Desaturated Test) are based on the pairing of numbered coloured caps in racks, allowing the direct identification of the confusion axes of dyschromatopsia.[20-23] The panel tests are adequate for children over 7 years of age. The Farnworth D-15 Hue test is easier and fast to perform. Its main indication is the diagnosis of hereditary dyschromatopsia through the identification of the axis of colour confusion (protan, deutan and tritan deficiencies).[4] It is also useful to assess the severity of the colour vision deficiency; however, because of the marked chromatic differences between the 15 caps, patients with mild CVD may not be detected with this test.[5] The Farnsworh D-100 Hue Test is the most advanced panel test.[23] It has 85 caps, and allows the diagnosing any type of dyschromatopsia. However, its main limitation is the long duration of the examination, which makes its use burdensome. The test is relatively difficult to understand and needs a certain level of discernment from the patient. Young patients may get tired of the test faster than adults and this could increase the error rate of the test results.[22,23] The Lanthony 15 Hue Test is also difficult to perform due to the low level of differences in saturation ('chroma' 2) and high chromatic similarities between the caps. However, it is a rapid test that allows an easier diagnosis of mild-to-moderate anomalous dichromatism.[19]

In the arrangement or ordering test, the observer is asked to arrange a set of movable, coloured samples mounted in caps by similarity in a sequential chromatic pattern.[13-16] The caps are numbered on the back and can be moved about freely during the testing. The Farnsworth-Munsell D-15 consists of 15 coloured caps placed in a box, with one reference cap at a fixed location. The test is designed to indicate red–green and the blue–yellow discrimination loss and estimate the severity of the defect. The examiner prearranges the caps in random order on the upper lid of the open box and the observer is asked or required to arrange the caps in order according to colour in the lower tray, starting with the cap closest in colour to the fixed reference cap. The test is done at a comfortable distance under daylight illumination.

The order of the caps is plotted directly on the score sheet on a diagram that shows correct cap positions extending in a circle from the reference cap (*Figure 2*). Other arrangement tests include Farnsworth-Munsell 100-Hue and Lanthony Desaturated D-15. Both the panel D-15 and the 100-Hue tests are able to differentiate protan, deutan and tritan defects by the axes along which confusions are made.

Figure 2. The Farnsworth-Munsell D-15 panel

Lantern tests

Lantern tests are used for the assessment of colour vision for occupational purposes, such as airline pilots, seamen and railway personnel.[13-16,24] A lantern test consists of a series of coloured lights or combinations of pairs of coloured lights being shown to the observer. The observer has to name the colour of each light.[24] Lantern tests require that an individual is presented with one or two coloured lights at a distance and has to name them as soon as they are presented. Incorrect naming of some colours indicates CVD. However, the tests do not identify the type or quantify the severity of CVD. The value of lantern hue tests lies in their simulation of working conditions.[24] Several different models are available, such as the Spectrolux, Beyne and Farnsworth lantern.

Comparison test

In the comparison test, the observer is asked to find the two-colour tones that subjectively are perceived as identical.

The anomaloscope is an optical instrument to identify and diagnose CVDs in red and green vision.[19,20] The Nagel anomaloscope is the gold standard to identify and diagnose CVD in red and green vision (*Figure 3*). It evaluates an individual's Rayleigh equation by manipulating stimulus control knobs to mix red and green light to match the yellow light used as the test stimulus. The Rayleigh equation is a special type of colour matching that involves matching a spectral light near 589 nm to a mixture of spectral or near spectral lights between 670 nm and 545 nm, and it can differentiate normal trichromats from observers with congenital red–green colour deficiency and allows classification of these defects.[1,25] The anomaloscopic measurement includes a comparison of the hues of two illuminated fields. For the red–green measurements, the reference field is illuminated with an adjustable proportion of red (670 nm) and green (546 nm) diodes, which creates the impression of green, lemon, yellow, orange or red.

The patient observes a vertically oriented bi-field composed of the top half, which is a mixture of red and green lights, and bottom half made of yellow light. The patient mixes the proportion of red and green to equal the intensity of the yellow. Normal trichromats can match all hues by the appropriate mixture of three coloured lights within a narrow range of matches. The normal observer will produce a result of around 42 units with a scale of 0 being pure green and 73 being pure red. Deficient colour vision will correspond to a broader range and with a poor threshold of more than four units.[13]

The first anomaloscope designed by Nagel used a heating bulb and was powered by alternating electric current, which had an enormous impact on the measurement results.[25,26] The colour sensitivity was correlated to ambient temperature and patient's body temperature. In high temperatures the results shifted towards the red area, suggesting a decrease in sensitivity to red colour. The voltage fluctuation in the power grid could significantly affect the intensity of the light emitted by the lamp and affect the test result. The Oculus HMC anomaloscope is the latest generation of anomaloscope. It is equipped with LEDs emitting light in three ranges (549, 589 and 666 nm), which allows for examination of colour perception in the red–green area (referred to as the Rayleigh test).[25] Additional LEDs with light wavelengths of 436, 480 and 490 nm facilitate examination in the blue–green area, which is referred to as the Moreland test.[25] This latest anomaloscope is designed with diodes used to as light sources; they do not warm up and the power supply ensures a stable electric current.

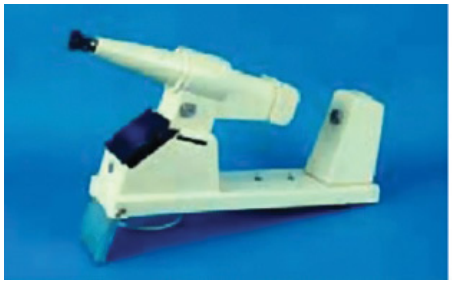
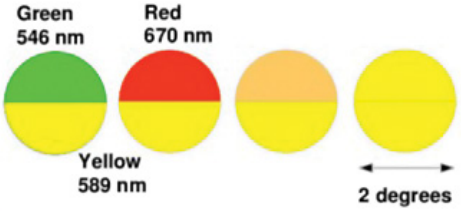


Figure 3. Nagel anomaloscope

The anomaloscopes are very accurate tools for testing colour vision. They are colorimeters measuring the threshold of chromatic perception obtained by additive mixing of spectral colours. They quantify and qualify all types of dyschromatopsia from trichromatism. However, their main limitations are their lack of availability and the need for extensive training of users. Electronic anomaloscopes are, however, easier to handle than the Nagel Model I anomaloscope.[27] However, the anomaloscopes are relatively complex and expensive optical instruments and they are not chosen as a secondary test for a purpose.

Comparison of the different tests

The pseudoisochromatic test, which includes the Ishihara test, HRR test, CVTME and Neitz test are all based on colour confusion. These tests have been designed from a known chromatic deficiency and can only reveal the type of dyschromatopsis (deficiency in the perception of colours) for which they were performed. The Ishihara test and CVTME detect only deutan and protan defects by the axes along which confusions are made.[15,28] The Neitz and Richmond HRR tests evaluate defects in all three axes of colour confusion (protan, deutan and tritan).[29-32] Although the pseudoisochromatic tests are rapid and easy to perform, they are insufficient for an accurate diagnosis of the axes and degree of chromatic deficiency. It is recommended to repeat the test for greater reliability.[6,30] The Richmond HRR test



provides the clinician with more information than the Ishihara test. Although the Ishihra test is known for its high sensitivity and excellent specificity for the detection of protan and deutan deficiencies, it has no plates for tritan, and the number of errors that are made gives little indication of severity of deficiency. Its four protan-deutan classification plates are also not very reliable.[5,30,31]

The Richmond HRR pseudoisochromatic tests are ideal to evaluate colour vision from 3 years old,[31] while the Ishihara test, Neitz test of colour vision and CVTME are adequate for children aged 4–6 years.[19,29,30] Fish *et al.* evaluated the validity, reproducibility and feasibility of the CVET for the diagnosis of congenital dyschromatopsia among 155 children using the Ishihara pseudoisochromatic cards, Farnsworth D-15 Hue standard test and the CVET.[19] They found that the CVET is a rapid, reliable, reproducible and accessible test for young children to be used for the diagnosis of congenital dyschromatopsia.[31]

Ideal colour vision testing should reliably detect, categorise and grade the severity of protan, deutan and tritan CVDs. Cole *et al.*[31] reported results from the new Richmond HRR pseudoisochromatic test for colour vision. Colour vision was diagnosed using the Ishihara, the Farnsworth D-15 test, the Medmont C-100 and type 1 Nagel anomaloscope. The design of the 2002 HRR test is based on re-engineered principles.[33] The test is composed of 24 plates each displaying either one or two symbols, which can be a cross, a circle or a triangle. The patient is asked to name the shape of each symbol they see and indicate its location, which can be in one of four quadrants of each plate. The authors concluded that the new HRR test is as good as the Ishihara test for the red–green CVDs, but unlike Ishihara it has plates for the detection of the tritan deficiency. The original HRR sometimes failed tritan, although not always. The colours of tritan symbols in the revised test are better aligned with the tritan confusion locus and are less saturated.[34]

Conclusion

Screening of CVD is relatively quick and easy. The Ishihara charts are still the most widely used tests that help to diagnose the type of deficiency and its severity, followed by the Farnsworth-Munsell D-15. Although the anomaloscope is regarded as the gold standard for assessing colour vision, it is not readily available in clinical practice due to the costs. In the absence of an anomaloscope it is possible to achieve a clinically precise colour vision assessment by combining some of the tests to obtain an approximation. In education and industry, screening for CVD is needed for vocational guidance in occupations or professions that require colour judgement.

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