Colour vision: A review of the Cambridge Colour Test and other colour testing methods

Authors:
Nabeela Hasrod[1]
Alan Rubin[1]

Affiliations:
[1]Department of Optometry, University of Johannesburg, South Africa

Correspondence to:
Nabeela Hasrod

Email:
nabzicakes@gmail.com

Postal address:
PO Box 17011, Doornfontein 2028, South Africa

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The evaluation of colour vision and discrimination of an individual forms an integral part of a routine eye and vision examination. With the increasing prevalence of inherited colour vision deficiencies, defects of colour vision can be detected in an optometric practice by means of a variety of tests available. The present article comprises an overview of the design and function of a selection of colour vision tests that are administered manually and, in some cases, have been modified to form a computerised version.

Introduction

With the increasing importance of colour discrimination needed for various activities, as well as colour vision deficiencies (CVD) that occur as a result of congenital or acquired conditions, colour vision screenings and examinations are used not only for early identification of CVD, but also for monitoring the progression or remission of disease. Colour vision loss may sometimes occur from the side-effects of certain drugs used in the treatment of diseases such as diabetes, hypertension, HIV and AIDS and others.[1]

Colour vision can be assessed qualitatively and quantitatively using tests that are grouped as arrangement tests, matching tests, vocational tests or pseudo-isochromatic plates. Sometimes simple or more sophisticated computerised procedures, such as the Cambridge Colour Test (CCT), are used to evaluate colour function or discrimination.

Literature review

The human retina comprises two classes of photoreceptors: rods and cones. Rods are responsible for vision in dim light, and cones mediate vision in bright light to enable the perception of colour. Individuals with normal colour vision have three types of cone photoreceptors: short wave sensitive or blue, middle wave sensitive or green, and long wave sensitive or red cones.[2] All such individuals have normal trichromatic colour vision. Individuals with severe colour vision defects usually either have non-functional red (protanopes) or green (deuteranopes) cone photoreceptors and have dichromatic rather than trichromatic colour vision.[3] Those with milder colour vision defects usually have either their red or green cone photoreceptor pigments replaced by an anomalous pigment with altered spectral sensitivity; such individuals are classified as having protanomalous or deuteranomalous trichromatic colour vision.[4]

One of the main applications for colour vision screening is to assess and detect deficiencies that occur in the visual system as a result of congenital or pathological causes.[5] The evaluation of trichromatic colour vision in individuals is based largely on colour discrimination and colour matching.[6] As human retinae include three types of wavelength sensitive cones, colour is a trichromatic process and various tests have been developed to assess trichromatic colour vision by means of arrangement, matching, and vocational and pseudo-isochromatic plates.[7]

Normal trichromatic vision can be defined as the ability to distinguish and discriminate light on the basis of wavelength composition; that is, independent of its intensity.[8] Colour perception is dependent on the absorption of light by three classes of photoreceptor cones in the retina, namely short (*S*-), medium (*M*-) and long (*L*-) wavelength sensitive cones, whose peak sensitivities are ≈420 nm, ≈530 nm and ≈560 nm respectively.[9] Each cone of the above classes obeys the *Principle of Univariance*; that is, the absorption of a long wavelength (low frequency, low energy) quantum has the same effect on a receptor as the absorption of a short wavelength (high frequency, high energy) quantum. It is the probability of absorption that changes photoreceptor sensitivity.[10] Any single photoreceptor is 'colour blind', since an appropriate combination of wavelength and radiance can produce an identical neural response. No individual receptor can differentiate between changes in wavelength and radiance and, although the probability of that cone being

stimulated by a photon of light depends on wavelength and radiance, the output can only vary by the degree of depolarisation within the receptor and is independent of wavelength.[11]

Using this principle, a comparison of signals from two or more cone classes (each with a different spectral sensitivity) is required to make a differentiation between wavelength and radiance.[12]

All possible colours can be plotted in a three-dimensional (3D) colour space because the normal retina contains only three classes of cones, each obeying the Principle of Univariance. The three axes of a 3D graph or stereo-pair can be used to represent different quantities relating to colour vectors. For example, a colour vector could be plotted in terms of red (*R*) or L-cone input, green (*G*) or M-cone input and blue (*B*) or S-cone input. The colour space is then described as *RGB*-space or *LMS*-space. A given *colour vector* [e.g. $\mathbf{c}_w = (1\ 1\ 1)$- or white (subscript, *w*)] can be plotted as a point in this 3D space and, as radiance is changed, the point (and its colour) will move along a vector that extends from the origin [usually but not always the colour *black* with 1 × 3 colour vector $\mathbf{c}_k = (0\ 0\ 0)$-, which is essentially an absence of colour]. The angle of the colour vector relative to the axes of the colour space corresponds to its chromaticity, where chromaticity can be defined as the quality of a colour or light with reference to its purity and its dominant wavelength.[13] Munsell, Ostwald and the *Commission Internationale de l'Éclairage* (CIE) describe colour space with different parameters,[14] and the CIE (1976) system which is used with the CCT, uses a parameter *Y* to measure brightness and parameters such as *x* and *y* (or *u* and *v* or *u'* and *v'*) to specify the chromaticity.[15]

Mollon (2000) explains that *dichromacy* of colour discrimination is the basic principle underlying the CCT.[9] A pair of physical stimuli can be chosen that yield the same chromaticity in two of the three classes of cones, but differ with regard to the remaining class. In alternating such stimuli, one can establish the integrity of the one isolated class of cones. For instance, consider a point that lies in the plane of the chromaticity of the medium wavelength and long wavelength cones. If a line were to pass orthogonally through that point, lights along that line would vary only in the line of the chromaticity of the short wavelength cones. This is called the 'tritanope confusion line', as someone who lacks short wavelength cones will confuse chromaticities in that line or direction. A tritanope, deuteranope or protanope is a person who confuses chromaticities along the short, medium or long wavelength confusion lines respectively.[8]

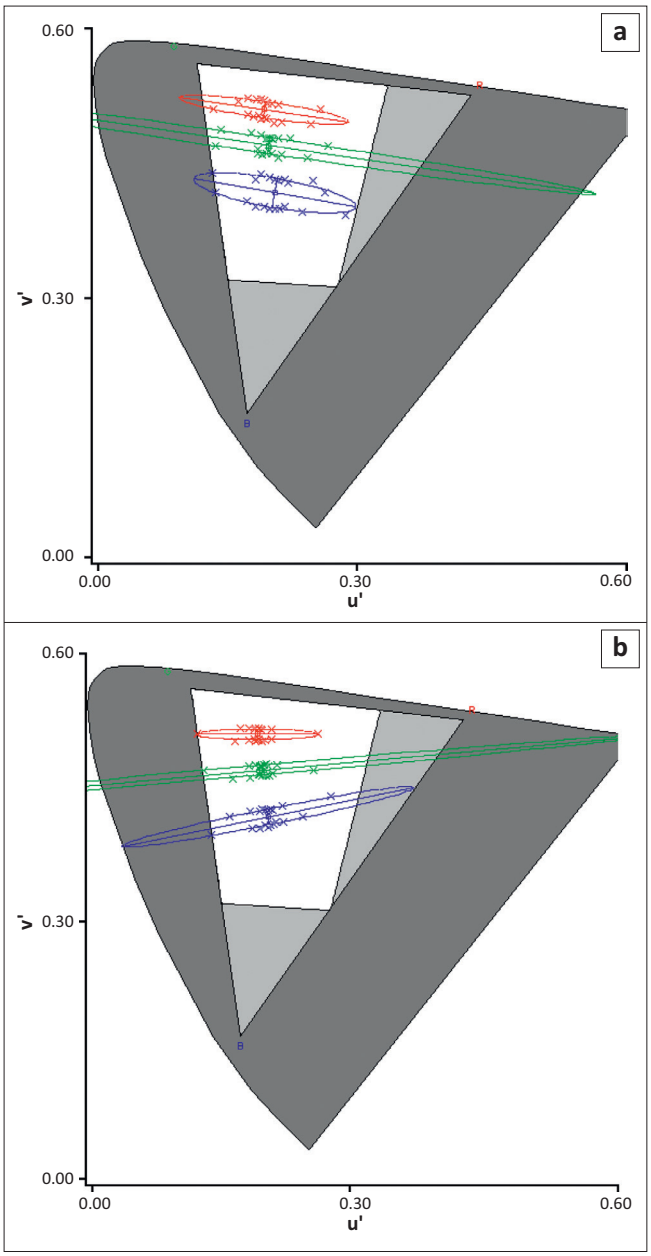
Cambridge Colour Test

The CCT is an example of a computerised test. Computerised colour vision testing offers the advantage of being able to adjust the difficulty depending on the patient's performance, as well as randomising plates to avoid the patient from recalling previously previewed plates.

The design of the CCT uses a computer version of pseudo-isochromatic plates and combines the *Principles of Chibret* and Stilling.[16] Chibret's Principle (1877) states the possibility of varying the chromatic difference of the target and field dynamically and adaptively, along different directions in colour space.[17] Stilling (1877) achieved non-hue noise by varying the size and luminance of the target and background elements.[17] Each of the computer pseudo-isochromatic plates in the CCT contains a Landolt C; that is, each stimulus is a large coloured letter C of specific hue and luminance that is presented in four different orientations; the opening in the letter can be up, down, right or left, which is embedded in a background comprising circles of varying size, colour and luminance. The CCT stimuli backgrounds eliminate luminance or contour cues, and the figures (the test stimuli of Landolt letters) must be identified solely by their hues.[1] As mentioned, this is accompanied by non-hue noise achieved by varying the luminance and size of compositional elements in accordance with Stilling's Principle.[17] The CCT controls the colour spaces (using the CIE *u'v'* [1976] chromaticity diagram) of the figures or stimuli (the Landolt letters) and the background and presents a random presentation of figure-background chromaticity differences. The patient presses one of four keys of a hand-held input device to indicate the openings of successive stimuli (the Landolt C) presented, making this task cognitively simple.[18]

Estimation of discrimination thresholds uses a staircase procedure which is an integral part of the two CCT tests, namely Trivector and Ellipses. The Trivector test makes use of the protan, deutan and tritan confusion lines to probe the sensitivity of the long, medium and short wavelength cones. Each target differs from the background along one of the three lines in colour space; that is, of either the deutan, protan or tritan confusion lines.[9] The Ellipses test determines the parameters of the three MacAdam ellipses that lie along the same tritan confusion line.[1] Discrimination ellipses show a loss of sensitivity for a range of directions around the background chromaticity, with the long axis of the ellipse being indicative of the type of loss.[17] The three MacAdam ellipses that are measured in the Ellipses test correspond to three different background chromaticities, and the ellipses are represented graphically using best-fit closed curves to the thresholds (indicated with crosses) measured for different directions relative to the background colour concerned.[9] Generally, protanopes display ellipses with a bottom-left slant and deuteranopes develop a top-left slant (Figure 1).

Normative data for normal trichromatic colour vision patients using the CCT were published by two groups of researchers from Brazil. One group from Sao Paulo[19] used the CCT v.2.0 with a VSG S card and Sony FD Trinitron colour monitor; the second group from Belem[19] used a self-built system for the IBM RISC 6000 workstation and IBM 6091 19i colour monitor. The results from both studies for the Trivector test were similar, and the absence of significant statistical difference between the two sets of data indicates the reliability of results produced by the CCT.[19]



Source: Mollon JD, Regan BC. Cambridge colour test handbook. Cambridge: Cambridge Research Systems, 2000.
Figure used with permission from John Mollon (and Steve Elliot of Cambridge Research Systems, Cambridge, UK).

FIGURE 1: Ellipses test results from a deuteranope (a) showing a 'top-left' slant and (b) protanope showing a 'bottom-left' slant of the ellipses.

The CCT has been used in a broad variety of studies; one example is the determination of colour discrimination losses in patients with chronic diseases such as multiple sclerosis.[20] In such cases, the CCT helped in characterising vision losses in both red-green and blue-yellow discrimination, indicating that both parvocellular and koniocellular visual pathways were affected. The CCT also identified the relationship between these losses and the degree of optic nerve involvement.[20] Parvocellular and koniocellular cells are located in the lateral geniculate nucleus (within the thalamus of the brain) which is the primary relay centre for visual information received from the retina of the eye. Parvocellular cells essentially respond to long and medium wavelength ('red' and 'green') cones whilst koniocellular cells are short wavelength 'blue' cones; the three types of cones are necessary for the perception of colour and form; that is, including gross and fine detail.[10] A colour vision test such as the Ishihara is not designed for detecting defects along the blue - yellow axis. However, the CCT has been developed to overcome difficulties in isolating the chromatic channels of the visual system, thus making it a versatile tool in both research and detection of a multitude of colour defects across all chromatic channels such as in multiple sclerosis.[20]

The CCT was also adapted to be used on animals such as squirrel monkeys.[21] Animal colour vision testing occurs to determine the presence, depth and acuteness of colour vision as well as to assess differences within species. Unlike other colour vision tests, this computer-based test allows researchers to modify the test so that the CCT can easily be used to evaluate colour vision in different species. The adapted version of the CCT is more efficient than other more conventional methods because it eliminates the need to equate the luminance of each chromaticity tested.[21] Results proved reliable because the stimulus parameters could be adjusted so that the animals were not able to use luminance differences to make correct discriminations.[21] In Mancuso et al., two squirrel monkeys were used and 16 different hues were tested.[21] Three separate colour vision tests were completed by each of the two monkeys and thresholds obtained were plotted on CIE *x*, *y* graphs where the *x*-axis showed the 16 different hues specified in terms of dominant wavelength of the most saturated colour tested, and the *y*-axis showed the corresponding thresholds for each hue. The time required to test 16 hues took about 2–4 months; consequently, the results represented colour vision testing conducted over a year. Their graphs[21] identified similar results for each test, and repeated measurements were highly consistent, showing that results produced by the CCT are highly repeatable even though these results were obtained from monkeys.

In a study in 160 normal trichromats by Paramei[1], using the CCT to assess colour discrimination across four life decades, the results indicated no significant differences in the CCT outcomes between two groups of normal trichromatic young adults (20–29- or 30–39-year-olds). There was, however, individual variability within each group, which increased with age.[1] Also, for normal trichromats of the same age range, binocular summation, eye dominance and learning do not have an effect on colour discrimination thresholds as determined by the CCT.[1]

Colour vision tests

Besides the CCT, there are a wide selection of tests available for the assessment of colour vision; efficiency of the tests is based on their sensitivities and specificities. Sensitivity is the percentage of people correctly identified as having a colour defect, and specificity refers to the percentage of people who are correctly diagnosed as having normal trichomatic vision.[12] Five main categories of tests are briefly described below: plate tests, arrangement tests, lantern tests, anomaloscopy and electroretinography.

Plate tests

The Ishihara pseudo-isochromatic plates detect red-green deficiencies; the design is based on the plates of Stilling.[14] The figure and background are made up of discrete discs that vary in size and luminance to ensure that the figure can be identified only by its chromatic difference from the background and not from a difference in the perceived luminance.[7] The test is carried out at 66 cm, comprising 38 plates, and the observer is given four seconds to identify the numerals or pathways.[12] The plates are divided into transformation, vanishing, hidden and classification plates, each with its own technique to enable the identification of a specific colour vision-related deficiency.

With transformation plates, the observer with a colour deficiency will see a different number to that seen by a person with normal trichromatic (NT) vision because some of the chromaticities that form the background and the figure fall on dichromatic confusion lines, whereas others fall off the line. This effect allows the individual to see the figure, although a different one to that seen by a NT.[22]

Vanishing plates are only seen by NTs because the design of these plates relies on selecting colours of the background and the figure from the protan and deutan confusion zones.[6] In the hidden plates, NTs will not see the figure because they can perceive the variance of the chromaticities along the long/medium wavelengths that are not perceived by those with a red-green colour defect.[6] Classification plates are used to identify the presence of a colour vision defect.[12] A person with a protan defect will see the figure only on the right side, and vice versa for a person with a deutan defect.

Arrangement tests

Arrangement tests involve asking observers to order a set of movable coloured objects according to either hue or saturation. An example of an arrangement test is the Farnsworth Dichotomous Test for Colour Blindness (D-15 test). It is conducted at 50 cm and has 15 Munsell hues mounted on chips. The patient is asked to arrange the 15 colour chips in a natural progression of colours. As some colour pairings from opposite sides of the hue circle fall on the dichromatic confusion lines, a colour-deficient subject may place them next to each other. The results of the test are plotted on a circular diagram and diagnosis is made based on the number and orientation of errors or crossovers.[5] However, because this test requires a patient to manipulate the chips, this can result in deterioration of the colour chips, and patients with dexterity problems may experience difficulties.[7]

The City University Test (CUT) was designed to reduce the problems associated with the D-15 test. It contains plates for the detection of protan, deutan and tritan deficiencies.[7] The second edition of the CUT contains 10 pages. Each page has a central reference colour surrounded by four testing colours. The patient is asked to match the closest surrounding colour to the centre reference. The other three plates lie on the dichromatic confusion lines, with one on the protan, deutan and tritan line respectively. The fourth colour is selected to be just noticeably different from the reference for a colour-normal subject.[5]

The selection of several colour combinations is based on the D-15 test, which is why the CUT may be considered a substitute for the D-15 test. Problems of the CUT, however, include the fact that it is possible that none of the test colours closely match the reference colour. Also, because the patient has to physically point to the matching colour, it poses a multitude of problems for disabled patients.[5]

The Farnsworth-Munsell 100 Hue Test is another example of an arrangement test widely used for measuring chromatic discrimination. The test consists of 85 caps, arranged in four boxes, each containing an anchor cap with which to begin the sequence. The total error score (TES) is the measure of accuracy of an observer in arranging the caps to form a gradual transition in chroma between the anchor caps.[23] Results from the test are computed by summing the partial error scores for every cap. In the computerised version of this test, the patient arranges the caps in each box and uploads the sequences to a linked software programme that calculates the TES scores and plots results on either polar or linear plot graphs. The programme therefore saves time in terms of manually calculating and analysing results.[18]

Lantern tests

Lantern tests are used for the assessment of colour vision for occupational purposes.[24] The lanterns are designed to mimic real-life situations, and patients are presented with one or two lights at a distance and have to name them as soon as they see them. Lanterns have seldom included blue stimuli, so tritan effects or defects are not likely to be considered. The pass/fail level depends on the number of colour-naming errors and is based on research done; all dichromats and 75% of anomalous trichromats fail this test.[4]

The Martin Lantern test has been adapted into a software form so that it can easily and widely be used without changing the existing standards and norms of colour testing. The testing distance of the software test was adjusted to have the patient sit 5 m away from the monitor, and presented with a double spot size of 0.51 mm, in comparison with the testing distance of 6 m for the Standard Martin Lantern test. The 43 cm liquid crystal display (LCD) monitor was set to maximum contrast and minimum brightness. Software was prepared and the red-green-blue (RGB) system of colours was incorporated to allow projection of pure colours as seen through the Martin Lantern filters.[24]

A total of 921 patients were tested with both the Martin Lantern test and the computerised version. On comparison between the Standard Martin Lantern and the computer

version, the results were consistent and comparable. The software eliminates various factors such as filter degradation that has occurred in the lantern over years of use. Similarly, the Ishihara charts in use are highly variable in colours and plate qualities, leading to ambiguous results. The computer-based test gives consistent and accurate colour projection that is highly reproducible and repeatable. Variables such as lighting conditions and dark adaptation are common to both the lantern and computer tests.[24]

Anomaloscopy

Although the most common procedure for testing red-green colour deficiencies involves Ishihara plates and pseudo-isochromatic plates, other methods such as the use of anomaloscopes require skilled examiners and properly calibrated devices.[22] The advantage of using computer-based approaches to test colour vision is that the automation reduces the effect of natural bias of the examiner on the results, which leads to improved reliability of results. Digital storage of data also facilitates subsequent analysis and research.[22]

The anomaloscope evaluates an individual's Rayleigh matches, which are proportions of red and green light that need to be mixed to match the yellow light used as the test stimulus. This procedure tests for red-green deficiencies.[25] A vertically orientated bi-field composed of the top half (a mixture of red and green lights) and the bottom half (yellow light) is presented to a patient. The proportion of red and green lights in the mixture and the intensity of the yellow light are adjustable, and the patient is asked to control both the top and the bottom fields until a match is obtained.[12]

A NT observer will accept a narrow range of matches. With a scale of 0 being pure green and 73 being pure red, the NT will produce a result of around 42 units.[12] A protanomalous observer will need more red in the mixture whereas a deuteranomalous trichomat will need more green in the mixture to match to yellow.[25]

A dichromat will be able to match the yellow to pure red, pure green and all mixtures in between by adjusting its intensity, whereas a protan observer will need to turn down the intensity of the yellow light when matching the field to the red one, owing to their reduced sensitivity to red light.[25] Definite diagnosis of protanopia, protanomaly, deuteranopia and deuteranomaly can be diagnosed using anomaloscopy.

A Pickford-Nicholson anomaloscope was simulated using a cathode ray tube (CRT) monitor, and this computer screening system was tested by comparing its diagnoses with diagnoses yielded by another colour vision test (Ishihara plates). The sensitivity of the computer test was equal to that produced by the Ishihara plate test, supporting its use as a screening test for observers with anomalous chromatic vision.[22]

Electroretinography

In contrast with the various psychophysical methods of colour vision assessment that rely on the patient's subjective perception of colour, the electroretinograph (ERG) is an objective means of determining the colour vision phenotype. In the ERG, a corneal electrode placed on an anaesthetised dilated eye records the retinal response to standardised flashes of light. Colour vision defects characterised as deutan and protan can be discriminated by the log ratio of the sensitivity at short (480 nm) and long (620 nm) wavelengths (sensitivity quotient).[4]

Computer-based colour vision tests

In addition to the CCT, another computer-based approach for screening colour deficiencies was done by presenting the Ishihara plate on a CRT monitor.[26] Technical restrictions of CRTs in computer monitors imply that not all perceivable colours can be adequately presented on a monitor. The generation of colour is done by mixing light emitted by three phosphors in the red (R), green (G) and blue (B) regions; this technique leads to an RGB coordinate system to describe colours on a computer monitor by the intensities of the cathode rays emitting from the three phosphors. Certain shades of orange, yellow and blue-green colours cannot be represented on a CRT monitor, which leads to the assumption that the spectral emission of Ishihara plates on a CRT monitor will be different from the spectral emission of reflected daylight on paper plates. This effect is caused by the many orange and red dots on the Ishihara plates.[26] An identical spectral emission of the reflected daylight of the plates and the emission from a CRT monitor is not possible. Nevertheless, calibration of the monitor allows a controlled spectral emission for the Ishihara plates represented on a CRT monitor in contrast to uncontrollable daylight. Results of tests done with both the Ishihara plates and the PC-based test were both comparable and reliable for screening purposes. The fact that a monitor can be controlled allows a higher degree of repeatability of the examination results using emitted light by controlled constraints. This control can be seen as an advantage of a CRT monitor presenting the Ishihara plates, because daylight cannot be controlled.[26]

Other technologies besides CRT can be used in monitors, for example, light emitting diodes (LED) and LCD; computer colour tests have been designed for such monitors but are not addressed any further in this review.

Additional colour vision tests

Colour vision screening for individuals with intellectual disabilities can be done using tests adapted with easier procedures because limited comprehension of testing expectations on the part of patients can lead to confusion in their responses, which makes it difficult to determine whether such a patient is manifesting a colour deficiency or simply not understanding the given instructions.[2] The Colour Vision Test Made Easy (CVTME) is one such adapted test. It uses vanishing pseudo-isochromatic plates with shapes

familiar to the intellectually disabled rather than numbers.[27] A demonstration card is used for explanatory matching purposes; this test is designed to highlight malingering and guessing as well as the patient's ability in understanding the instructions given.[27]

The Neitz Test for colour vision is one of the newest methods for screening colour vision defects. It detects more deficiencies because it identifies both the red-green and yellow-blue classes of defects. It can be administered under varying lighting conditions such as fluorescent light and daylight, and takes about 5 min to administer and score. The Neitz Test uses both vanishing and transformation designs, and there are three different forms of the test. In each form, grayscale and coloured dots are surrounded by a neutral background, and the patient has to correctly match a figure to one of nine possible options.[27]

Results from studies show that on comparison between the Neitz and CVTME tests, the CVTME proved to be more reproducible and is the preferred colour vision screening test for individuals with an intellectual disability. The Neitz Test proved inappropriate because of its high failure rates as well as its greater difficulty in administration and completion by patients.

Conclusion

There is no one test that will fulfil all the needs of a colour vision assessment. The choice of test could be determined by the initial reason behind the assessment of patients' colour vision. The practitioner should be aware of the correct procedure for carrying out the test and also how to interpret results, with limitations of the test kept in mind.

The CCT allows the examiner to assess colour vision qualitatively and quantitatively using pseudo-isochromatic plates. Having the added advantage of being computerised, it provides the benefit of being able to adjust the difficulty depending on the patient's performance, randomising plates to avoid the patient from recalling previously previewed plates, and providing a more comprehensive method of testing the colour vision of an individual by means of its two detailed testing procedures. A possible disadvantage of the procedure is the duration of testing, but research by the first author is directed towards investigating (1) the reliability of the CCT procedure and (2) assessing whether it may be possible to reduce test duration without necessarily compromising test reliability and adequacy of diagnosis of colour deficiency.

In general, proper colour vision assessment is typically performed using several procedures per patient which usually would include tests from each of the categories as briefly discussed in this review. For example, one might use the D-15, Farnsworth-Munsell 100 Hue test, Ishihara plates and the CUT. Where colour deficiency seems present the CCT might also be used.

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Competing interests

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Authors' contributions

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