CLINICAL AND EXPERIMENTAL
OPTOMETRY

REVIEW

Assessment of inherited colour vision defects in clinical practice

Clin Exp Optom 2007; 90: 3: 157–175 DOI:10.1111/j.1444-0938.2007.00135.x

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Background: Colour vision deficiency (CVD) has a high prevalence and is often a handicap in everyday life. Those who have CVD will be better able to adapt and make more informed career choices, if they know about their deficiency. The fact that from 20 to 30 per cent of adults with abnormal colour vision do not know they have CVD suggests that colour vision is not tested as often as it should be. This may be because of practitioner uncertainty about which tests to use, how to interpret them and the advice that should be given to patients on the basis of the results. The purpose of this paper is to recommend tests for primary care assessment of colour vision and provide guidance on the advice that can be given to patients with CVD.

Methods: The literature on colour vision tests and the relationship between the results of the tests and performance at practical colour tasks was reviewed.

Results: The colour vision tests that are most suitable for primary care clinical practice are the Ishihara test, the Richmond HRR 4th edition 2002 test, the Medmont C-100 test and the Farnsworth D15 test. These tests are quick to administer, give clear results and are easy to interpret. Tables are provided summarising how these tests should be interpreted, the advice that can be given to CVD patients on basis of the test results, and the occupations in which CVD is a handicap.

Conclusion: Optometrists should test the colour vision of all new patients with the Ishihara and Richmond HRR (2002) tests. Those shown to have CVD should be assessed with the Medmont C-100 test and the Farnsworth D15 test and given appropriate advice based on the test results.

Submitted: 13 November 2006
Revised: 23 January 2007
Accepted for publication: 1 February 2007

Key words: anomaloscope, Farnsworth D15 test, handicap of abnormal colour vision, Ishihara test, Medmont C100, predictive value of colour vision tests, Richmond HRR test

Colour vision deficiency (CVD) is a common functional disorder of vision affecting eight per cent of males and 0.4 per cent of females in Caucasian societies.[1] Because it is such a common disorder and has undoubted practical consequences for everyday life,[2] optometrists should test the colour vision of all new patients and provide appropriate advice and counselling to those who have abnormal colour vision.

It seems that not all optometrists do this because from one fifth[2] to one third[3,4] of adults with abnormal colour vision are unaware of their colour deficiency. This is unfortunate because patients who know they have abnormal colour vision are better able to find adaptive strategies and will be able to avoid disappointments in their choice of career. One third of the 102 subjects with abnormal colour vision surveyed by Steward and Cole[2] said their career choice had been affected by their colour vision deficiency, one quarter reported they had been precluded from an occupation because of it and one quarter said they had difficulties with colour in their current job. Only seven of their 102 subjects, all mild deuteranomals, reported no problems with colour in everyday life.[5]

Advice on colour vision can help those with abnormal colour vision who are still at school. Snyder[6] recounts that he was drilled by his kindergarten teacher to learn the names of colours and was dismayed at her lack of success, which made him feel anxious and different. He says he was greatly helped by having his abnormal colour vision diagnosed early in primary school because he quickly learned to use other cues to enable him to assign the correct names. Colour is used as a didactic tool in schools to identify objects and to group objects and ideas. In addition, it is used as a systematic identifier in some learning systems, such as the Cuisenaire method. Therefore, it is unfortunate that a high proportion of school children are unaware of their colour vision deficiency. Steward and Cole[2] report that 60 per cent of the anomalous trichromats and 30 per cent of the dichromats in their survey did not know of their colour vision deficiency, while they were at school.

Advice about abnormal colour vision can even help those who are retired. One elderly subject in the Steward and Cole sample[2] was grateful to learn at the age of 80 that he had abnormal colour vision because he had always thought his difficulty with colour was because he was not bright enough to have learned his colours properly when he was at school.

DETERRENTS TO ASSESSING COLOUR VISION

The clinical assessment of colour vision is not difficult so it may be worth giving thought to why it is not always done in routine clinical practice. There is a number of possible reasons. The first is that there is no single test of colour vision that provides the clinician with all the information needed to advise patients. Many practitioners use only the Ishihara test to assess colour vision. While the Ishihara test is very good at detecting red-green abnormal colour vision, it provides no useful information about its severity,[7] a classification into protan/deutan is not always possible[8,9] and it does not include a test for the tritan colour vision deficiencies.

The second reason is that proper assessment of abnormal colour vision needs several tests, which takes time, and the clinician has to decide which supplementary colour vision tests should be used. It is not easy to decide which of the large number of colour vision tests to purchase for use in a primary care setting. Birch[1] lists 18 different pseudoisochromatic plate tests, eight kinds of sorting/arrangement tests, five anomaloscopes and five lantern tests in a detailed review that still does not include every colour vision test. While the Ishihara test and the Farnsworth D15 test are widely used, there is no universal agreement on the tests that should be used in a routine clinical assessment of colour vision. Birch[1] (pages 113–116) suggests three batteries of colour vision tests but two of them include the anomaloscope, which is not an instrument private practitioners would contemplate purchasing because of its cost.

The third reason is that there is no treatment for abnormal colour vision so there may seem little point in diagnosing it. The main reason to detect and diagnose CVDs is so patients with abnormal colour vision can be given advice that may be helpful to them but practitioners who rely solely on the Ishihara test can only advise patients who fail the test that they have abnormal colour vision and can only explain the general nature of abnormal colour vision. Such advice has limited value for patients. Even practitioners who make a more thorough assessment face uncertainty when trying to advise patients on the connection between the clinical diagnosis and the practical problems they are likely to experience.

Another impediment to routine testing of colour vision is that the classification of CVDs is complex and may not be easily remembered by practitioners who do not routinely diagnose abnormal colour vision with an anomaloscope. Table 1 summarises the various forms of abnormal colour vision and is included for practitioners who may need to have their memory refreshed.

This review sets out a recommended protocol for the assessment of colour vision that is practical for use in primary care clinical practice. It also summarises the relationship between test results and the practical consequences of abnormal colour vision to provide the basis for meaningful and useful advice to patients.

RECOMMENDED COLOUR VISION TESTS FOR PRIMARY CARE PRACTICE

The tests recommended for the assessment of colour vision in primary care clinical practice are shown in Table 2. These tests have been selected on the basis of a number of criteria including: the test is readily available, is not unduly expensive, can be administered quickly and interpreted easily, is reliable and there are data available linking the result of the test to the practical problems patients with abnormal colour vision experience in everyday life. All four tests are recommended for purchase and use in primary care practice.

Ishihara test[a]

The Ishihara test has to be included in the basic battery of tests for the assessment of colour vision in clinical practice because it is widely accepted, readily available and not unduly expensive. It is a splendid test for the detection of red-green colour vision deficiency: it has high sensitivity and

a. The Ishihara test was designed by Shinobu Ishihara (1879–1963), who was a surgeon in the Japanese army before specialising in ophthalmology. He took an appointment at Tokyo University in 1908 but remained an instructor at the Army Medical College. His insights into colour vision may have been helped by studying in Germany from 1912 to 1915. On his return he resumed his work with the Army Medical College before becoming Professor of Ophthalmology at Tokyo University in 1922. Some of his research was on the selection of soldiers and he was asked to devise a test to screen military recruits for colour vision deficiency. He was helped by a colour-blind physician who tested the plates, which were originally painted in watercolours and used hirangana symbols. The first edition using Arabic numerals was published in 1917 but few were sold until 1929 when the International Congress of Ophthalmology in Holland recommended its use for testing military personnel. In 1958, it was adopted in Japan as the official test for school children when a law was introduced to require colour vision testing in schools as part of a general medical assessment. (source: http://www.cleareyeclinic.com/ishihara.html). The Ishihara test was not the first pseudoisochromatic test of colour vision; the German ophthalmologist Jakob Stilling had devised his test in 1878 but the Ishihara test has proved to have the best sensitivity and specificity of all the pseudoisochromatic tests.

Classification	Prevalence[b]	Mechanism	Characteristics
MONOCHROMASY			
Typical monochromasy	rare	Once thought to be due to an absence of cones or to cones being filled with rhodopsin but now proposed to be the result of mutation of genes encoding the cone-specific alpha and beta sub-units of the cation channel.[11]	Colour blind. No perception of colours. Colours distinguished by brightness differences only. Very insensitive to red light. Nystagmus. Low visual acuity 6/36 to 6/60. Painless photophobia.
Blue cone monochromasy	rare	S (blue) cone pigment only. No L (red) or M (green) cone pigment	Colour blind. Colours distinguished by brightness differences only. Rudimentary colour vision in mesopic vision from rod and blue cone activation. Very insensitive to red light. Nystagmus. Low visual acuity 6/12 to 6/24. Painless photophobia.
DICHROMASY			
Protanopia[c]	1% of men 0.01% women	Absence of L (red) cone pigment	Very reduced ability to identify colours. Confuse red, yellow and green, white and green, and blue and purple. Reduced sensitivity to red light.
Deuteranopia	1% of men 0.01% women	Absence of M (green) cone pigment	Very reduced ability to identify colours. Confuse red, yellow and green, and white and green.
Tritanopia	1 in 13,000 both men & women equally	Absence of S (blue) cone pigment	Very reduced ability to identify colours. Confuse blue with blue-green and green, and white with yellow.
ANOMALOUS TRICHROMASY			
Protanomaly	1% of men 0.03% women	L (Red) cone pigment absorption spectrum shifted to shorter wavelengths of light	May confuse white with green and confuse reds, yellows and greens but loss of colour discrimination varies greatly between individuals. Reduced sensitivity to red light. Make abnormal colour matches: for example will add excess red in the colour match R + G = Y.
Deuteranomaly	5% of men 0.35% women	M (Green) cone pigment absorption spectrum shifted to longer wavelengths of light	May confuse white with green and confuse reds, yellows and greens but loss of colour discrimination varies greatly between individuals. Make abnormal colour matches: for example will add excess green in the colour match R + G = Y.
Tritanomaly[d]	rare	Partial loss of S cone pigment	Loss of colour discrimination for blues, blue-greens, and greens.

[a] This table is adapted from Table 1 in International Recommendations for Colour Vision Requirements for Transport. CIE Technical Report 143. Vienna; CIE: 2001.
[b] The prevalences quoted are for Caucasians. The prevalence of colour vision deficiencies is generally lower for other races.[14]
[c] Protanomaly and protanopia are collectively referred to as protan colour vision defects, and deuteranomaly and deuteranopia are referred to as deutan defects. Protan and deutan colour vision defects are often collectively described as red-green defects. Tritanopia and tritanomaly are often described as the tritan or blue-yellow colour vision defects.
[d] Tritanomaly is probably a partially expressed form of tritanopia rather than a separate kind of abnormal colour vision.[12,13]

Table 1.[a] Types of congenital defective colour vision in accordance with the classification of von Kries[10]

specificity[7,9,15,19] and can perform acceptably even when it is given under the wrong illumination.[20] Its only problem is that it is so readily available that those who wish to pass, so they can pass the colour vision standard for an occupation, can obtain a copy and learn the correct answers.

Common mistakes in the interpretation of the Ishihara are:

- using the wrong fail criterion leading to misdiagnosis (Table 2 gives advice on the fail criteria to use).
- assuming that patients who make many errors have a severe colour vision deficiency. Number of errors on the Ishihara test is not a measure of severity, except that a very small number of errors may indicate a mild CVD.[7,16]

The Ishihara has plates to differentiate protan and deutan CVD that are well designed but do not always yield a diagnosis. Sometimes the diagnosis is wrong and in 30 to 40 per cent of cases no diagnosis is possible because both numerals are seen or neither is seen.[8,9]

The Ishihara test is published in a full 38-plate edition, an abridged 24-plate

Test	Capability	Interpretation
Ishihara test	Detects protan and deutan CVD with high sensitivity and specificity	Errors on three or more of the numeral plates indicates red-green CVD with a small chance (2%) of misdiagnosing normal colour vision. Five or more errors indicates certain red-green CVD.[1,7,9.15] Number of errors is not a useful measure of severity. Subjects making very few errors will probably have a mild defect but those who make a large number of errors may be mild or severe.[7,16]
	Plates with two numerals, one red and one red-purple, on a grey background may differentiate protan and deutan defects	Failure to see the red numeral indicates protan and failure to see the red-purple numeral indicates deutan. However, these plates do not differentiate protan and deutan CVD in 30% to 40% of cases either because both numerals are seen or neither numeral is seen.[8,9]
Richmond HRR test (2002)	Detects protan and deutan CVD with a sensitivity and specificity only slightly less than that of the Ishihara test. Ideal confirmation test for the Ishihara test.	Two or more errors with the six symbols on the four red-green screening plates indicates abnormal colour vision but a few patients (4%) with normal colour vision will make two errors.[15] Three or more errors indicates certain red-green CVD. The majority (98%) of those with a red/green defect make three or more errors on the screening plates.[15]
	Detects tritan defects	No data on detection of tritan defects with the Richmond HRR 2002 test but the screening plates of the original AO HRR test have been shown to detect tritan defects[17] but not all.[8] If no errors are made on the four symbols on the two tritan screening plates ask if one of each pair of symbols in the tritan screening and classification plates is much fainter than the other. If the tritan symbols look fainter, a tritan defect is probable.[8]
	May differentiate protan, deutan and tritan defects.	Correct classification as protan or deutan on 86% of occasions, 3% wrongly classified, remainder ambiguous.[15] Tritan defects clearly differentiated if detected.[8]
	Classifies severity as mild, medium and strong.	Errors in first five classification plates indicates mild CVD (30% CVDs). Errors on next three classification plates = medium CVD (45% CVDs) Errors on last two classification plates = strong CVD (25% CVDs). However, meaning of 'medium' and 'severe' is uncertain as some mild CVD are classified 'medium' or 'strong' and dichromats may be classified as 'medium'.[15]
Medmont C100 test	Distinguishes protan or deutan abnormal colour vision with high sensitivity and specificity. Test only those who have failed the Ishihara test as CVN patients may make minus or plus settings and there is some overlap in average settings of CVN and CVD observers but there is no overlap of protan and deutan settings.	An average minus setting from five readings diagnoses protan CVD. An average plus setting diagnoses deutan CVD.[18] Magnitude of the average setting is not an index of the severity of CVD. The Medmont C100 should not be used to detect CVD or judge its severity.
Farnsworth D15 test	Categorises those with abnormal colour vision as either 'mild' or 'moderate/severe'.	A fail is defined as two or more diametrical crossings and indicates 'moderate/severe' CVD (60% of CVD). A pass indicates a 'mild' CVD (40% of CVD).
	May differentiate protan, deutan and tritan defects.	Differentiation is possible only when CVD is severe enough for diametrical crossings to be made.

Table 2. Tests recommended for the routine assessment of colour vision

edition and a 14-plate edition for quick screening. It does not matter which edition is used because the fail criterion is three or five errors and total number of errors has no diagnostic significance. It is a pity that the abridged editions omit some of the most sensitive plates.[1] Optometrists will probably wish to have the 38-plate edition even though it contains 13 pathway plates for patients who cannot read, which will rarely be used.

The Ishihara can be used to test the colour vision of children as young as five years. It is important to test colour vision at the earliest age possible, as colour is used as a teaching and communication tool in the earliest years of school. Birch[1] recommends using plates 1, 6, 7, 10, 14 and 24 for young children because those plates use only the numbers 1, 2, 3 and 5, the first numbers learned by children. The tracing plates do not work well with very young children because of their uncertain motor co-ordination and concentration, so it is hard to tell whether inaccurate tracing is due to an inability to see the pathway, a failure to understand or con-

centrate on the task, or unsteady motor co-ordination.

Paediatric optometrists and ophthalmologists may wish to purchase the Ishihara Test for unlettered persons (10 plate: London; Hodder Arnold, 1998; eight plate: Tokyo; Kanehara and Co, 1993). This test is designed for children aged four to six years and contains symbols rather than numbers and has simpler pathways to trace. Birch[1] reports that this test works well and gives detailed advice on how to use it.

Richmond HRR test 2002 4th edition[b]

The Richmond HRR 2002 test (Figure 1) is well worth including in the basic test battery for assessment of colour vision. It serves as a confirmation of the result of the Ishihara test and can guard against the possibility that the patient has learned the correct answers for the Ishihara. It has a sensitivity and specificity almost as good as the Ishihara.[15]

It can also detect tritan defects, which the Ishihara does not. This might be thought to be of little importance as inherited tritan defects are rare, having a prevalence of only 1 in 13,000[21] and blue and yellow are not as important in colour codes as are red, green and yellow, however, tritans can encounter occupational colour problems. Cole[8] reports that in his sample of nine tritans, one was a fashion writer in a metropolitan newspaper, whose aesthetic judgements of blue, blue-green and yellow might well have misled her readers and another was an adviser on interior décor for a carpet manufacturer but she could not appreciate all the subtle variations of blue, green, yellow and off-white in her employer's carpets.

The HRR test in its original AO HRR form has been shown to detect tritan defects[17] although it may miss milder tritan defects.[8] Table 2 gives some advice on how its sensitivity to tritan defects can be enhanced by asking patients about the relative visibility of the two numerals on the tritan plates.

There are other tests for tritan CVD. The Farnsworth F2 plate is known to detect tritan defects very well.[8,22] It is not available commercially but can be made from Munsell colour papers.[1] There is also the Lanthony tritan album, which is commercially available, although its efficacy has not been tested.

The Richmond HRR test can also differentiate protan and deutan defects and it provides a measure of the severity of the colour vision deficiency. It does not fulfil these two tasks perfectly[15] but the information provided can be useful (Table 2).

The last advantage of the HRR test is that it can be used with very young children because it uses symbols, a circle, a triangle and a cross, which can often be named or traced by young children before they can read numbers. Alternatively, key cards can be made so children can identify the symbols they see.

Medmont C-100 test[c]

The Medmont C-100 test (Figure 2) is not well known but it must be a part of the basic battery of colour vision tests. It has only one function, which is to differentiate protans and deutans among those who have red-green abnormal colour vision. It does this exceptionally well with essentially perfect sensitivity and specificity.[18,27] It is an inexpensive test and takes only a minute or two to administer.

It is an important test because the protan and deutan plates in the Ishihara test and the Richmond HRR test cannot be relied on[8,15] and the only other means of diagnosing protan colour vision deficiency is the anomaloscope, an instrument that is to be found only in clinics that have a special interest in colour vision.

A protan diagnosis enables clinicians to provide important advice to patients, namely that they have a loss of the ability to see red signal lights. This is because of the absence of their L cone photopigment in the case of protanopia or a shift of the spectral absorptance of the L cone photopigment to shorter wavelengths in the case of protanomaly. The loss of red light sensitivity is substantial: it can reduce the distance from which red signals can be seen by up to 40 per cent[28,29] and can slow response time to red signals.[30] The loss of red light sensitivity occurs in both protanopes and mildly affected protanomals.[31–33] Mild protanomals have a substantial loss of ability to see red lights. Because of this diminished ability to see red signal lights, protan colour vision deficiency is associated with a higher risk of traffic accident.[29]

The Medmont C-100 can also diagnose women who have normal colour vision but

b. The HRR pseudoisochromatic test was developed by Hardy, Rand and Rittler.[23,24] It was first published by the American Optical Company in 1955 and therefore, is known as the AO HRR test. A second edition was published in 1957 using material from the first print run but with a rearrangement of the order of the plates. The AO HRR test has long been out of print to the grave disappointment of the colour vision cognoscenti, who liked its elegant design principles and its ability to detect tritan defects and to classify and grade colour vision deficiencies.

Richmond Products published a replica of the test in 1991 but it was not well received. On the basis of his colorimetric analysis, Dain[25] concluded that it 'was a pale imitation of the real thing'. Richmond Products published a fourth edition in 2002, the colours of which had been carefully re-engineered with the assistance of Jay and Maureen Neitz and James Bailey.[26] Colorimetric analysis shows that the colours of the 2002 edition align well to the confusion loci[25] and it performed creditably in a recent validation.[15] It is a test well worth adding to the battery of colour vision tests in private clinical practice. It is available from Richmond Products http://www.richmondproducts.com/13396RHRR4thEditionProduct.htm.

c. The Medmont C-100 owes it origin to Estvez and colleagues,[36] who thought of applying the principle of flicker photometry (sometimes referred to, not always correctly, as silent substitution[18]) to the assessment of colour vision. The first commercially available instrument using this principle was the OSCAR, produced by a Dutch company Medilog. OSCAR stands for 'objective screening of colour anomalies and reductions'. OSCAR is no longer produced and the Medmont C-100 is its successor.

The Medmont C-100 presents a single light generated by two flashing red and green LEDs that alternate at 16 Hz. Only one of the LEDs is on at a given time but the flash rate is such that the appearance of the stimulus is a flashing yellow light. A single control operated by the patient adjusts the relative luminances of the two LEDs, while keeping the luminance of the resultant flashing yellow stimulus constant. The patient is instructed to adjust the control until the flicker is a minimum. This occurs when, for the particular patient, the brightness of the light from the red and green LEDs is equal. Protans choose a setting of the control that increases the brightness of the red LED compared to that set by patients with normal colour vision because they have reduced sensitivity to red light, while deutans choose a setting that increases the brightness of the green LED. The Medmont C-100 is available from the Australian company Medmont International Pty Ltd. http://www.medmont.com.au/.

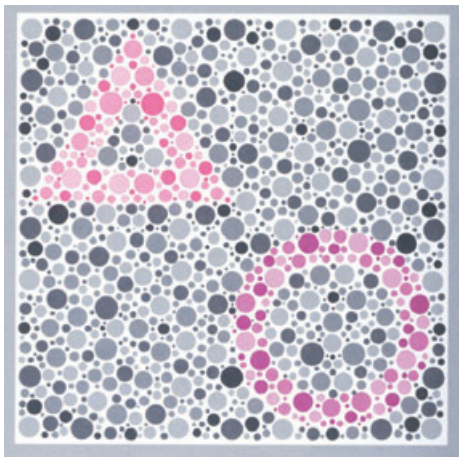

Figure 1. A diagnostic plate from the Richmond HRR test. The colours of the symbols lie (in this case) on the protan and deutan confusion loci. This means that depending on the saturation of the colour of the symbols and the severity of the colour vision deficiency, they may not be distinguished from the grey dots of the background. They are 'vanishing' plates, as are some of the plates in the Ishihara. There are also plates where the symbols have colours that lie on the tritan confusion loci. The tritan plates in the HRR test also have symbols with colours that lie on the so-called tetartanopia confusion locus but as tetartanopia does not exist, these are not of any value. There are 20 plates, four for screening red-green (protan/deutan) CVD, two for blue-yellow (tritan/tetartan) CVD, 10 for classifying and assessing the severity of red-green CVD and four for classifying and assessing the severity of blue-yellow CVD. All the plates are based on the same principle illustrated in this figure but the symbols on the screening plates are very desaturated and the plates grading severity progressively increase in saturation.

Figure 2. The Medmont C-100 test. Left: The subject views a yellowish flickering light generated by alternating red and green LEDs and adjusts the control knob until the flicker disappears or is a minimum. Right: The settings chosen to achieve no or minimal flicker are read on an arbitrary scale from -5 to +5, where +2.0 to -2.0 is the extreme range of normal settings but typically colour vision normal settings are within ±1.0. The scale is colour-coded red for protan settings, green for deutan and yellow for normal.

Figure 3. The Farnsworth D15 test. The patient arranges the 15 loose colour caps in order of colour starting from the fixed colour cap. After the patient has reviewed the arrangement and is satisfied with it, the order of the colours as arranged by the patient is recorded on a circular diagram, on which colours are represented by the numbers 1 to 15. Patients with normal colour vision usually make no error but may make one or two minor transpositional errors, as do those with mild CVD. Those with a moderate-to-severe CVD make more dramatic errors: they place colours that lie on the opposite side of the colour circle, those that lie on their confusion locus, next to each other. These are diametrical errors and two or more diametrical errors is a 'fail'.[37] If diametrical crossing errors are made, the orientation of the crossing enables a diagnosis of protan, deutan or tritan to be made.

are carriers of the abnormal gene for protanomaly or protanopia.[18,34,35] It does this by detecting Schmidt's sign, which is a loss of red light sensitivity exhibited by protan heterozygotes. It seems it will also diagnose deutan heterozygosity.[35] Clinicians can use the Medmont C-100 to advise women who have a brother with CVD whether they are carriers. The heterozygosity of the mothers of CVD sons can also be demonstrated with the Medmont C-100 but this is not necessary as the CVD of their sons is sufficient proof of their heterozygosity. It is also unwise to test the heterozygosity of mothers because the mother might not be the birth mother.

Farnsworth D15 test[d]

The Farnsworth D15 test (Figure 3) is the best known and most widely used of the colour sorting tests and must be part of primary care colour vision assessment. It categorises patients with abnormal colour vision into one of two categories: those who pass and have a 'mild' colour vision deficiency and those who fail and have a 'moderate-to-severe' deficiency. The test has good test-retest reliability for pass/fail with a coefficient of reliability of between 0.96 and 1.0.[37]

The primary use of the D15 is categorisation into 'mild' and 'moderate/severe' but if the test is failed the orientation of the diametrical crossings gives information on the type of CVD. It can be relied on for classification by type when there are diametrical crossings.[37]

There is some uncertainty about the criterion for failing the Farnsworth D15 test. The criterion could be any error but those with normal colour vision sometimes make simple transposition errors and would fail with this criterion. It could be one diametrical crossing, which might be taken as indicating a substantial loss of colour discrimination but some patients, even those with normal colour vision, make a single diametrical crossing from colour 7 to colour 15 because there is a large colour difference between colours 7 and 8. Two or more diametrical crossings is widely accepted as the best criterion for a fail.[37]

The test was originally designed[38] to set a level of difficulty such that those who passed it would be able to identify the colours of wires used in transformers. Clinicians have widely presumed that those who pass the Farnsworth D15 test have a mild deficiency that is unlikely to cause significant handicap in everyday colour tasks. This is not entirely true: while many of those who pass the D15 test can recognise the colours of signal lights and recognise complex surface colour codes, a good number cannot (Table 3).

Other sorting tests

There are several other sorting tests that are commercially available and could be included in the basic battery of colour vision tests. There are several variants of the Farnsworth D15 test, including the Lanthony and Adams tests that use desaturated colours to set a higher level of difficulty, so that those who have CVD and pass can be presumed to have a very mild deficiency. The H16 test uses more saturated colours than the D15 and therefore sets a lower level of difficulty to identify those with severe colour vision deficiency but it is not commercially available. The City University Test is also a derivative of the D15 test. It sets a level of difficulty similar to the D15 test but is in book form.

Other sorting tests are the Lanthony's New test, the Roth 28 hue test, the Lanthony 40 hue test and the Hahn double 15 hue test. The Hahn test combines the function of the standard D15 test and the Lanthony desaturated test. Last but by no means least, there is the well-known and widely accepted Farnsworth-Munsell 100 hue test that requires a hue circle of 85 closely spaced colours to be arranged in order of colour. It provides a measure of hue discrimination and has good norms but it takes from 10 to 15 minutes to administer and for this reason is not often used in primary care clinical practice.

With the exception of the Farnsworth Munsell 100 Hue test, which takes time to administer, none of these alternative sorting tests has wide acceptance and all lack a body of experience and experimental evidence relating the test result to performance at practical tasks. For these reasons, the Farnsworth D15 is the test of choice for a primary care clinical practice.

The Lanthony Desaturated Test could be considered as a further test to identify CVD patients who have a very mild defect. Hovis, Lu and Neumann[39] found that this test was good for identifying those with a CVD that was sufficiently mild to enable them to recognise the colours of electrical wires.

Recommended lighting of the tests of colour vision

The Ishihara, the Richmond HRR test and the Farnsworth D15 test are designed to be given under lighting that is close to illuminant C. This is especially important for the HRR test and the Farnsworth D15 test, although lighting is not as critical as is often thought.[20,41] Lighting can be a problem as most optometrists will prefer to administer these tests when the patient is in the examination chair and the local

d. The Farnsworth D15 test was designed by Dean Farnsworth, who worked for the Munsell Division of the Kollmorgen Corporation in the 1940s and also in the Department of Psychology at New York University, where he designed the Farnsworth-Munsell 100 hue test and the precursor to the Farnsworth D15 test, both of which use Munsell colour papers. Later, he worked at Medical Research Laboratories at the Naval Submarine Base (NSMRL) in Connecticut, USA, where he was a Commander in the US Navy. He designed the Farnsworth Lantern test while he was at the NSMRL. He was highly regarded in colour science and the first issue of *Vision Science* in 1962 was dedicated to him to mark his death in 1959. His photograph, resplendent in his Naval commander's uniform, is the frontispiece to the first issue.

The Farnsworth D15 was originally designed in 1943 as the B20 test with 20 colours but it lost a few colours in its evolution to a commercially available product. The D15 test presents 15 colours in a random order with a 16th colour fixed as the starting point for arranging the colours in order of hue. The colours lie on a hue circle around illuminant C so that all colours from red, through yellow, green, blue to purple are represented. The colours have been chosen so that pairs lie on dichromatic confusion loci. For patients with a moderate-to-severe colour vision deficiency the pairs of colours on the confusion loci look the same and are placed next to each other, a startling misarrangement for a person with normal colour vision. Dain[40] gives a good account of the principles and technical details of sorting colour vision tests including details of quantitative scoring methods. The Farnsworth D15 test is available from Gretagmacbeth and its resellers http://www.gretagmacbeth.com. Gretagmacbeth is a division of X-Rite Incorporated and is the successor to the Munsell Color Company.

Study	Colour task and criterion for satisfactory performance	$P_{(P)}$	$P_{(F)}$
Cole, Lian and Lakkis[52]	Naming 10 surface colours of various sizes. No more than one error	0.73	0.90
Ramaswamy and Hovis[49]	Naming 8 VDU generated colours. 99th percentile of CVN observers	0.70	0.90
Hovis, Lu and Neumann[39]	Naming 10 colours of large gauge (3.5 mm) electrical wire colours. 95th percentile of CVN observers	0.73	0.72
	Naming 10 colours of small gauge (1 mm) electrical wire colours. 95th percentile of CVN observers	0.82	0.94
Cole and Orenstein[50]	Naming 10 colours of paint, fabric and cotton samples: large sizes. ≤2 errors (max error made by CVN)	0.76	0.73
	Naming 10 colours of paint, fabric and cotton samples: small sizes. ≤3 errors (max error made by CVN)	0.69	0.80
Cole and Maddocks[47]	Naming 3 signal colours (R, G, W) of the Farnsworth lantern test. ≤2 errors in runs 2 and 3.	0.59	0.96
Cole, Lian and Lakkis[48]	Naming 3 signal colours (R, G, W) of the Farnsworth (Optec 900) lantern test. ≤2 errors in runs 2 and 3.	0.32	1.00
	Naming 3 signal colours (R, G, W) of the Farnsworth (Original) lantern test. ≤2 errors in runs 2 and 3.	0.39	0.98

Predictive value of a pass, $P_{(P)}$ = Number who pass the test and perform as well as those with normal colour vision/Number who pass the test. Predictive value of a fail, $P_{(F)}$ = Number who fail the test and perform less well than those with normal colour vision/Number who fail the test. This Table is an adaptation and extension of Table 5 in Cole, Lian and Lakkis.[52]

Table 3. Farnsworth D15 test predictive values of passing, $P_{(P)}$ and of failing, $P_{(F)}$ reported by or derived from various studies

light source may be an incandescent lamp. Optometrists should give consideration to lighting of the tests they use for colour vision testing. This can be provided by a daylight fluorescent lamp (colour temperature about 6500 K and preferably a high colour rendering index greater than 90)[e] or preferably a specially designed easel light such as the 'True Daylight Illuminator' sold by Richmond Products (http://www.richmondproducts.com/1339 Rilluminator.htm), which is very reasonably priced.

e. Suitable fluorescent lamps with the right colour temperature and excellent colour rendering properties are readily available and can be used to replace standard fluorescent lamps in the consulting room. These lamps are recommended for use in hospitals to ensure best rendition of skin and tissue colours that are often important diagnostic indicators in clinical practice. They are worth installing in optometric consulting rooms for this reason as well as to illuminate colour vision tests properly.

ADVICE TO PATIENTS

The difficulties of giving advice

Clinicians know that it is not always easy to explain eye conditions to patients and advise on the consequences of those conditions. There is always great potential for misunderstanding and misremembering. It is no different for patients diagnosed to have abnormal colour vision, although there is the special problem of the colour vision normal practitioner talking about colour to a CVD patient, whose experience of colour is totally different. When the practitioner is also colour vision deficient, the biblical injunction 'And if the blind lead the blind, both shall fall into the ditch' (Matthew 15:14) comes to mind.

It should not be assumed that the patient who learns of his abnormal colour vision for the first time will receive the news with interest or gratitude. Some will reject the advice. Steward and Cole[2] report that of the 18 patients in their survey who were previously unaware of their abnormal colour vision, half expressed disbelief and denied they had any problem with colour and half were accepting and acknowledged that on reflection they did have problems with colour. Pickford and Cobb[3] found 44 per cent of a sample of 36 subjects diagnosed to have CVD for the first time exhibited denial, which they define as 'a wide range of attitudes from plain disbelief in the tests to an unwillingness to agree that the defect, if it does exist, would have any influence on their daily life'. Only 22 per cent of the sample demonstrated a coping attitude, that is, acceptance of the defect and an effort to adapt. The rest of the sample exhibited some form of overcompensation about their defect.

Optometrists are well versed in colour vision and know the characteristics of abnormal colour vision but principally in terms of the colours likely to be confused and luminosity functions, they have not

experienced the coloured world of those with abnormal colour vision. It is now possible to transform colour images to represent their colour appearance for dichromats: the digital technology is available and the physiological mechanisms of normal and abnormal colour vision are well enough known for transformation algorithms to be constructed.[42,43] Transformation programs are freely available on the internet so any digitised colour image can be transformed.[44,45]

Transformation of colour images to dichromatic appearance can provide the clinician with a fuller appreciation of the coloured world of those with abnormal colour vision. Figures 4 to 8 illustrate the coloured world of dichromats. In essence their coloured world is yellow, white and blue with variations of saturation and brightness of these colours—a diversely coloured world as the Figures show but decidedly less colourful than that of a person with normal colour vision. Figures 4 to 8 are worth studying to gain an appreciation of the difficulties that people with severe colour vision deficiency can experience.

Predicting problems with colour from clinical tests

There are now several investigations that have related the results of clinical colour vision tests to performance at practical colour tasks. Those that investigated the predictive ability of the Farnsworth D15 test are summarised in Table 3.

In essence, these investigations show that almost all patients (more than 95 per cent) who fail the Farnsworth D15 test will make errors identifying the colours of signal lights[46–48] and surface colour-codes.[39,49–52]

Of those who pass the Farnsworth D15 test most (approximately 75 per cent) will be able to recognise surface colour-codes without error or very few errors. A 'mild' classification by the Richmond HRR test is an even better predictor: almost all (87 to 100 per cent) will make no or few errors with surface colour-codes.[49,52,53] More than one half of those who pass the Farnsworth D15 will have problems with signal lights, especially aviation and maritime signal lights, which can have low illuminance and small angular size because they are often observed at long distances.

General advice

Table 4 summarises the advice the primary care clinician can give to patients with abnormal colour vision and is based, in part, on the investigations summarised in Table 3. More information about the practical consequences of abnormal colour vision is to be found in the review by Cole.[54]

The top section of Table 4 lists the general advice that can be given to all patients with abnormal colour vision: that they have a colour vision deficiency, that it is inherited and there is no really effective treatment. Figure 9 has been included to remind practitioners of the mode of inheritance of the red-green CVDs and it can also be used as an aid for explanation to patients.

The subsequent sections of Table 4 detail the further advice that can be given on the basis of the results of the Richmond HRR test, the Medmont C100 and the Farnsworth D15 test.

Career advice

It is difficult to give definite advice to patients on career choice. Some occupations have a statutory colour vision requirement but these vary between countries and between states within countries and are often poorly defined and administered. Moreover, they are often appealed against in the courts and every successful or partly successful appeal causes change to the colour vision requirements or the way they are administered. There are also several occupations, for which there is no statutory colour vision requirement but for which abnormal colour vision is a handicap.[54] For these reasons, it is not possible to provide a comprehensive list and full details of all occupational colour vision standards in this paper.

Occupational colour requirements fall into two broad categories.

1. Normal colour vision

Normal colour vision is required for occupations that involve precise colour matching and for occupations for which it is deemed that recognition of signal lights and other colour codes is absolutely critical to safety. These include deck officers and seamen, train drivers, air traffic controllers (in Australia) and some occupations in the defence forces. All patients with CVD, however mild, can be told that it is very likely that these careers will not be open to them.

2. Defective colour vision that is sufficiently mild to enable the colour task to be performed

The two most common occupational colour tasks that give rise to an occupational colour vision standard are the recognition of signal lights and surface colour codes. Usually, the ability to recognise signal lights is tested using a lantern test, which simulates the task. Sometimes, the ability to recognise surface colour codes is tested using the Farnsworth D15 test or a trade test, however, it is worth noting that a lantern test can be used to test the ability to recognise surface colour codes: those who pass the Farnsworth lantern test are able to recognise surface colour-codes.[55]

The Farnsworth lantern test is used to test colour recognition ability of CVD entrants to civil aviation and the defence forces in Australia and the USA. About 20 to 30 per cent of those with abnormal colour vision pass the Farnsworth lantern test.[48] Fewer are able to pass lantern tests such as the Holmes-Wright and Spectrolux lanterns used in the UK and some European countries because they simulate more difficult conditions of observation.[46,56,57]

Table 5 summarises the advice that could be given to patients about the occupations that have a colour vision standard or for which abnormal colour vision is likely to be a handicap. Patients with abnormal colour vision who have yet to settle on a career could be given a photocopy of Table 5 to help choose a suitable career.

Table 5 is not complete; there are several other occupations for which abnormal colour vision may be a handicap, including identifying and grading gems in the jewellery trade, cotton and wool

Figure 4A. Connotative use of colour. The most common connotative use of colour is in road traffic signals. Signal colour conveys a message. For the deuteranope (centre) and the protanope (bottom) the signals are less obvious, although their colour can be deduced by their position in the signal array and the brown-orange appearance of the red signal and the white appearance of the green signal. The brake lights on the car are also less obvious, however, the colours of the yellow turn indicator and the yellow warning signs are preserved, as is the blue in the information signs. The green direction sign becomes dark grey and has lost colour contrast with the background. The transformations in this figure and all subsequent figures have been made using the Vischeck algorithms.[45]

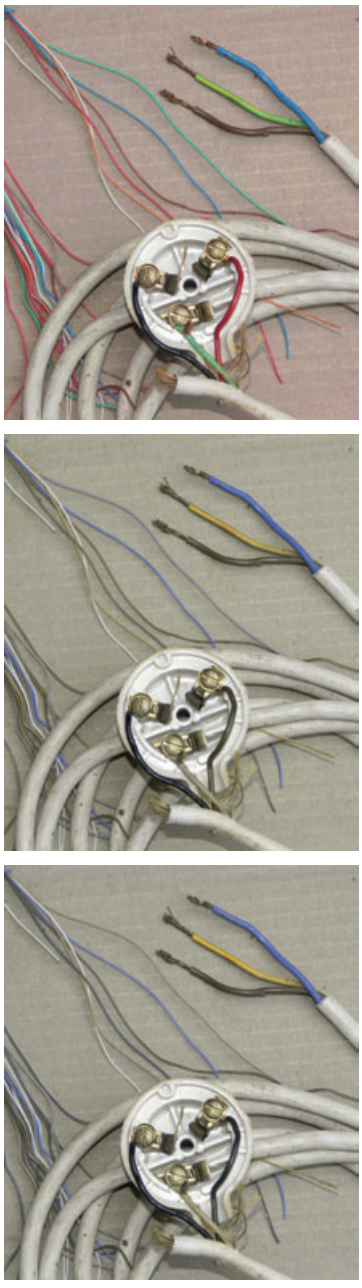

Figure 4B. Connotative use of colour. Another common connotative use of colour is to identify telecommunications and electrical cables. Deuteranopes (centre) and protanopes (bottom) can identify the blue, yellow and white colours but will tend to make errors with the red, green, brown and black code. Obviously, they will have problems with the telecommunications cable code because there are more colours. They will recognise the blue and white cables but will be uncertain about the red, orange, brown and green.

Figure 5A. Connotative use of colour. Colour indicates how well meat is cooked. About 22 per cent of people with abnormal colour vision report that they have problems judging when meat is cooked.[2] This photograph and its transformations to the colour appearance for deuteranopes (centre) and protanopes (right) shows that their lack of perception of red makes it hard for them to identify the uncooked piece of meat.

Figure 5B. Connotative use of colour. Colour indicates ripeness of fruit. Nearly 30 per cent of people with abnormal colour vision report they have trouble judging the ripeness of fruit,[2] however, it is evident from these transformations to deuteranopic (centre) and protanopic (right) colour perceptions that lightness/darkness and yellowness provide cues for judging ripeness and for differentiation of different kinds of fruit and vegetables, even if they do not look so appetising for those of us with normal colour vision.

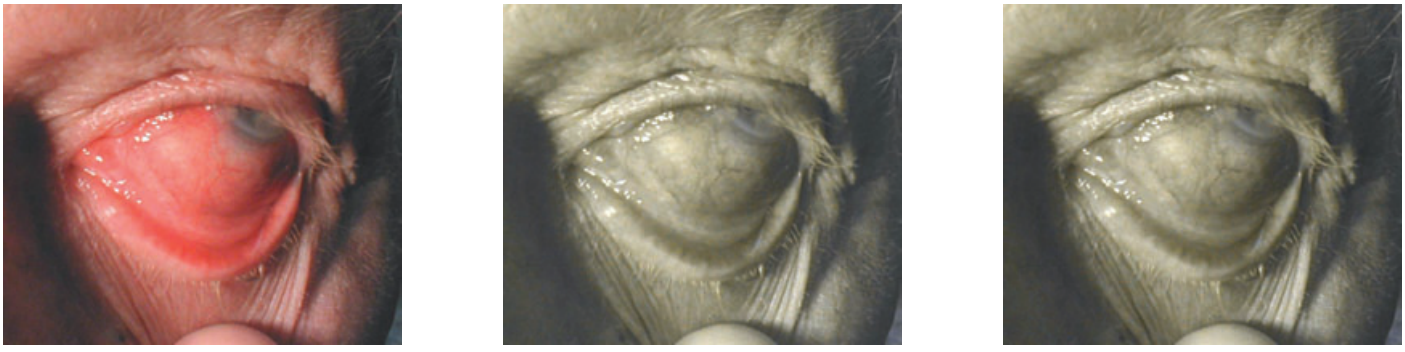

Figure 5C. Connotative use of colour. Colour is a natural connotative code for the diagnosis of illness. Medical practitioners and optometrists who have abnormal colour vision often report that they have trouble seeing redness of inflammation.[69,71] Eighteen per cent of those with abnormal colour vision report that they have difficulty seeing skin rashes and sunburn.[2] They also report that they do not see blushing.[71] These transformations to deuteranopic (centre) and protanopic (right) colour perceptions of a red eye demonstrate this problem.

Figure 6A. Denotative use of colour. Colour is often used to distinguish an object from others that are similar, as is illustrated by the phrases 'my car is the red one' or 'get me the red file'. This is especially the case in police work, where colour is often used to describe suspects, evidence and motor cars. The transformations to deuteranopic (centre) and protanopic (bottom) colour perceptions show that those with dichromatic vision cannot easily locate cars by a colour descriptor. They will be able to identify the yellow car and the blue, white and silver cars but not the red and green cars. Note that the illuminated brake lights in the red car in the second row of parked cars are not evident in the dichromatic transformations.

Figure 6B. Denotative use of colour. Colour is often used as an identifier at school. An instruction to colour a drawing in a certain colour can be bewildering for the colour vision deficient school child, as these transformations of coloured pencils and pens to deuteranopic (centre) and protanopic (bottom) colour perceptions illustrate. Parents should write the names of the colours on the pencils.

Figure 7A. Colour in search. Colour often marks out objects and facilitates search for them. The flowers are very hard to see in the deuteranopic (left: centre) and protanopic (left: bottom) transformations. It is well known that those with abnormal colour vision have difficulty seeing flowers on trees and bushes, especially from a distance. Blake[75] says it was many years before he realised what people were talking about when they admired flowering gum trees. He also reports that when he and his family went strawberry picking his bag was still nearly empty when those of his family were filled quickly. He could not see red strawberries on the bushes.

Figure 7B. Colour in search. Colour aids search as the CVD golfer knows from his inability to find red tees. The red tee and the piece of red wire are easily seen on the grass in the colour normal photograph (right: top) but are hard to see in the deuteranopic transformation (right: bottom). The orange golf ball is visible but mainly because of the white shine on the ball.

Figure 7C. Colour and search. Colour coding in maps is used to code the class of feature (connotative) and also to mark out and differentiate (denotative) for example, blue for district names and route numbers. These maps are useable for dichromats despite their reduced colour palette but search for particular features will be a little harder. For example, find the four post offices in the dichromatic transformations, which are coded as red dots in the original map. The best colour coding for maps is clearly to use yellow, blue and either red or black. This illustration from a street map of Melbourne published by Melway shows that the map designers have done well by the colour blind. Deuteranopic transformation only is shown on right.

Figure 8A. Aesthetic value of colour. The dichromats may see a diminished range of colours but can still appreciate the colourfulness of flowers, albeit with some colours missing and the green foliage looking less green and fresh. Only the deuteranopic transformation is shown.

Figure 8B. Aesthetic value of colour. The painter of the painting on the left is an extreme deuteranomal and an enthusiastic amateur artist. Some of his paintings tend toward monochrome using blues and greys with touches of yellow but some are boldly colourful, like the one illustrated.[76] In his colourful paintings he avoids the use of green. He sees the deuteranopic transformation (right) as having the same colour appearance as the original painting.

Figure 8C. Aesthetic value of colour. Dichromats (deuteranope right) have a different appreciation of the colours of Autumn as commented on by Blake.[75] Photo: V Maczynski. Reproduced with permission. Authorisation L7W9KTX6.

Test	Test result	Advice to patient
Ishihara	Fail 3 or 4 errors probable CVD ≥5 errors certain CVD	Red-green abnormal colour vision. Inherited colour vision deficiency affecting 8% of men and 0.4% of women. Sex linked recessive inheritance: inherited from mother (women are carriers of the abnormal gene, which is expressed in 50% of their sons). All daughters of a male CVD patient will be carriers but sons will have normal colour vision. (Figure 9). There is no treatment for abnormal colour vision. Claims have been made that certain coloured lenses will help. They may enable some colour vision tests to be passed by altering the colours in the test but there is little evidence that they are beneficial in everyday colour tasks,[1,60] except to help differentiate colours that look the same to the CVD observer (for example, using a red filter to distinguish retinal haemorrhage from melanin pigment).[71] Great variability in loss of colour discrimination but almost all will experience some problems with colour[5] although if the CVD is mild, they will not necessarily be of any practical consequence. All are unsuitable for precise colour matching tasks either because of loss of colour discrimination or anomalous metameric colour matching or both. All will have some loss of ability to search for objects marked out by colour, even if the deficiency is mild.[61] A few occupations require normal colour vision (for example, master, mate and navigational watchkeepers of ships; train drivers) and, depending on severity of the CVD, may be precluded from other occupations by a colour vision standard (Table 5). May have problems in other occupations that use colour extensively (for example, graphic design, artist, architect, medical practitioner).[54]
Richmond HRR 4th edition 2003	Fail RG screening plates 2 errors probable CVD >2 errors certain CVD	Red-green abnormal colour vision confirmed
	One or more errors with tritan symbols on screening plates and/or classification plates.	Blue-yellow abnormal colour vision, which may be tritanopia or tritanomaly, the latter being a partial expression of the abnormal gene for tritanopia.[12] Inherited colour vision deficiency affecting 1:13,000 people, men and women equally affected.[21] Autosomal dominant inheritance.[22,62] Will tend to confuse blue, grey and yellow; white and yellow; blue, blue-greens and green.
	Errors only on first 5 classification plates ('Mild')	Mild anomalous trichromasy.[15] Most (>85%) will be able to name surface colour-codes with no or few errors, especially if <3 errors made with the classification plates.[49,52,53]
	Errors on next 3 classification plates ('Medium') or last 2 classification plates ('Strong')	Has a moderate or severe colour vision deficiency. Will be either a dichromat or moderate anomalous trichromat. The distinction between medium and strong is not useful.[15]
Medmont C-100	Average of 5 settings is minus (having failed the Ishihara test)	Has a protan (red) deficiency. Affects 2% of men and 0.04% of women. Will have difficulty seeing dim or distant red signal lights regardless of severity of CVD.[31–33] Higher risk of traffic accident because red signals may not be seen or not seen in time.[28,29]
	Average of 5 settings is plus	Has a deutan (green) deficiency
Farnsworth D15	Pass: no errors arranging the colours, or only minor transpositions or only 1 diametrical crossing	Mild anomalous trichromasy. Most (75%) are able to recognise surface colour-codes with no or very few errors. Most errors will be to confuse red, orange and brown or blue and purple. Almost all will be able to recognise a seven-colour code without error, especially if the stimuli are large.[39,50–52] About 40% will pass the Farnsworth lantern test,[47,48] which is used in aviation and defence forces in Australia and USA to test whether colour vision is 'safe'. Fewer will pass the lantern tests in use in Europe.[56,57]
	Fail: two or more diametrical crossings	Has a moderate or severe colour vision deficiency. Will make errors recognising colours of surface colour-codes.[39,49–52] Children can be helped by labelling pencils with colour names. Will have problems with signal lights and will fail lantern tests.[46–48] Will be excluded from occupations that use a lantern test to assess colour vision.

Table 4. Advice that can be given to patients with abnormal colour vision

OCCUPATIONS INVOLVING COLOUR MATCHING	
Colour matching and quality control of colour in paint, textile and plastics industries	Normal colour is necessary as all people with CVD have some reduction of colour discrimination and those with mild CVD will make anomalous colour matches that are not acceptable to those with normal colour vision. Employers usually test the colour vision of employees before they are assigned to a colour-matching job. This may include colour aptitude testing using a test such as the ISCC Color Aptitude test to select those with superior ability from among those with normal colour vision.
Painter and decorator	Painters may be required to mix colours to match a sample colour or an existing colour. No formal colour vision standard. Normal colour vision desirable.
Cabinet making and joinery	CVD may be handicap in matching woods and timber stains although there is little empirical evidence to confirm this but see Voke.[59]
TRANSPORT	
Maritime	Normal colour vision is required for deck officers and navigational watch-keepers of commercial vessels over a given size in most countries under ILO Convention 147. Colour vision standards for below-deck officers and crew, which exclude those with moderate-to-severe CVD.
Aviation	Commercial pilots must pass a lantern test, which excludes 75% to 80% of applicants with CVD if the Farnsworth lantern is used,[48] as it is in Australia and USA. Other lantern tests used in Europe have a higher fail rate.[56,57] Sometimes a waiver is issued for those who fail the colour vision standard but this may restrict employment opportunities. Private pilots with CVD may be restricted (for example, to daylight flying) if they fail the pilots colour vision standard. Air traffic controllers have to pass the pilots colour vision standard but normal colour vision is required in Australia (and possibly other countries) because of the introduction of elaborately colour-coded computer displays for air traffic control. Airport ground staff may be subject to a test of colour vision to exclude those with moderate-to-severe CVD because coloured signals and markings are used on airport aprons.
Rail	Train drivers and signallers are usually required to have normal colour vision because signal lights are critical to rail safety. Rail workers in other safety critical positions have to pass a colour vision test, usually a lantern test, which excludes those with moderate-to-severe CVD.
Road	Bus and tram drivers are often subject to colour vision test. Standard may require normal colour vision or passing a lantern test. Very few jurisdictions have a colour vision standard for private drivers or commercial drivers. Those with moderate-to-severe CVD should be warned of the risk of making errors with signal lights, especially those with protan CVD.[29] CVD drivers are helped by residual colour cues, especially if the signals are well designed (for example, bluish-green green signal, high intensity red signal), by position cues and the flow of other traffic.
DEFENCE AND SECURITY FORCES	
Armed forces	Armed forces have colour vision standards that apply to a wide range of occupations within the armed forces but not all. Normal colour vision may be required for critical occupations, such as aircraft pilots and officers and deck crew in the navy. Otherwise, passing a lantern test is usually required, which excludes 75% to 90% depending on the lantern used, or there may be a trade test.
Police	Police have to be able to recognise the colours of signal lights without hesitation, especially when driving at risk. They need to be able to use colour to identify and describe people and vehicles, to describe evidence using colour descriptors and be able to search for objects marked out by colour. There is usually a colour vision requirement for entry into the police force. In some jurisdictions normal colour vision may be required but usually the standard is based on a lantern test, which excludes about 80%.
Fire and rescue services	Firefighters need to be able to recognise colour codes on containers of hazardous substances and on pipelines.[63] Flame colour is an important cue to judging the nature of a fire. Fire appliance drivers need to recognise traffic signal colours without hesitation, especially when driving at risk. Rescue workers need to be able to search for objects marked out by colour. Fire and rescue services usually have a colour vision standard that excludes those with moderate-to-severe CVD.
OCCUPATIONS THAT REQUIRE SURFACE COLOURS TO BE RECOGNISED	
Telecommunication technician/linesman, Electronics technician	Telecommunication cables are colour coded with 10 or more colours and there is no redundancy. Telcos usually have an in-house colour vision standard for their technicians and linesmen. Those with moderate-to-severe CVD should not choose to train as a telecommunication technician/linesman.
Electrician	Electrical cables are coloured-coded but usually with a limited number of colours (green, black, red, blue but sometimes orange, brown, cream, violet and grey).[64] There may be redundancy (for example, green and yellow stripes on the earth cable and alphanumeric markings) but not always, so there is a risk of error if the colours are confused. This may occur especially with old or soiled cables or when light is poor. Electricians may be subject to a trade test on entry to training. Those with moderate-to-severe CVD should not choose to train as an electrician.

Table 5. Occupations for which abnormal colour vision is a handicap

Monitor of power and telecommunication networks or industrial processes or other complex systems	Power and telecommunication networks, industrial processes and other complex systems are often monitored using colour-coded computer displays. These can use 10 or more colours. Often there is redundancy but not always. Even when there is redundancy, those with CVD will be slower and more likely to make errors.[65] Many employers test colour vision to ensure that those employed to monitor processes or systems by means of colour-coded computer screens will be able to distinguish the colours. This will be particularly in those industries in which errors may lead to serious economic loss or loss of life. The colour vision tests will exclude those with moderate-to-severe CVD but normal colour vision is sometimes required where the consequences of accident are very serious.
Medical practitioner	There is no colour vision standard for entry into a medical course (except in some Eastern countries, notably Japan, but it has recently relaxed its requirements).[66] However, diagnosis of disease often requires colours to be recognised (pallor, rashes, jaundice, cyanosis, redness of inflammation, blood in vomit and faeces, dip-stick test for diabetes and other colour-coded diagnostic tests). It is known that CVD medical practitioners can fail to see the colours diagnostic of disease[67,68] and may make diagnostic errors as a result.[69] CVD medical practitioners should know they have abnormal colour vision so they can guard against the risk of error when colour is important to diagnosis or choose to practise in a branch of medicine that is not reliant on colour for diagnosis.[70]
Optometrist	There is no colour vision standard for entry into an optometry course but CVD optometrists will have problems differentiating retinal haemorrhage from melanin pigment spots (they can use a red-free filter to help), judging pallor of the optic nerve head and seeing inflammation of the anterior surface of the eye and surrounding skin.[71]
Dentist	There is no colour vision standard for entry into a dental course but CVD dentists will have problems seeing oral inflammation and judging patients' health from skin colour. They may also have problems matching teeth colour in restorative and prosthetic dentistry and should be encouraged to seek the advice of their colour normal assistant in making these colour matches.[72]
Pathologist and other occupations in the biological sciences that involve histology	Pathologists use coloured stains to differentiate cellular structures and mark diseased tissue. CVD pathologists have been shown to make more errors with certain stains than those with normal colour vision.[73] There is no colour vision requirement for pathologists but it is recommended that CVD pathologists should be aware of their colour vision deficiency and be helped to find adaptive strategies to avoid error, however, at least one CVD pathologist disagrees.[74]
Horticulturist	Colour of flowers and fruits is important in horticulture. CVD may be a handicap but there is no evidence to show that this is the case. CVD fruit pickers may be slower and fail to see fruit to be picked according to one person with CVD.[75]
Fruiterer	Colour is used to judge the ripeness and quality of fruits. CVD is likely to be a handicap as is shown in Figure 5b.
OCCUPATIONS THAT INVOLVE AESTHETIC JUDGEMENT OF COLOUR	
Architect Interior decorator Artist Graphic artist/designer Fashion designer Fashion retail	Usually no colour vision standard for entry to these occupations but moderate-to-severe CVD will be a handicap. They can adapt, as many CVD artists have,[76] by limiting their colour palette to blues, yellows, white, greys and blacks. Those with CVD should think carefully before deciding on careers of this kind. Steward and Cole[2] recount an anecdote of how one deuteranopic retail shop assistant adapted: she asked to be transferred to the largely black and white world of men's formal wear and asked a colleague to arrange coloured shirts, ties and cummerbunds in order of colour.

Table 5. Continued

graders, using colour-coded maps as a geographer, meteorologist or demographer, and judging freshness of meat in meat processing.[58,59]

CONCLUSION

Optometrists should test the colour vision of every new patient at the time of their first visit to the practice using the Ishihara Test and a test for tritan defects, which can be the Richmond HRR 2002 test or the Farnsworth F2 test, if the practitioner is prepared to make the F2 test using Munsell papers.

Those who fail should be further assessed. The further tests recommended for primary care practice are the Richmond HRR 2002 test, the Medmont C-100 test and the Farnsworth D15 test. These tests can be relied on to provide sufficient information to enable patients to be told the type of CVD they have and whether it is mild or moderate-to-severe. The enthusiastic practitioner might add the Lanthony Desaturated test, which can identify CVD patients with very mild CVD, however, a few people with normal colour vision make errors on the Lanthony test, which means it does not provide any useful information when a CVD patient makes errors. The test is useful only when CVD patients make no errors, from which it can be concluded that they have very mild CVD, as they have performed as well as the better performing colour vision normal patients.

On the basis of information from the four tests of colour vision, patients with CVD can be given confident advice on the kinds of problems they are likely to have with colour and how it might affect their choice of career. Not all patients will welcome the advice but many will be appreciative and find it useful.

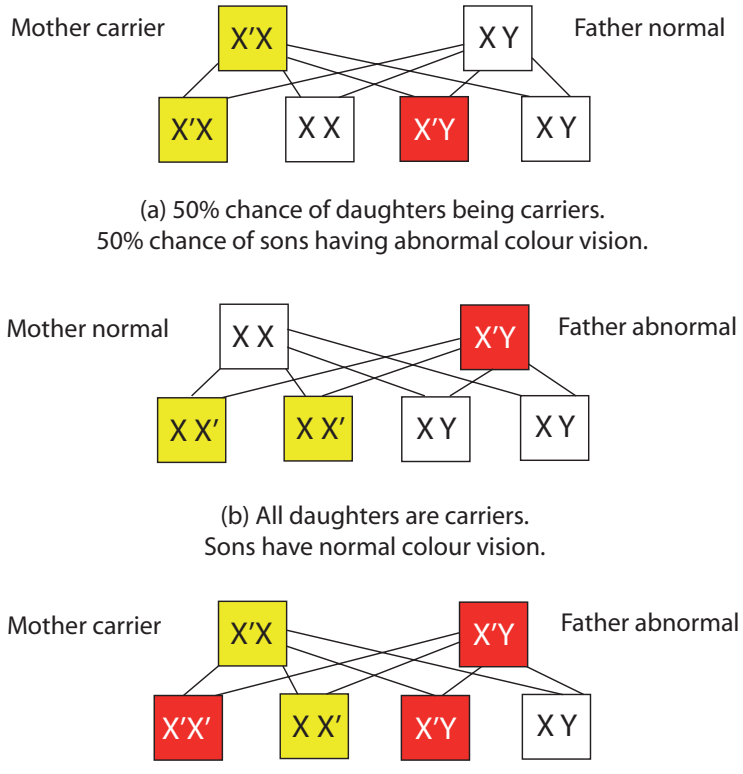

Figure 9. Inheritance of the sex-linked red-green colour vision deficiencies. The genes for the L and M cone photopigments are carried on the X chromosome. X' designates the X chromosome carrying the abnormal gene for colour vision. The yellow boxes represent carriers and the red boxes those with abnormal colour vision.

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