CLINICAL AND EXPERIMENTAL
OPTOMETRY

INVITED REVIEW

Clinical colour vision tests

Clin Exp Optom 2004; 87: 4–5: 276–293

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Submitted: 28 April 2004
Revised: 22 June 2004
Accepted for publication: 1 July 2004

The structure and function of the available and significant clinical colour vision tests are reviewed in the light of the needs in the clinical examination of congenital and acquired colour vision deficiencies. The tests are grouped and described as pseudo-isochromatic plates, arrangement tests, matching tests and vocational tests. The colorimetric constructions of the test types are described and the efficiency of their performance and usefulness discussed. Recommendations are made for basic and extended test batteries, when examining of congenital and acquired colour vision deficiencies in the consulting room.

Key words: colour, colour blindness, colour vision deficiencies, colour vision tests

The number and variety of clinical colour vision tests that have been developed and published over the years are huge. It is beyond the scope of this paper to review all of them. Therefore, it is necessary to limit consideration to those tests that are currently commercially available and used in the clinical evaluation of colour vision, as against those used for research purposes. Reference to some landmark tests that are no longer available is inescapable.

It is important to review first the needs and aims of a colour vision examination. These may be grouped into three categories;

1. Screening for the presence of a congenital or acquired colour vision deficiency. While this really falls short of a true colour vision examination, the process of detection of congenital red-green deficiencies is, by far, the most common colour vision activity.
2. Diagnosis of the type and severity of colour vision deficiency.
3. Assessment of the significance of the colour vision deficiency in a particular vocation, employment or occupation. This is usually an assessment of congenital red-green deficiencies rather than tritan or acquired deficiencies. This assessment may be in the form of performance on a nominated clinical test, a test that replicates or mimics aspects of the intended occupation or a practical test at the intended place of employment using the actual methods and system of work. Assessment for occupational suitability may not necessarily be an evaluation of a colour vision deficiency. The work intended may involve colour vision demands that can be met only by those with normal colour vision and a superior ability or aptitude for colour contingent decisions (for example, colour matching and assessment in the textiles or paint industries, grading of gemstones).

Similarly, the form of a colour vision test may be classified under four sub-types.

1. Pseudoisochromatic plate tests, in which the observer is required to identify a numeral (most usually), a letter or a shape embedded in a background and differentiated from it on the basis of colour only.
2. Arrangement tests, in which the observer is required to arrange a set of colours into an ordered sequence based on hue (usually) or to group colours by some attribute (most often colours separated from greys).
3. Matching tests, in which the observer is required to adjust two colours until they match, is required to report on a pair of colours as matching or not matching or is required to select the best match from a number of options.
4. Naming tests, in which the observer

must name a colour correctly and/or respond with an appropriate action that arises from correct identification of the colour (stop, start et cetera) without necessarily naming the colour.

It has been accepted for many years and from many research publications that no one colour vision test is all-fulfilling. If a full and unequivocal colour vision diagnosis is required, it is necessary to use a battery of tests. If the issues can be narrowed down to a single decision (for example, protan/deutan or suitable/unsuitable for a particular job), a single test may suffice.

SCREENING FOR COLOUR VISION DEFICIENCIES

In colour vision screening, the decision is simply whether a colour vision deficiency is present. Given the preponderance of protan and deutan congenital colour vision deficiencies, the majority of colour vision tests for screening are limited to these deficiencies. Tritan colour vision deficiencies are relatively uncommon and have less of an occupational and functional impact as colour coding systems rely much less on blue-yellow discrimination. Acquired blue-yellow colour vision deficiencies have at least the same prevalence as red-green, so that any screening system for acquired colour vision deficiencies should be designed to detect both red-green and blue-yellow deficiencies.

TYPE DIAGNOSIS

Most attention has been paid to the differential diagnosis of protan and deutan deficiencies[1] because it is generally accepted that protans are more at risk occupationally, given that their ability to detect (as against recognise) red is markedly poorer than deutans and normals, as a consequence of their loss of sensitivity to red. In acquired deficiencies, the major issue is the differential diagnosis of red-green as against blue-yellow, which is further refined into the three type classification of Verriest,[2] in which Types 1 and 2 are red-green deficiencies (linked to cone disease and optic nerve disease, respectively) and Type 3 is a blue-yellow deficiency (most frequently linked to retinal and choroidal disease).

SEVERITY DIAGNOSIS

Severity diagnosis is most important in congenital colour vision deficiencies in evaluating suitability for a particular occupation and advising patients with abnormal colour vision. Those who have a mild colour vision deficiency could be capable of undertaking the colour vision task safely, quickly and effectively and be entirely acceptable. The more affected represent a real risk. Partly as a consequence of the need to have a pass/fail categorisation in industry, the processes of extent diagnosis have evolved as completion of a series of tests of differing difficulty and the categorisation into a discrete set rather than on a continuous scale. There are few tests of severity that provide a result on a continuous scale.

This discrete categorisation is less appropriate when dealing with acquired deficiencies, when the evaluation and monitoring of subtle day-to-day and eye to eye variation of a colour vision deficiency necessitates a continuous or finer stepped scale.

Similarly, the evaluation of persons with normal colour vision for particularly demanding colour matching or grading requires tests capable of distinguishing fine differences in normal colour vision on a very finely-stepped scale.

THE BASIS OF COLOUR VISION TESTS

Lakowski[3,4] championed the approach that the understanding of colour vision tests must be based in the colorimetric design of the test and its relationship to the characteristics of congenital colour vision deficiencies. The fundamental characteristic that should drive colour vision design is the loci of the colours confused by persons with abnormal colour vision. The colour confusions of congenital dichromats based on the protan and deutan data of Pitt[1] and the tritan data of Wright[5] are provided in Figure 1. They are plotted in the CIE 1976 u'v' colour space,[6] which is an approximation to uniform chromaticity.

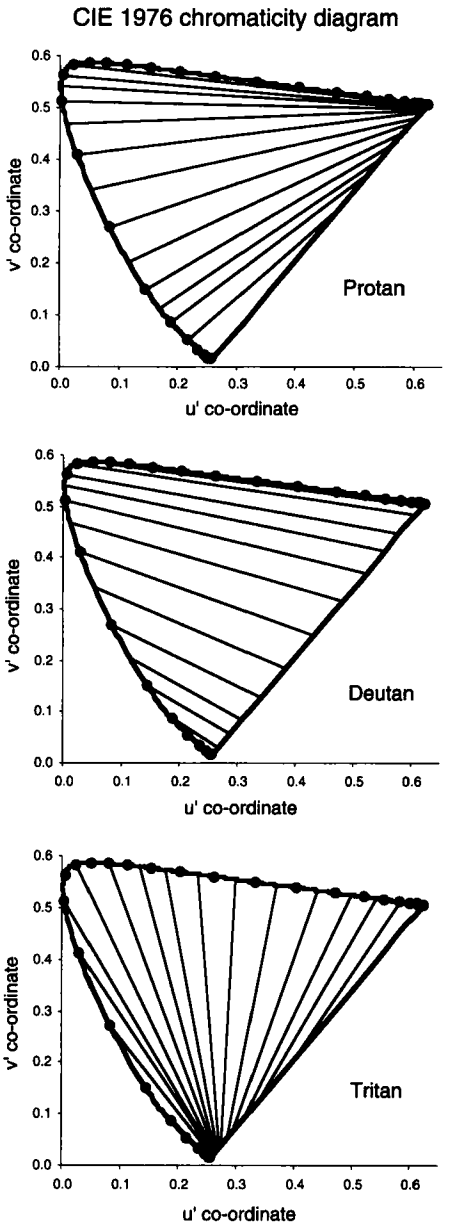

Figure 1. Confusion lines of congenital dichromats data from Pitt[1] recalculated into CIE u'v' space[6]

Some tests make use of the loss of red sensitivity characteristic of protan deficiencies. This is represented in Figure 2, the sensitivity of the normal represented by adding the Smith and Pokorny[7] L and M cone fundamentals for normal colour

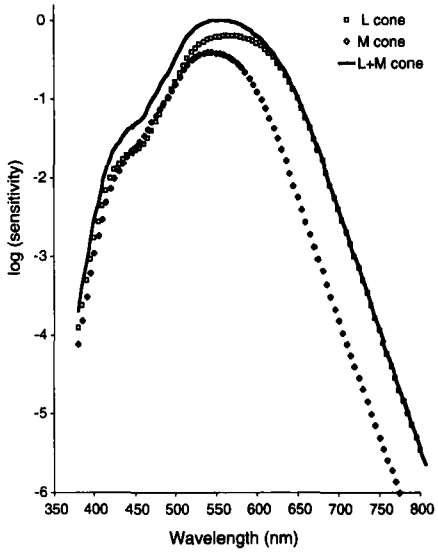

Figure 2. Spectral sensitivities of the Smith and Pokorny[7] L- and M-cone fundamentals plotted with L+M to represent deuteranopia, protanopia and normal spectral sensitivity, respectively. Note the logarithmic sensitivity scale and the loss of red sensitivity of the protanope.

vision compared with the M (representing deuteranopes) and L (representing protans). The loss of sensitivity in the red region of the spectrum (to about 25 per cent at 610 nm and 10 per cent at 650 nm) is well illustrated and clearly distinguishes protanopes from deuteranopes.

PSEUDOISOCHROMATIC PLATE TESTS (PIC TESTS)

There are several variants of these tests, which are generally constructed as an object delineated by a colour difference with a background of the same luminous reflectance, to avoid non-colour clues. The object may be a number, a letter, a symbol, a stylised object, an optotype (Landolt C or illiterate E) or a pattern to be traced. Printing variations and individual differences in spectral sensitivity mean that there are, almost inescapably, luminous reflectance differences between figure and background and most designers have introduced variability of luminous reflectance within the figure and background to mask any systematic difference. Of all of the types of colour vision test, these have the greatest choice and variety. It is best to use a generic approach to understand the underlying principles.

There are several types of plate design.

Demonstration or malingerer's PIC plates

In this type of PIC plate, the figure is defined by a significant luminous reflectance contrast with the background, so that colour vision is not necessary for a correct response. Figure 3 shows such a design. Identification requires understanding of the instructions and the ability to assemble the darker elements into a 3 but does not require colour vision. There may also be a colour difference that lies off the dichromatic confusion lines.

Disappearing or vanishing PIC plates

In these plates the object is defined by a colour difference from the background and if the colour differences are aligned on or close to the dichromatic confusion lines, the object will not be visible. If the colours used are in the region of colour space of the more saturated red, yellows and greens (typically v' greater than 0.5 in Figure 1), the protan and deutan confusion lines are very close and the colours may be chosen to straddle both the protan and deutan confusion lines. Such a plate will be failed by both protans and deutans. It serves to detect both types but not to distinguish them. Many disappearing plates are constructed in this way (Figure 4). A shortcoming of disappearing plates is that they may be unnerving to the colour deficient person, who repeatedly reports seeing nothing. They can also be a lot slower to administer because the colour deficient person spends time striving to see something in them.

Ambiguous or alteration plates

The design intention in these plates is to provide an alternate response for the colour vision deficient person. Figures are constructed using some colours that will be confused with the background and some that will not, so that there is always some response for the colour vision deficient person and they will be satisfied having given a confident response. This provides reassurance to the examiner that the observer understands the test. Figure 5 shows the design of ambiguous/alteration plates.

Combination plates

Several PIC plate designs incorporate a disappearing figure with a demonstration figure in the same plate. In this case, the normal will report two figures while the CVD will report just one. These plates are useful because there is always something to which the CVD can respond. In some cases, the demonstration figure is made less obvious than the disappearing figure with the intention that only the more obvious will be reported.

Diagnostic plates

These plates are essentially disappearing plates but with two figures, one designed to be confused by protans and one by deutans rather than designed to be failed by both. The colours used are mostly chosen from the parts of colour space where the confusions of protans and deutans are most different (that is, typically v' less than 0.5 in Figure 1). Figure 6 shows the typical colorimetric construction of a diagnostic plate. Whenever plates are designed for protans, it must always be remembered that the spectral sensitivity of protans is significantly lower in the red region of colour space (Figure 2). Therefore, a plate, designed to have a figure and background of the same luminous reflectance for normal observers, will contain significant non-colour clues for the protan and it will be necessary to compensate in the design of the test.

Quantitative plates

These diagnostic plates usually form a series with increasing colour difference. The most comprehensive series is in the Hardy-Rand-Rittler test and the chromaticities used in the severity plates are represented as an example in Figure 7.

Figure 3. A representation of a demonstration plate in which the figure is delineated by luminous reflectance difference from the background, so that detection is not a function of colour vision

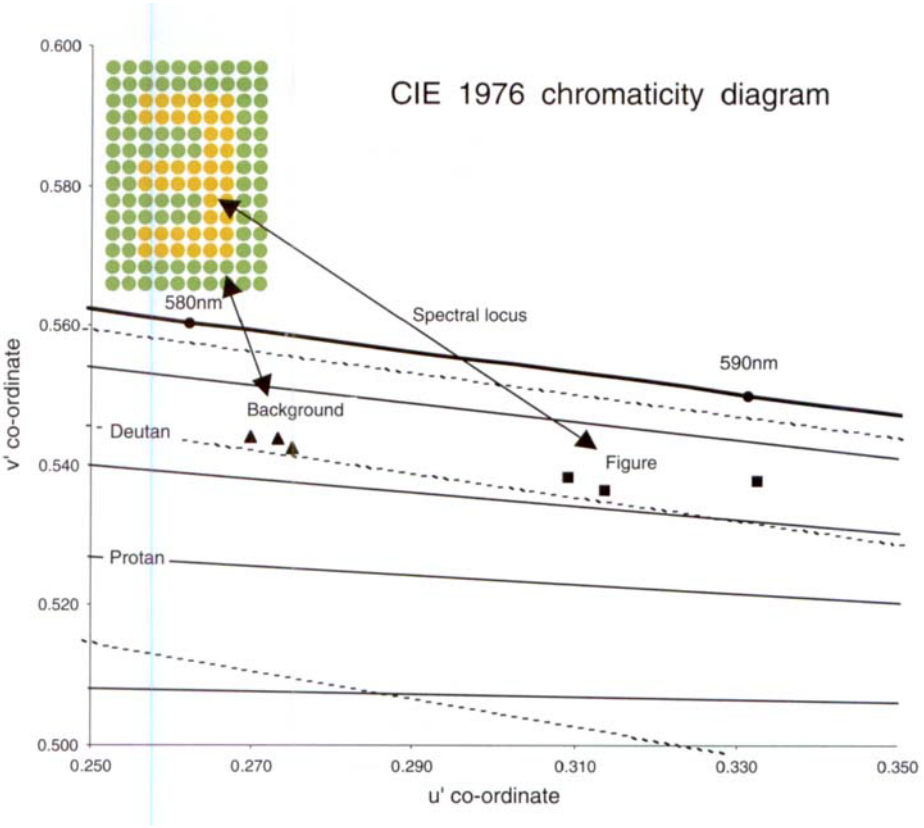

Figure 4. Chromaticities of a disappearing plate from Ishihara's test. The colours of the figure and the background are in the portion of colour space, where there is little difference between protans and deutans. The colours straddle both confusions lines and the figure will not be seen by either type of CVD.

Hidden plates

This ingenious style of plate is designed to contain figures visible only to colour deficient observers. The figure and background are constructed from a variety of colours (to the colour normals) but all the figure colours lie around a confusion line and all the background colours lie on a different confusion line. While the design might merit in-depth description, unfortunately it does not translate into a plate style that gives useful results. In Figure 8 are shown the chromaticities of an idealised hidden plate.

AVAILABLE TESTS

Many PIC tests have been produced over the years. Some have achieved more acceptance than others and some are no longer commercially available. Some have not received much acceptance outside their country of origin and for others there is little by way of validation. Following is a consideration of those currently available.

Ishihara's Test

This test was first published in 1906 and was the first PIC test in commercial production. It has been reprinted in numerous editions over the years and, worldwide, it is the most used colour vision test. The figures on each plate are embedded in a random pattern of variably-sized dots. The test comprises a demonstration plate, disappearing, alteration, hidden and diagnostic plates. The most used edition contains numerals (serifed) and tracing plates. Currently available are 38- and 24-plate editions. There is also a children's version that employs letters rather than numerals. It is remarkable that a colour vision test designed about 30 or more years before Pitt[1] published the dichromatic confusion data has been so successful and so enduring.

Over the years, there has been a number of evaluations of Ishihara's test (published by Igaku-Shoin, Tokyo) and it was evident from an early stage that there were very visible differences between editions[8,9] and some residual brightness clues.[10] Belcher, Greenshields and Wright[11] carried out the most comprehensive validation study but the editions that were the subject of this and the early evaluations of the test are now rare. The modern differences in colour reproduction have been highlighted.[12] More recently, there are some data on Ishihara's test that reinforce its excellent performance.[13-15]

The various studies[7-18] of the efficiency of Ishihara's test may be summarised as showing that it is still the 'gold standard' for rapid identification of congenital red-green deficiencies. The individual plates of Ishihara's test have sensitivities and specificities typically between 0.85 and 0.95[14,15] and the test as a whole performs very close to 1 in both sensitivity and specificity. There is a tendency for it to pass very mild deutans and to fail some normals

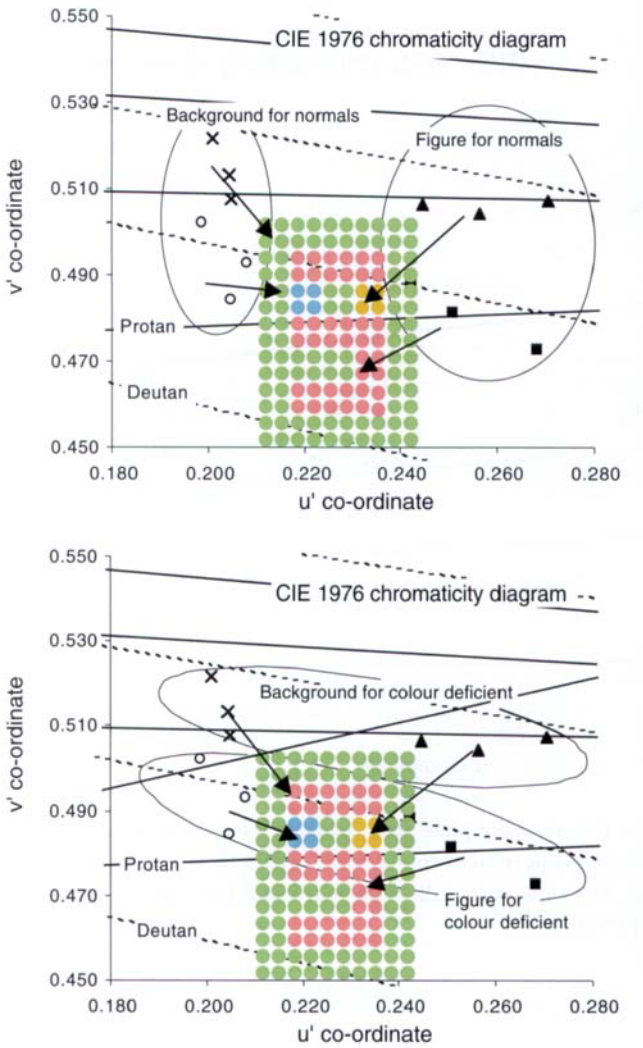

Figure 5. Form of an alteration plate, in which part of the figure consists of colours that are not confused with the background and part of the figure is confused with the background. There is a fourth colour that is similar to the background (and not paid attention to by the normal) but is confused with the main figure colour and incorporated into the figure by the CVD. Thus, the normal sees a 3 while the CVD sees a 5. Therefore, there are, four groups of colours that are associated in different ways by normals and colour deficients.

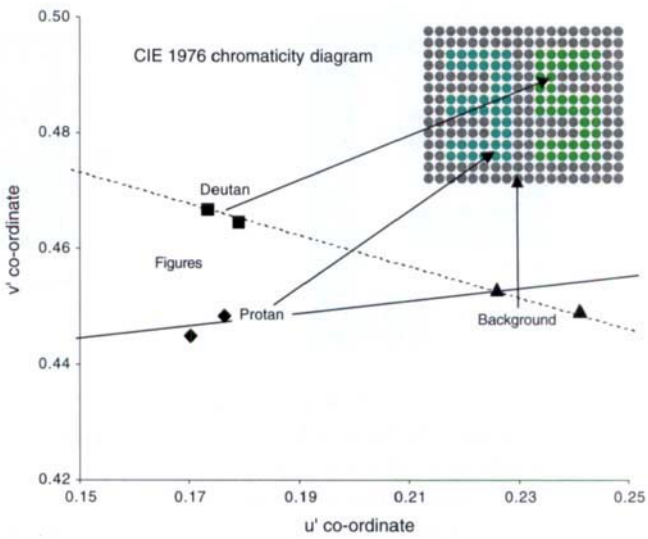

Figure 6. Colours of diagnostic plate from the SPP 1 test showing the two colours of the figures, one being confused with the background by protans and the other by deutans

with poor discrimination (but without being identifiably protan or deutan).[14,15] Given that the major use of Ishihara's test is a means for assessing occupational suitability, the acceptance of very mild deutans is rarely likely to be significant and other test methods can be adopted in these uncommon cases. The normals with low discrimination who fail Ishihara's test yet cannot be shown to have a congenital red-green deficiency are interesting and have been termed 'pigmentfarbanomaly' as they fail only printed but not spectral tests.[19] Having established with further testing that they do not have a red-green deficiency, they are usually acceptable in all but the most demanding colour-based occupations.

Shorter versions of Ishihara's test have been suggested with equal diagnostic validity.[11,20]

Ishihara's test has two shortcomings in that it has no tritan plates and does not provide a severity diagnosis. Relatively mildly affected CVDs may make as many errors as dichromats and the use of such a test has been likened[22] to a visual acuity chart comprising only 6/6 letters. It should be used only as a pass/fail test to detect red-green colour vision deficiencies. In addition care should be taken to set an appropriate pass/fail criterion that takes into account the tendency for some normals to make a few errors.[22,23]

American Optical Hardy-Rand-Rittler plates

The American Optical Hardy-Rand-Rittler (AOHRR) pseudoisochromatic plates (currently published by Richmond Products) were first published in the 1955,[25] having been developed from the hand-made AO-HRR Polychromatic plates.[26]

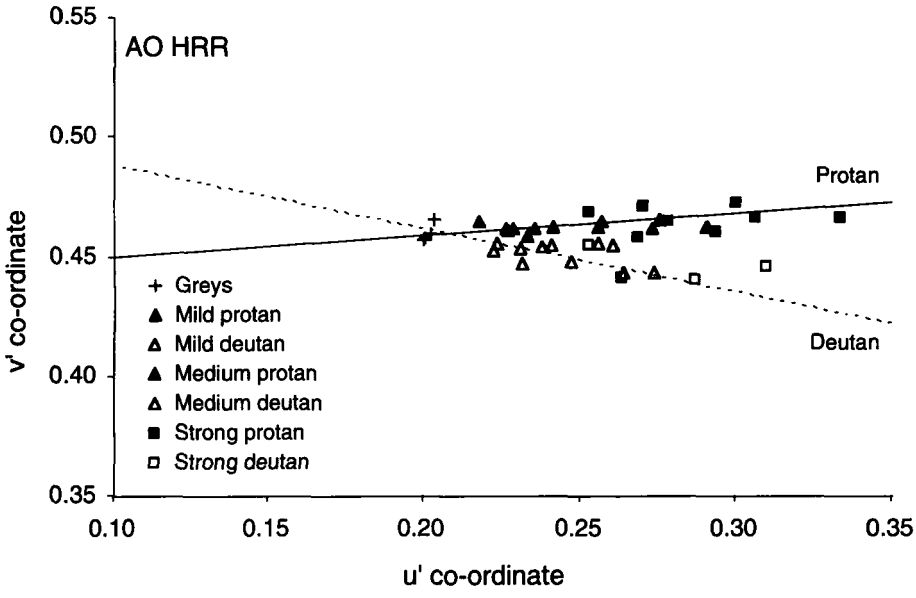

Figure 7. Colours of three diagnostic plates from the AOHRR test showing the two colours of the figures, one being confused with the background by protans and the other by deutans and three levels of difficulty, by which to grade severity of deficiency

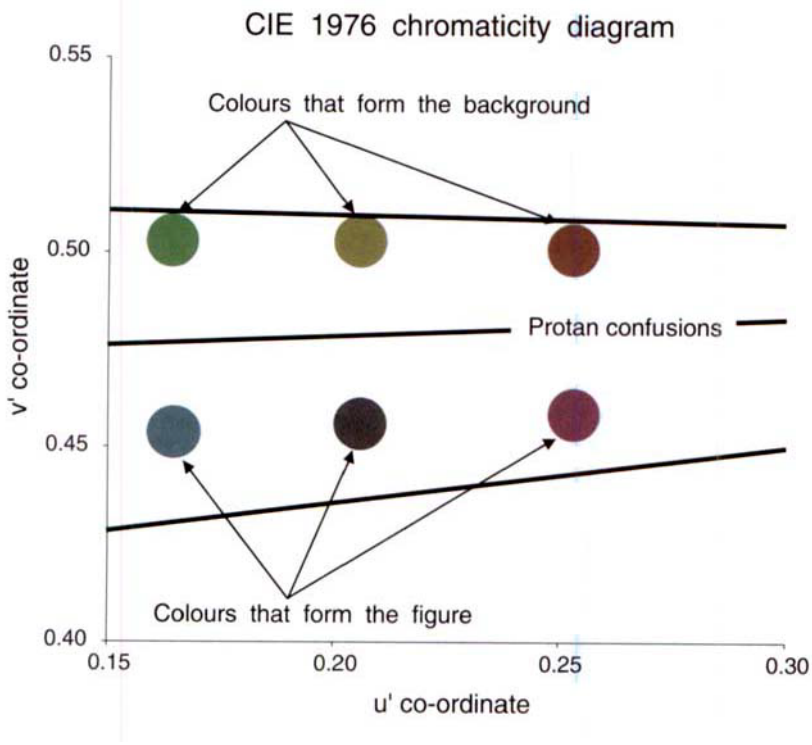

Figure 8. An idealised representation of a hidden PIC plate. The background comprises the three upper colours and the figure the three lower colours. To the colour vision normal the large difference in redness-greenness (in the u' direction) masks the small blue-yellow difference between the figure and background. For the congenital red-green CVD, for whom the red-green variation is much reduced or reduced to nothing, the small blue-yellow difference should become evident.

The second edition (1957) was from the same print run (Rittler MC, Personal communication) and only the plate order was changed. The test was well regarded [11,25-31] but when the print run was exhausted, American Optical could not be persuaded to invest in the production of another edition, which meant replacing superseded printing inks. Nevertheless, the test remains in current use by those fortunate to have copies.[32-36] Eventually, Richmond Products published a third edition in 1996 (Richmond 3), which was visibly less saturated than the original. In 2002, Richmond Products published a fourth edition (Richmond 4), which was re-engineered by Bailey and Neitz.[37] Visually, this appears to be a more faithful reproduction of the AOHRR but is still visibly different. Finally, in 2003, Waggoner published the Waggoner HRR that is a modified version, lacking the tetartan figures and having some additional red-green screening plates of a different design.

These various editions of the AOHRR have been subject to a colorimetric comparison,[38] which concludes that the Richmond 4 is well aligned on the confusion lines and is isomeric with the original AOHRR but the strong protan and deutan figures are less saturated than the original. This latter situation was confirmed (Neitz J, personal communication) as being intentional as some dichromats failed to make errors in the strong plates in the AOHRR. The Waggoner HRR is well aligned on the confusion lines but the colours are highly metameric with the AOHRR. It remains to be seen if that translates into a significant difference in clinical performance.

Standard Pseudoisochromatic Plates (SPP)

The SPP plates are published in two volumes. The first volume is designed for the examination of red-green CVDs.[39] The plates have a regular matrix of dots with a calculator style numeral. It comprises demonstration, combination (mainly), disappearing and diagnostic plates. Like Ishihara's test, it is designed only for red-green CVDs (although two of the demonstration plates are good tritan screening plates)

and is not quantitative. Individual plates and the test as a whole have very similar sensitivities and specificities to Ishihara's test[39-43] and the test has the advantage that, being less widely available, it is less accessible for those with abnormal colour vision who wish to pass a colour vision screening by memorising a test.

Volume 2 is specifically designed for acquired CVDs.[43-46] The plates have exactly the same physical layout as Volume 1 but are designed, colorimetrically, for red-green, blue-yellow and scotopic acquired CVDs. It has achieved a degree of acceptance as a useful test of acquired deficiencies and has been suggested as appropriate for examining congenital CVDs.[42]

Colour Vision Testing Made Easy (CVTME)

CVTME (published by Waggoner) is a PIC colour vision test specifically designed for children. There are two issues that merit specific attention, in addition to colorimetric design. First, children must understand what is expected of them. In PIC tests, this may be the naming of relatively simple shapes (they will need to know the names of the shapes), the identification of numbers (they will need to know their numbers) or they will need to point to other examples, for example, symbols (they will need to understand the concept of same and different). Second, to perceive a shape in the PIC plate, they will need to assemble the individual dots into the recognisable shape or symbol. This means that the shape or symbol will need to be sufficiently delineated in colour from the background and the shapes or symbols used need to be sufficiently different from one another.

The CVTME test uses only symbols. The first set of plates contains simple shapes (circle, square and star) with a luminance contrast defined symbol often present in addition to the defined colour difference. A second set of three plates uses cognitively more complex symbols (stylised outlines of a sailing boat, balloon and string and dog). The child points to examples in black and white. There are only colour-defined shapes in the second series.

There have been two clinical evaluations of the test. The first[47] showed that two of 21 CVD adults passed and five per cent of boys (age five to seven years) failed. No anomaloscope data were available for the subjects, so a definitive diagnosis was not available. It has been shown that its colorimetric design is appropriate although the colour differences are greater than in Ishihara's test.[48] This may be appropriate given that it is intended for children but it may indicate that the test is more likely to pass the mild deuteranomals. Neither study contained sufficient mild deuteranomals to make this judgement. Like the SPP Volume 1, the sensitivities and specificities of individual plates and the test as a whole are very similar to those in Ishihara's test. There are no tritan plates, no quantitative diagnosis and no type diagnosis.

Other PIC tests

There is a variety of other PIC tests that have come and gone without providing sufficient advantage over those in common use to merit more than a mention. They are dealt with in some detail elsewhere.[49-51]

None of these tests has made much impression on the extremely widespread use of Ishihara's test as the screening test of choice, the AOHRR as the test of choice for quantitative diagnosis and the SPP Volume 2 as a test for acquired colour vision deficiencies.

ARRANGEMENT TESTS

In the arrangement tests, the subject is asked to sort colours either into a sequence (usually based on hue) or into groups (most often greys versus colours).

Farnsworth Munsell 100 Hue Test (FM100)

The FM100 Hue test was developed by Farnsworth[52,53] in the early 1940s along with other sorting tests including the Panel D-15, the B-20 and H-16, which have not achieved widespread use. The Munsell system provides a notation of colour as Munsell hue, Munsell chroma and Munsell value. It is an example of a colour order system based on equal perceptual steps. In the FM100 the colours all have the same Munsell chroma and Munsell value and, therefore, vary only in Munsell hue. In the Munsell system, five hues are used, red (R), yellow (Y), green (G), blue (B) and purple (P). These are partitioned by five more hues, RY, YG, GB, PB and RP. Each hue is subdivided into 10 steps, for example, 1RP to 10RP. Therefore, there are 100 hues in the Munsell system however, there are not 100 hues in the FM100 as manufactured. Farnsworth found that the difficulty of distinguishing between adjacent hues was not equal around the hue circle. Therefore, he removed 15 hues in an attempt to make the colour spacing more uniform. The chromaticities[54] are plotted in Figure 9. Chromaticity differences and a rolling average of chromaticity are plotted in Figure 10 to demonstrate that, not only are there considerable random variations in the colour differences but also a systematic change such that the colours in the regions of caps 40 to 60 and (to a lesser extent) 80 to 85 are relatively more closely spaced. The consequence of this to the performance of the test will be discussed later. In Figure 11, the plot of CIE L* (lightness) with cap number shows a systematic change. For the observant subject, this provides a clue, which is enhanced for protans, given their loss of red sensitivity.

Farnsworth divided the 85 colours into four boxes (hues 85 to 21, 22 to 42, 43 to 63 and 64 to 84). Each box has a fixed hue at each end, one removed from the first and last moveable hues in the box, that is, hues 84 and 22 in box 1). The task of the subject is to arrange the moveable hues so that they provide a gradual progression between the two fixed hues.

Farnsworth provided a scoring method, which assigns a score to each hue, which is the sum of the absolute differences between the number of the hue and the numbers of the those hues placed either side of it. Farnsworth[52] was not specific about what should happen at the ends of each box, whether the adjacent hue was the fixed hue in the same box or the first moveable hue in the next box. Moreland[55] has argued that the second method gives an unwanted box end artefact, while Dain and Saunders[56] show that the second method has the useful calculation check (for those scoring the test manually), in

that the total error score (TES) is always an integer multiple of four.

There are two options when plotting the results on the polar plot that Farnsworth used. The score for a given hue number may be associated with the hue as arranged or it may be associated with the location of the hue. Farnsworth used the first method but Kinnear[57] advocated the second method as being easier for the manual scorer as well as giving a better plot. These are referred to as the Farnsworth and Kinnear methods, respectively. Except for Kinnear's opinion, there is no evidence that either method is superior.

From Figure 9, it can be seen that in two regions of the hue circle, the hue change is aligned with or close to the confusion lines of the dichromats and, as a consequence, dichromats will make substantial errors in the regions. In other regions, the hue change is perpendicular to the confusion lines and the dichromat will perform as well as a colour normal. When the test is scored and plotted in a polar diagram, as instructed by Farnsworth, they will form a pattern of errors characteristic of the deficiency enabling a protan, deutan or tritan diagnosis. The anomalous trichromats will make fewer and lesser errors in the same hue regions. Thus, the

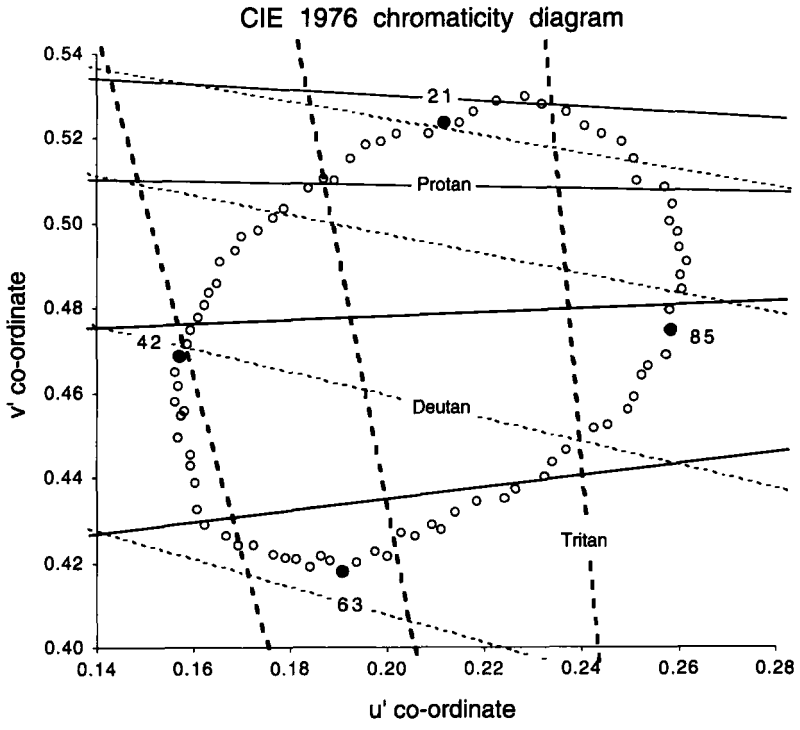

Figure 9. Chromaticities of the FM100 test with the end box caps in solid figures. Where the colour changes parallel the confusion lines, the CVD will have difficulty arranging the colours. Where the chromaticity differences run perpendicular to the confusion lines, the CVD will be able to complete the test as well as a normal.

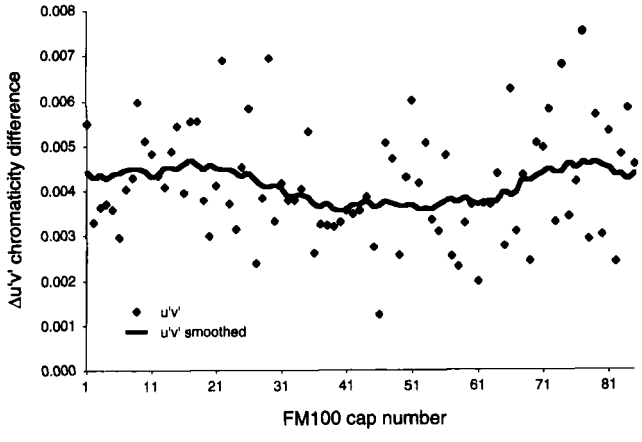

Figure 10. Chromaticity differences in the FM100 test with a running average plotted as a solid line. The colour differences tend to be relatively smaller around cap 83 and cap 45, which might be linked to tritan deficiencies being over-estimated.

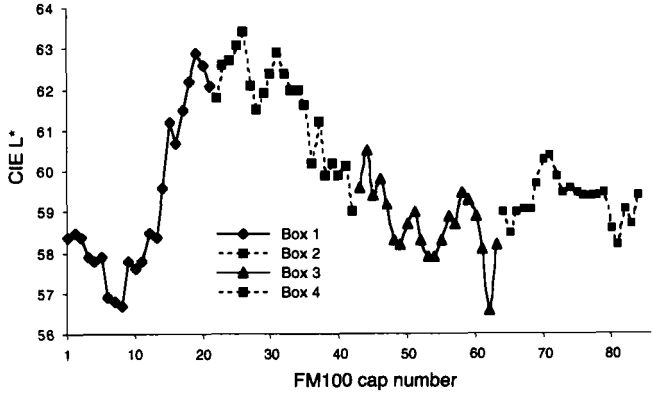

Figure 11. Lightness differences in the FM100 test. The changes in lightness are a clue to correct arrangement of the test without needing colour vision. The effect is accentuated in protan deficiencies.

FM100 may be used as a quantitative test as well as providing a type diagnosis for congenital CVDs.

The major advantage of the FM100 is that the design does not presuppose which colours will be confused by congenital CVDs and it can be used to assess colour vision deficiencies that do not follow the classical lines, most notably, acquired deficiencies. The test is also sufficiently difficult that few normals can perform the test perfectly. The test can, as a consequence, be used to identify colour normals with very good discrimination for very demanding colour vision occupations such as in the textiles, fashion, paint and gem trades.

Performance of the FM100 is age-related with performance improving with age to about 20 years and then gradually deteriorating.[58-61] At both ends of the age range, the subjects make errors indicating a tritan deficiency. In the older age groups this is a consequence of the yellowing of the crystalline lens, while in the younger groups, it has been attributed to a late developing blue-yellow system, the unequal spacing of the hues or lower IQ (although this last factor does not, on its own, account for the tritan nature of the errors). Because the FM100 TES is age-dependent interpretation of the result requires reference to the age norms that have been developed. One set of data[58] is redrawn in Figure 12.

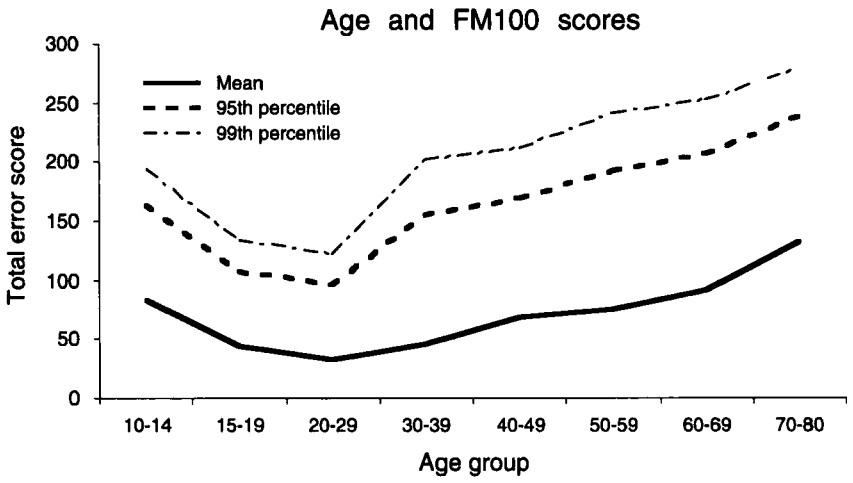

Figure 12. Age changes in the total error score of the FM100. Scores above the lower dashed line occur in only five per cent of normals and are clinically significantly poorer than normal. Scores above the upper dashed line occur in only one per cent of normals and are highly clinically significantly poorer than normal. Redrawn data of Verriest, Vandevyvere and Vanderdonck.[57]

Individual differences in the density of macular pigment can affect performance of the FM100. It has been demonstrated that simulated macular pigment produced the expected differences in result[62,63] and using the FM100, Woo and Lee[64] set out to show that the macular pigment differences between Caucasians and Asians caused significant differences in FM100 performance. They did concede that there were other possible sources of the differences. Subsequently Dain, Cassimaty and Psarakis[65] demonstrated that the difference between Asian and Caucasian observers is very small when age and pupil size are taken into accounted. There is a small but significant difference between Asians and blue-eyed Caucasians but not brown-eyed Caucasians.

There are some learning effects in repeated performance of the FM100 and some chance variability.[66-68] Changes of FM100 with time (as a measure, for instance, of the course of an acquired deficiency) and differences between eyes must be interpreted with care. Aspinall[66] and Reeves, Hill and Aspinall[67] provide guidance on judging the significance of differences between eyes and repeated tests over time.

The FM100 performance is dependent on the illuminance.[67-69] The various studies of age-related changes have used different illuminances, so the choice of illuminance should be linked to the age norms being used for interpretation. Bowman[70] has argued that the test may be made more sensitive in identifying the loss of colour discrimination in age-related maculopathy. From the work of Bowman[70] and Dain and collaborators,[71] a level of 200 to 250 lux is the optimum.

There have been two major issues in the further analysis of FM100 error scores. First, it was noted that total error scores were not symmetrically distributed. It was proposed that a square root transformation be applied for analysis of population data for diabetics.[72] This automatic transformation has been cautioned against and the actual distributions must be examined first[73] and the sources of skewness investigated.[74]

The second issue is the development of computer-based methods to assist in scoring and interpretation. There are methods intended to speed up the calculation.[75] There are also several methods to assist in the identification of polarity in the polar plot to provide a type diagnosis. For results of anomalous trichromats, whose TES may be only slightly abnormal, and acquired CVDs, who may make both red-green and blue-yellow errors, the polarity of the plot is not always clearly visible. Methods have been developed to derive polarity and a total score.[54,76-86] The most enduring of these methods is that of Vingrys and King-Smith,[86] who propose using the colour difference vectors in the arranged hues to provide a measure of the direction of errors (angle), specificity of direction of the errors (S index) and overall level of confusion (C-index).

It should also be noted that totally random arrangements of the test generate distributions of TESs with a fifth percen-

tile of 1200 and a performance leading to a TES of 1200 or greater can be used to demonstrate the absence of any colour vision.[86]

The FM100 is a remarkable test for assessment of colour vision. It is especially valuable for assessing and monitoring acquired CVDs and assessment of those with normal colour vision to identify those with superior colour discrimination skills. Like all colour vision tests, it has its limitations. It does not distinguish colour vision normals from mildly anomalous trichromats and does not always differentiate protanopes from deuteranopes.[87,88] As a consequence, its usefulness in the investigation of congenital CVDs is rather limited.[49-51] It is most often the test of choice in assessing acquired CVDs[89-93] and superior performance in normals.[49-51]

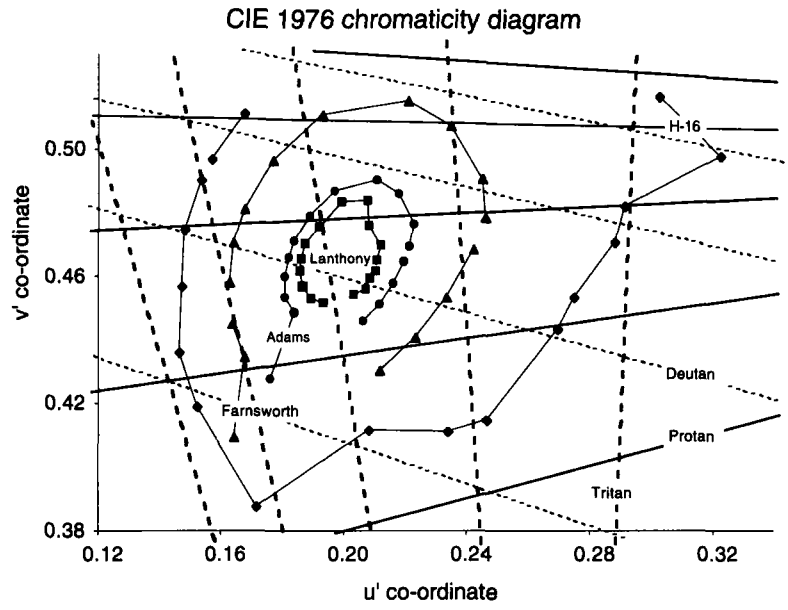

Figure 13. Chromaticities of the Lanthony, Adams and Farnsworth D-15 tests with the Farnsworth H-16 to demonstrate the increasing colour difference and hence, ease of completion

Farnsworth-Munsell Dichotomous D-15 or Panel D-15 (D15)

The FM100 can be exquisitely sensitive in assessing colour vision but it takes too long to perform for it to be used as a routine test. As he developed the FM100, Farnsworth[53] experimented with tests that also incorporated the whole Munsell hue circle but using fewer hues. The test that has endured out of these is the D-15,[93,94] which comprises one fixed colour and 15 moveable colours. The subject is required to arrange the moveable colours in order, starting with the fixed colour. In its original form, the test is scored in a circular plot of the 16 colours by joining the dots in the order of the arrangement by the subject. Interpretation is by visual inspection.

It can be seen from Figure13 that Farnsworth aligned pairs of colours on the protan and deutan confusion lines. There are relatively fewer pairs of colours aligned on the tritan confusion lines, as there is a gap between the starting colour and colour 15. Conversely, there are many more options for simple transpositional errors for tritans, particularly in the region of caps 2 to 6.

The colour differences in the pairs of colours are sufficiently large that colour vision normals and mildly affected CVDs can complete this test without error. It was intended by Farnsworth that the test dichotomise subjects into the lesser and greater affected and also into protan and deutan. It has been shown repeatedly to do this successfully and there is some evidence that it is effective in identifying the lesser affected, who can use the simpler colour codes (like colour coded wiring) safely and be acceptable into certain occupations.[95-97]

As such, it should be the second test (after Ishihara's) in any clinician's battery of tests.[94] The D-15 has been used widely in evaluation of acquired CVDs.[49,92,98-101]

Farnsworth proposed visual inspection of the plotted results and a count of the number of crossings of the hue circle as the analysis method. Rather than counting the number of crossings, Bowman[102] proposed a sum of the colour differences as a measure of the magnitude of the errors. The colour vector method that Vingrys and King-Smith[85] proposed for the analysis of the FM100 can also be applied to the D-15. This gives information on the direction and specificity of the errors, as well as a measure of the total errors. In some advanced acquired colour vision deficiencies the errors become large in number and variable in direction. The analysis of results that could arise from a purely random arrangement and which may indicate the absence of useful colour vision can also be carried out on the D-15.[103]

With the exception of the starting colour, which is Munsell chroma 6, the colours of the D-15 are also included in the FM100. The owner of an FM100 may extract the appropriate caps to construct a D-15 (using a Munsell chroma 4 for the starting colour) and this method is a valid equivalent to the D-15.[104,105]

Lanthony Desaturated D-15

Given the success and wide acceptance of the D-15, it is a logical step to manipulate the Munsell chroma and value of the hues to provide an easier test (by which to sub-classify those who fail the D-15) and a harder test (by which to sub-classify those who pass the D-15). The D-15 uses hues

with Munsell value 5 chroma 4, while the Lanthony D-15[106] uses Munsell value 8 and chroma 2, so the colour differences are substantially smaller (Figure 13). A higher level of illuminance than any other test (600 to 800 lux) is specified for the Lanthony Desaturated D-15.[106] It has been used widely for the study of acquired CVDs.[107-110] CVD subjects passing the D-15 may, as expected from the smaller colour differences, fail the Lanthony D-15 but the small colour differences also lead to colour vision normals making minor transpositional errors. This tends to blur the distinction between normal and abnormal.[110]

Adams desaturated D-15

Adams and colleagues[112] proposed a desaturated D-15 with the same value as the standard D-15 but chroma 2. From the chromaticities in Figure 13, it can be seen that it is intermediate in difficulty between the D-15 and the Lanthony D-15. While intended initially for acquired colour vision deficiencies,[113-114] it has been shown to be effective with congenital CVDs,[115] providing a reliable type diagnosis more often than the Standard D-15 and a sub-classification of those passing the D-15. The test has never been commercially available but can be constructed with colours from the Munsell Color Company. Hahn[116] has produced a double D-15 with both chroma 4 (D-15) and chroma 2 (Adams D-15) variants in the same package with, presumably, similar performance. This is commercially available.

Lanthony New Colour test

Lanthony[117-121] designed this test with acquired CVDs in mind but it can also be used for the assessment of congenital CVDs. The test is a combination of arrangement by hue, separation of colour from grey and arrangement of greys by reflectance. The test has four levels of difficulty (Munsell chroma 2, 4, 6 and 8). The first stage is a colour and grey separation test. Colours remaining with the greys are plotted and show a polar plot. The second stage is a D-15 arrangement test and the last stage is to arrange the remaining colours with the greys (if any) to identify whether reds are arranged with the darker greys, indicating a pseudo-protanomaly indicative of receptor disease. In the D-15 format the colours are approximately equally spaced around the hue circle (Figure 14), so that there is no bias to any particular response. Unlike the D-15 tests, there is no set starting colour. There are few reports on this test other than by its designer.[50,51,117-121] It has proved to be simple enough in structure to be used on children down to the age of six years and sensitive enough to show the slower development of blue-yellow discrimination (BY Ling and SJ Dain, Personal communication).

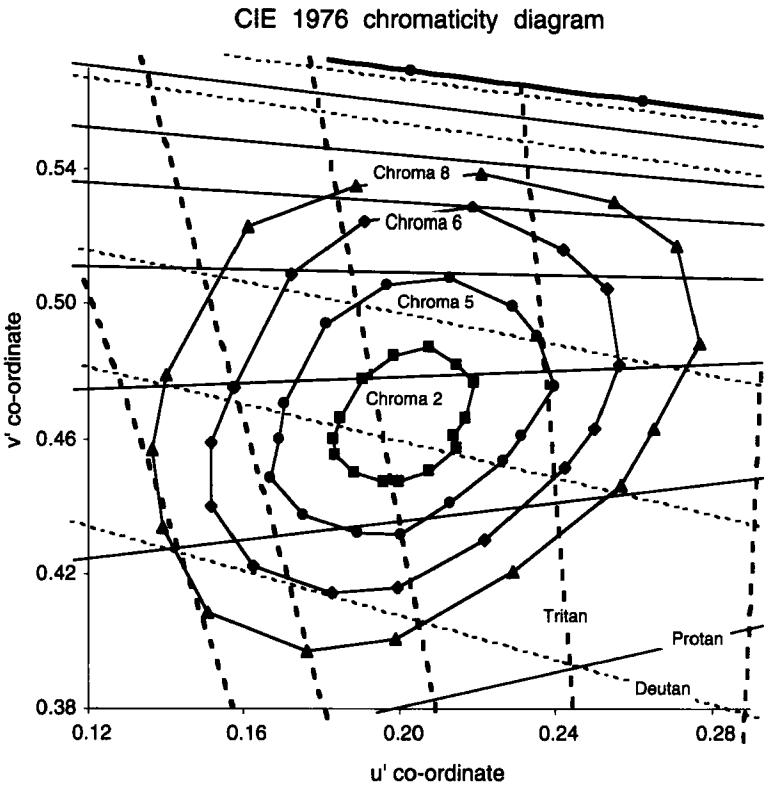

Figure 14. Chromaticities of the Lanthony New Color Test to demonstrate the increasing colour difference with chromas 2, 4, 6 and 8 and hence, ease of completion and the approximately uniform distribution around the colour circle (unlike the D-15s)

Other sorting tests

Farnsworth also described the B-20 test[53] and the H-16.[50,51] The H-16 comprises higher chroma colours (6 and 8) and is purported to fail only protanopes and deuteranopes, providing an alternative to the anomaloscope. This appears not to be reliable in identifying dichromats.[122]

Sahlgren's test requires the separation of greys from colours. It is designed specifically to be used in conjunction with Ishihara's test to distinguish acquired from congenital CVDs. Acquired CVDs tend to do worse on the Sahlgren's test, while congenital CVDs do worse on Ishihara's test. It has been used with some success but not widely.[50,123,124]

Large size variants of the D-15 have been constructed to look at the performance of congenital dichromats[125] and low vision patients.[126]

As a compromise between the sensitivity but tediousness of the FM100 and the quickness but insensitivity of the D-15,

Diagnosis	Anomaloquotient mean *		Range of matches (scale units)	Neutral adaptation changes range of matches?	Yellow setting
Normals	1.0	0.8 - 1.5	0-5	No	Constant
Low discrimination normals	1.0	0.8 - 1.5	>5	No	Constant
Protanomals	0.2	0.06 - 0.6	⇑ with ⇑ severity	No	⇓ with ⇑ red in mixture
Deuteranomals	3.5	3.0 - 9.0	⇑ with ⇑ severity	No	Constant
Extreme protanomals	very variable		Includes normal match and pure red	Yes, reduces markedly	⇓ with ⇑ red in mixture
Extreme deuteranomals	very variable		Includes normal match and pure green	Yes, reduces markedly	Constant
Protanopes	not applicable		0 - 73	No	⇓ with ⇑ red in mixture
Deuteranopes	not applicable		0 - 73	No	Constant

Anomaloquotient is a measure of the red green ratio in the match

Table 1. Rayleigh equation results with congenital colour vision deficiencies

Roth proposed a 28 Hue test[127] and Ohta a 40 hue test.[128] Neither of these tests offers sufficient advantage to have made it popular.[129,130] More recently, a desaturated 28 Hue has been proposed and validated.[131,132]

COLOUR MATCHING TESTS

Anomaloscopes

The colour matching tests that are used as the gold standard for diagnosis of protan and deutan colour vision deficiencies are all based on the Rayleigh equation:

Red + Green ≡ Yellow

Rayleigh[133] used a mixture of the lithium (670 nm) and thorium (535 nm) spectral lines to match the sodium doublet (589 nm). More recently, having found that 535 nm was a little too short a wavelength and caused desaturation of the yellow, other green wavelengths have been used. The equation still bears Rayleigh's name irrespective of the actual wavelengths used. In the first commercially available form, the Schmidt and Haensch Nagel Anomaloscope Mark 1 used 670.8 nm + 546 nm ≡ ≈ 589.3 nm. A generic specification for the equation has been proposed as ≥ 640 nm + 540-555 nm ≡ ≈ 590.[49] This specification excludes the, otherwise very attractive, use of unfiltered light emitting diodes (LED),[134] as the typical green LED, with a dominant wavelength of 565 nm, is too yellow.

The Nagel Anomaloscope Mk 1 is considered to be the gold standard for the diagnosis of protan and deutan CVDs but is no longer commercially available.[135] Two equivalents are available, the Neitz OT (which uses interference filters rather than the prism dispersive method of the Nagel) and the Oculus Heidelberg which uses light emitting diodes and interference filters. The Mk 1 Heidelberg[134] incorporates only the Rayleigh equation, while the Mk 2 also incorporates the Moreland equation for tritan CVDs (see below). Both of these anomaloscopes are designed to perform the same way as the Nagel and, correctly adjusted and calibrated, there is no reason not to accept that they do. The red-green scale runs from zero (pure green) to 73 (pure red) and the normal match is intended to be at 42 scale units.

A Rayleigh equation anomaloscope permits the full classification of a congenital CVD. In particular, it always distinguishes anomalous trichromats from normals, and dichromats from anomalous trichromats and identifies extreme anomalous trichromats. Table 1 sets out the diagnostic criteria.[49,51,135]

There has also been a number of attempts to provide an equationto investigate blue-yellow deficiencies in the same way. The development of tritan equations (mainly blue + green ≡ blue-green and blue + yellow ≡ white) has been well documented.[136]

The Nagel Mk 2 incorporated a Trendelenberg equation (470 nm + 517 nm ≡ 480 nm) by swinging the eyepiece tube around to a different part of the spectrum. There are several difficulties with blue-yellow equations, most notably the influence of macular pigment, coloration of the crystalline lens and the spectral blue plus spectral green match being desaturated compared with the spectral blue-green. The development of the Moreland 2 equation,[136-138] blue (436 nm) + green (490) ≈ blue-green (480 nm + 580 nm) has minimised these problems and the equation is incorporated in the Oculus Heidelberg Mk II (a relatively inexpensive instrument) and the Besançon Anomalometer[139] (a very expensive research tool) has a similar equation. The combined power of these two equations in characterising acquired CVDs, using the Verriest classification, has been set out well in three papers given at the same conference.[140-142]

OSCAR and Medmont C-100

These tests are essentially the same. OSCAR is no longer commercially available. The test principle is flicker matching of red and green in a dual light emitting diode. It is essentially a two point (560 nm and 650 nm) comparison of the long wavelength portion of the spectral sensitivity function in Figure 2. The subject is given control of the luminance ratio of the red and green and asked to set for minimum flicker. The frequency has been chosen to be around the critical fusion frequency (CFF) of the red-green system but below the CFF of the luminance system.[143] The ratio of red and green is characteristic of normal colour vision but the protan, having a lowered sensitivity to red but not green, must introduce more red into the match and is clearly identified. Original claims for the OSCAR test included the reverse phenomenon for deutans but, as can be seen in Figure 2, the loss of sensitivity of deutans for green is very small compared with the loss of sensitivity of protans for red. In practice, deutans are not reliably distinguished from normals but it does distinguish protans from the deutans. The tests do this exceedingly well[144-148] and it is an important distinction to make, given the general acceptance that protans are occupationally more disadvantaged than deutans.

The City University Test (CUT)

The CUT is not strictly a matching test but it is a forced choice test of which colour is the closest match. It is derived from the colours of the D-15.[149] Five colours are presented on each page and the subject has to indicate which of the four colours most closely resembles the fifth, centrally placed colour. One choice is the adjacent D-15 hue, one lies on each of the protan, deutan and tritan confusion loci. It is of similar difficulty to the D-15 but has the practical advantage that the subject does not handle and soil the Munsell colours. In its first edition, it comprised 10 plates using the same chroma that were of uneven effectiveness.[129] The second edition[150] reduced these to six plates and introduced four plates using Munsell chroma 2 of a smaller size. It was intended that the smaller desaturated colours would provide a more difficult section in much the same way as a desaturated D 15, however, congenital CVDs make no more errors on the second series.[151] There are several studies of the effectiveness of these tests.[129,151-161] The consensus is that it is a reasonable alternative to the D-15 for congenital CVDs. The second edition is accepted in some occupational situations in preference to the D-15.[160] When dealing with acquired colour vision deficiencies, the colour differences in protan and deutan confusions are up to twice as large as those for tritan confusions.[151] More recently, a third edition has been published, which contains some odd-one-out style plates. There seems to have been no validation of this latest edition.

Intersociety Color Council Colour Matching Aptitude Test (CAT)

This test is designed specifically to assess normals for superior aptitude.[162-164] The task is to match a given colour with one from a series that vary in saturation. There are red, green, yellow and blue series. It is used widely both in combination with the FM100 and as an alternative. The rating of the subject does not correlate highly with the FM100 but the aptitudes for hue arrangement and saturation matching may not be closely linked.[165] Unfortunately, this test is no longer commercially available but the Graham HSV test is in similar form and was produced to fill this gap. It appears to be without published validation.

COLOUR NAMING TESTS

Colour naming is often unreliable in the more affected congenital CVDs but they have grown to rely on other clues and may, in very restricted circumstances, perform relatively well, however, they are relatively easily fooled by luminous intensity differences. Colour naming is frequently needed in occupational situations (like railways, maritime and driving) and lantern tests have been developed as a practical representation of the real life situation stemming from the famous (at the time) case of Mr Trattles.[166] There has been a number of lanterns, of which the Farnsworth Lantern and the Holmes-Wright Lantern deserve most mention. Vingrys and Cole[167] have provided the most comprehensive consideration of lantern tests and there have been no commercially available additions to the list since them (there is one substitution, see below).

Farnsworth Lantern (FaLant)

Farnsworth developed a two-light lantern for use in the US Navy.[168,169] The colours were, nominally, red, green and white, reflecting the naval use of this colour code. The red and green were desaturated and the white relatively yellow, so that they lie close to the protan and deutan confusion lines. As a consequence, they are not compliant with maritime or aviation specifications. The Farnsworth Lantern is more difficult to pass than the D-15 and is often used to sub-classify the milder colour vision deficient observer.[170,171]

The FaLant is no longer commercially available but the Stereo Optical OPTEC 900 is accepted (including by the US Navy) as equivalent to the FaLant.[172]

The FaLant is easy and quick to carry out in normal room illumination.[173] As it is not available widely but is frequently specified as a vision standard, there has been some interest in using the performance on other clinical tests as a predictor: failing the D-15 test accurately predicts failure but passing the D-15 is a poor predictor of passing the FaLant .[174-176]

Holmes-Wright Lantern (H-W)

Recently, the Holmes-Wright Lantern has become unavailable but deserves mention as an object lesson in relating a consulting room test to real life situations. It was developed to replace the Board of Trade lantern after an inquiry on vision standards in maritime occupations.[177] There are two versions (A and B)[178] for two applications (two light and three light, respectively). The colours are red, green and white and comply with maritime and aviation colour limits. The luminous intensities have been chosen to replicate

	Protan and deutan		Tritan
Function	**Basic necessity**	**Improvements**	
Screening	Ishihara's test	CVTME is dealing with children, SPP vol 1 if malingering is a problem.	SPP1 demonstration plates SPP2 AOHRR 4th edition
Quantification	D-15 as a simple separator of the occupationally affected from unaffected.	Other D-15s with different sensitivities. AOHRR 4th edition (probably)	As protan and deutan
Type	Medmont C-100	Rayleigh anomaloscope	As screening

Table 2. Detection and diagnosis of congenital CVDs

Function	Basic necessity	Improvements
Screening	SPP Vol 2	
Quantification	FM100	D-15s with different sensitivities. Lanthony New Color Test
Type	D-15 or FM100	Rayleigh and Moreland anomaloscope

Table 3. Detection and diagnosis of acquired CVDs

the real-life range of these values. The Holmes-Wright Type A is the direct replacement for the Board of Trade lantern: it is used more widely and better accepted.[179-182] The Type B is reported to be in use by the Royal Air Force and the Royal Navy.[179] Those with congenital CVDs[181] make at least one error. The most common error is misnaming white as green or *vice versa.* Even the unobservant normal may also make such mistakes.[181] If the pass criterion is set at no more than two errors, the failure rate of congenital CVDs is around 80 per cent.[179,182]

Other lanterns

The College of Optometrists in the United Kingdom instituted a competition for the design of a lantern. The winning design (based on the work of Fletcher[183]) is being prepared for commercialisation (R Fletcher, Personal communication).

Other recent attempts have yet to be commercialised. Hovis[184] has proposed and validated a lantern suitable for testing rail employees. Cole and Maddocks[185] modified a FaLant to omit the green colour and simulate the Precision Approach Path Indicator (PAPI) used in airports. Tanabe and associaters[186] used red, yellow and yellow-green LEDs. Modern LEDs include a blue-green that complies with transport signal requirements and a white that complies with maritime requirements, so there would appear to be promise in the use of LEDs.

DIAGNOSIS OF COLOUR VISION DEFICIENCIES

It will have become evident that there is no one test that will fulfil the needs of screening, type diagnosis and quantification, not to mention the issues of occupational relevance and acquired CVDs and still be an economic possibility. Certainly, an anomaloscope is the central key to the definitive diagnosis but it remains relatively costly and rarely found outside research and teaching institutions.

It is necessary to use a battery of tests and decisions to come to a full diagnosis in the absence of an anomaloscope. This can be achieved simply and suggested basic and improved batteries of tests are set out in Tables 2 and 3.

Practical occupational tests

The author is frequently requested to undertake some kind of practical testing of colour vision in specific cases. These usually arise because a claim has been made that clinical tests bear no resemblance and have no relevance to real occupational colour contingent decisions. The CIE committee on colour vision standards advises against such practical tests.[182] Clinical tests can be carried out in controlled situations and in a fashion that is consistent across all applicants. Practical tests will usually be inconsistent if carried out in different locations and different weather conditions. Thus, the perceived inequity and irrelevancy of the test are replaced by the real inequity between different applicants. Both the D-15[187-190] and the City University test[159] are reasonable interpretations of the colour code.

Another, more acceptable and equally controlled alternative is the use of simulated practical tests. Lantern tests are consulting room realisations of real-life tasks and, not surprisingly, are good predictors of real life performance.[188-190] The key to an appropriate and defendable controlled test is an understanding of the critical colour vision decisions to be made.[191] The issues of occupation and colour vision are explored elsewhere in this volume.[192]

REFERENCES

1. Pitt FHG. Characteristics of Dichromatic Vision. London. Medical Research Council. 1935.
2. *Pokorny* J, *Smith* VC, *Verriest* G, Pinckers AJLG. Congenital and Acquired Colour Vision Defects. New York: Grune and Stratton; 1979.

3. Lakowski R. Theory and practice of colour vision testing. A review. Part 1 *Br J Industr Med* 1969; 26: 173-189.
4. Lakowski R. Theory and practice of colour vision testing. A review. Part *2. Br J Industr Med* 1969; 26: 265-288.
5. Wright WD. The characteristics of tritanopia. *J Opt Soc Am* 1952; 42: 509-520.
6. Commission Internationale de l'Éclairage. Recommendations on Uniform Color Spaces, Color-Difference Equations, Psychometric Color Terms. Supplement No 2 of CIE Publication No. 15 (E-1.3.1) 1971. Paris: Bureau Central de la Commission Internationale de l'Éclairage. 1978.
7. Smith VC, Pokorny J. Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm. *Vision Res*, 1975; 15: 161-171.
8. Hardy LH, Rand G, Rittler MC. Test for detection and analysis of colour blindness. II. Comparisons of editions of the Ishihara test. *Arch Ophthalmol* 1946; 35: 109-119.
9. Hardy LH, Rand G, Rittler MC. The Ishihara test as a means of analysing defective colour vision. *J Gen Psychol* 1947; 36: 70-106.
10. Joshi VG. Brightness contrast as a source of error in the Ishihara test for colour blindness. *Br J Physiol Opt* 1961; 18: 239-241.
11. Belcher S, Greenshields K, Wright WD. A colour vision survey. *Br J Ophthalmol* 1958; 42: 355-359.
12. Lee DY, Honson M. Chromatic variation of Ishihara diagnostic plates. *Color Res Appl* 2003; 28: 267-276.
13. Birch J. Efficiency of the Ishihara test for identifying red-green colour vision deficiency. *Ophthalmic Physiol Opt* 1997; 17: 403-408.
14. Dain SJ, Grey S, Tran L. Evaluation of the Hahn New Colour Test. *Color Res Appl* 1998: 23: 69-77.
15. Dain SJ. Evaluation of 'Colour Vision Testing Made Easy'. In: Mollon J, Pokorny J, Knoblauch K, eds. Normal and Defective Colour Vision. Oxford, England: Oxford University Press; 2003. p 347-353.
16. Crone RA. Quantitative diagnosis of defective colour vision. A comparative evaluation of the Ishihara test, the Farnsworth Dichotomous test and the H-R-R polychromatic plates. *Am J Ophthalmol* 1961; 51: 298-305.
17. Hardy LH, Rand G, Rittler MC. Test for detection and analysis of colour blindness. I. An evaluation of the Ishihara test. *Arch Ophthalmol* 1945; 3534: 295-302.
18. Kakajima A, Ichikawa H, Nagagawao O, Majima A, Watanabe M. Ishihara in colour vision defects. *Am J Ophthalmol* 1960; 49: 921-929.
19. Gorrell GJ. A study of defective colour vision with the Ishihara test plates. *Ann Hum Genet Lond* 1967; 31: 39-43.
20. Pokorny J, Smith VC, Verriest G. Congenital color defects. In: Pokorny J, Smith VC, Verriest G, Pinckers AJLG, eds. Congenital and Acquired Color Vision Defects. New York: Grune & Stratton; 1979. Ch 7.
21. Pickford RW. Tests for colour blindness. *Br Med Bull* 1953; 9: 82.
22. Cowan A, cited by Tiffin J Kuhn HS. Color discrimination in industry. *Arch Ophthalmol* 1942; 28: 851-859.
23. Cole BL. Misuse of the Ishihara test for colour blindness. *Br J Physiol Opt* 1963; 20: 113-118.
24. Johnson DD. The Ishihara test: on prevention of job discrimination. *J Am Optom Assn* 1992; 63: 352-360.
25. Walls GL. How good is the HRR test for color blindness? *Am J Optom Physiol Opt* 1959; 36: 169-193.
26. Hardy LH, Rand G, Rittler MC. The H-R-R Polychromatic plates. *J Opt Soc Am* 1954; 44: 509-523.
27. Rand G, Rittler MC. An evaluation of the AO HRR pseudoisochromatic plates. *Arch Ophthalmol* 1956; 56: 736-742.
28. Hogan MJ. Evaluation of vision screening methods in industry. *Arch Ind Hlth* 1957; 16: 93.
29. McCulloch C, Turner NC, Smiley JR. A field study of the H-R-R color vision plate test. *Am J Ophthalmol* 1959; 48: 124-129.
30. Cole BL. Comments on some color vision tests and their use for selection. *Aust J Optom* 1964; 47: 56-64.
31. Paulson H. Colour vision testing. In: Pierce JR, Levene JR, eds. Visual Science. Bloomington: Indiana Univ Press; 1971. p 164-176.
32. Aroichane M, Pieramici DJ, Miller NR, Vitale S. A comparative study of Hardy-Rand-Rittler and Ishihara colour plates for the diagnosis of non-glaucomatous optic neuropathy. *Can J Ophthalmol* 1996; 31: 350-355.
33. Birch, J. Clinical use of the American Optical Company (Hardy, Rand and Rittler) pseudoisochromatic plates for red-green colour deficiency. *Ophthalmic Physiol Opt* 1997; 17: 248-254.
34. Kaimbo WK, Bifuko ZA, Longo MB, Dralands L, Missotten L. Color vision in 42 Congolese patients with tuberculosis receiving ethambutol treatment. *Soc Belge d'Ophtalmol Bull* 2002; 284: 57-61.
35. Shute MH, Westall CA. Use of the Mollon-Reffin minimalist color vision test with young children. *J Am Assn Ped Ophthalmol Strab* 2000; 4: 366-372.
36. Adams AJ, Bailey JE, Harwood LW. Color vision screening: A comparison of the AOH-R-R and Farnsworth F2 plates. *Am J Optom Physiol Opt* 1984; 61: 1-9.
37. Bailey JE, Neitz M, Tait D, Neitz J. Evaluation of an updated HRR color vision test. *Vis Neurosci.* In press.
38. Dain SJ. Colorimetric analysis of four editions of the Hardy Rand Rittler pseudoisochromatic tests. *Vis Neurosci.* In press.
39. Hukami K, Ichikawa H, Tanabe S. Evaluation of the standard pseudoisochromatic plates, 1st ed. In: Verriest G, ed. Colour Vision Deficiencies V. Bristol: Adam Hilger; 1980. p 200-203.
40. Birch J, Hamon L. Comments on the use of the Standard Pseudoisochromatic Plates and the New Color Test of Lanthony. In: Verriest G, ed. Colour Vision Deficiencies VII. The Hague: W. Junk; 1984. p 221-226.
41. Honson VJ, Dain SJ. Performance of the Standard Pseudoisochromatic Plate test. *Am J Optom Physiol Opt* 1988; 65: 561-570.
42. Mäntyjärvi M, Karppa T, Karvonen P, Markkanen H, Myohanen T. Comparison of six colour vision tests for occupational screening. *Int Arch Occup Env Hlth* 1986; 58: 53-59.
43. Hovis JK, Cawker CL, Cranton D. Comparison of the Standard Pseudoisochromatic Plates—Parts 1 and 2—as screening tests for congenital red-green deficiency. *J Am Optom Assn* 1996; 67: 320-326.
44. Tanabe S, Hukami K, Ichikawa H. New pseudoisochromatic plates for acquired color vision defects. In: Verriest G, ed. Colour Vision Deficiencies VII. The Hague: W Junk; 1984. p 199-204.
45. Lakowski R, Yamazaki M, Kozak J. Objective data for the SPP test Part 2. In: Drum B, Verriest G, eds. Colour Vision Deficiencies IX. Dordrecht: Kluwer; 1989. p 469-477.
46. Marré M, Marré E, Eckhardt T. Evaluation of the SPP-II test. In: Drum B, Moreland J Serra A, eds, Colour Vision Deficiencies X. Dordrecht: Kluwer; 1991. p 161-165.
47. Cotter SA, Lee French AL. Evaluation of a new color vision test: 'Color Vision Testing Made Easy'. *Optom Vis Sci* 1999; 76: 631-636.
48. Dain SJ. Evaluation of 'Colour Vision Testing Made Easy'. In: Mollon J, Pokorny J, Knoblauch K, eds. Normal and Defective Colour Vision. Oxford, England: Oxford University Press; 2003. p 347-353.
49. Birch J, Chisholm IA, Kinnear P, Pinckers AJLG, Pokorny J, Smith VC, Verriest G. Clinical testing methods. In: Pokorny J, Smith VC, Verriest G, Pinckers AJLG, eds. Congenital and Acquired Color Vision Defects. New York: Grune & Stratton; 1979. Ch 5.
50. Birch J. A practical guide for colour-vision examination: Report of the Standardization Committee of the International Research Group on Colour-Vision deficiencies. *Ophthalmic Physiol Opt* 1985; 5: 265-285.
51. Birch J. Diagnosis of defective colour vision. Oxford: Butterworth-Heinemann; 2001.
52. Farnsworth D. The Farnsworth-Munsell 100 Hue Test for the examination of color

vision. Baltimore: Munsell Color Company; 1949, revised 1957.
53. Farnsworth D. Farnsworth 100 Hue and Dichotomous tests for color vision. *J Opt Soc Am* 1943; 33: 568-578.
54. Dain SJ, Birch J. An averaging method for the interpretation of the Farnsworth-Munsell 100 Hue Test. Part 1: Congenital color vision defects. *Ophthalmic Physiol Opt* 1987; 7: 267-280.
55. Moreland JD. Characteristics of the random 100-Hue observer. In: Drum B, Verriest G, eds. Colour Vision Deficiencies IX. Dordrecht: Kluwer; 1989. p 463-467.
56. Dain SJ, Saunders JE. FM100 Hue total error scores have discrete values. *Ophthalmic Physiol Opt* 1987; 7: 325-326.
57. Kinnear PR. Proposals for scoring and assessing the 100 Hue Test. *Vision Res* 1970: 10: 423-433.
58. Verriest G, Vandevyvere R, Vanderdonck R. Novelles recherches se rapportant à l'influence du sexe et de l'âge sur la discrimination chromatique, ansi qu'à la significance practique des résultats du test 100 hue de Farnsworth-Munsell. *Rev Opt Theor Instr* 1962: 41: 499-509.
59. Lakowski R. Effects of age on the 100-hue score of red-green deficient subjects. *Mod Prob Ophthalmol* 1974; 13: 124-129.
60. Verriest G, Van Laethem J, Uvijls A. A new assessment of the normal ranges of the Farnsworth-Munsell 100-Hue test scores. *Am J Ophthalmol* 1982: 93: 635-642.
61. Kinnear PR. New Farnsworth-Munsell 100 hue test norms of normal subjects for each year of age 5–22 and age decades 30–70. *Br J Ophthalmol* 2002: 86: 1409-1411.
62. Moreland JD, Dain S. Macular pigment contributes to variance in 100 hue tests. In: Drum B, ed. Colour Vision Deficiencies XII. Dordrecht: Kluwer Academic Publishers; 1995. p 517-522.
63. Aspinall PA. Simulated macular changes and their effects on 100-Hue performance. Unpublished manuscript. 1968.
64. Woo GC, Lee M. Are ethnic differences in the F-M 100 scores related to macular pigmentation? *Clin Exp Optom* 2002; 85: 372-377.
65. Dain SJ, Cassimaty VT, Psarakis DT. Differences in FM100-Hue test performance related to iris colour may be due to pupil size as well as presumed amounts of macular pigmentation. *Clin Exp Optom* 2004; 87: 322-325.
66. Aspinall PA. Inter-eye comparison and the 100 hue test. *Acta Ophthalmol* 1974; 52: 307-316.
67. Reeves BC, Hill AR, Aspinall PA. Normative data for the significance of change in error score on the Farnsworth-Munsell 100-Hue test. In: Drum B, Verriest G, eds. Colour Vision Deficiencies IX. Dordrecht: Kluwer; 1989. p 417-424.
68. Breton ME, Fletcher DE, Krupin T. Influence of serial practice on Farnsworth-Munsell 100-hue scores: The learning effect. *App Opt* 1988; 27: 1038-1044.
69. Verriest G, Buyssens A, Vanderdonck R. Etude quantitative de l'effet qu'exerce sur les rèsultats de quelques tests de la discrimination chromatique une diminution non sélective du niveau d'un éclairage C. *Rev Opt (Paris)* 1963; 42: 105-119.
70. Bowman KJ. The effects of illuminance on colour discrimination in senile macular degeneration. *Mod Prob Ophthalmol* 1978; 19: 71-76.
71. Dain SJ, Pereira SM, Palmer BG, Lewis P, Hammond T. Illuminance and the FM100 Hue Test. In: Verriest G, ed. Colour Deficiencies V. London: Adam Hilger; 1980. p 162-163.
72. Kinnear PR. Proposals for scoring and assessing the 100 Hue test. *Vision Res* 1970; 10: 423-433.
73. Lakowski R. Uses and abuses of the Farnsworth-Munsell 100-Hue test. In: Drum B, Verriest G, eds. Colour Vision Deficiencies IX. Dordrecht: Kluwer; 1989. p 375-396.
74. Dain SJ. Skewness and transformations of Farnsworth-Munsell 100-Hue test scores. *Vision Res* 1998; 38: 3473-3476.
75. Lugo M, Tiedeman JS. Computerized scoring and graphing of the Farnsworth-Munsell 100-Hue color vision test. *Am J Ophthalmol* 1986: 101: 469-474.
76. Robertson KM, Moreland JD. Study of familial retinitis pigmentosa sine pigmento combined with cystoid maculopathy. In: Verriest G, ed. Colour Deficiencies V. London: Adam Hilger; 1980. p 285-292.
77. Kitahara K. An analysis of the Farnsworth-Munsell 100-Hue test. *Docum Ophthalmol Proc Ser* 1984; 39: 233-238.
78. Benzschawel T. Computerized analysis of the Farnsworth-Munsell 100-Hue test. *Am J Optom Physiol Opt* 1985; 62: 254-264.
79. Allen D. Fourier analysis and the Farnsworth-Munsell 100-Hue test. *Ophthalmic Physiol Opt* 1985; 5: 337-342.
80. Smith VC, Pokorny J, Pass AS. Color-axis determination on the Farnsworth-Munsell 100-Hue test. *Am J Ophthalmol* 1985; 100: 176-182.
81. Birch J, Dain SJ. An averaging method for the interpretation of the Farnsworth-Munsell 100 Hue Test. Part 2: Color vision defects acquired in diabetic retinopathy. *Ophthalmic Physiol Opt* 1987; 7: 281-291.
82. Dain SJ, Birch J. Identification of polarity in FM 100-Hue plots: a comparison of methods. *Am J Optom Physiol Opt* 1988; 65: 254-262.
83. Knoblauch K. On quantifying the bipolarity and axis of the Farnsworth-Munsell 100-Hue test. *Invest Ophthalmol Vis Sci* 1987; 28: 707-710.
84. Victor JD. Evaluation of poor performance and asymmetry in the Farnsworth-Munsell 100-Hue test. *Invest Ophthalmol Vis Sci* 1988; 3: 476-481.
85. Vingrys AJ, King-Smith PE. Quantitative scoring technique for panel tests of color vision. *Invest Ophthalmol Vis Sci* 1988; 29: 50-63.
86. Aspinall PA. An upper limit of non-random cap arrangements in the Farnsworth-Munsell 100-Hue test. *Ophthalmologica* 1974; 168:128-131.
87. Birch J. Uses of the Farnsworth-Munsell 100-Hue test in the examination of congenital colour vision defects. *Ophthalmic Physiol Opt* 1989; 9: 156-162.
88. Lagerlof O. The Farnsworth-Munsell 100-Hue test in clinical practice. In: Drum B, Moreland JD, Serra A, eds. Colour Vision Deficiencies X. Dordrecht: Kluwer Academic; 1991. 241-249.
89. Aronson JK, Ford AR. The use of colour vision measurement in the diagnosis of digoxin toxicity. *Quart J Med* 1980; 49: 273-282.
90. Chisholm IA. An evaluation of the F-M 100-Hue test as a clinical tool in the investigation and management of ocular neurological deficit. *Trans Ophthalmol Soc UK* 1969; 89: 243-250.
91. Muller T, Kuhn W, Buttner T, Przuntek H. Distorted colour discrimination in Parkinson's disease is related to severity of the disease. *Acta Neurol Scand* 1997; 96: 293-296.
92. Mäntyjärvi M, Terasvirta M. Observations on color testing in ocular hypertension and glaucoma. *Int Ophthalmol* 1992; 16: 417-422.
93. Farnsworth D. The Farnsworth Dichotomous Test for Color Blindness, New York: Psychological Corporation; 1947.
94. Linksz A. The Farnsworth Panel D-15 test. *Am J Ophthalmol* 1966; 62: 27-37.
95. Voke J. Industrial requirements and testing of color vision. *Mod Prob Ophthalmol* 1978; 19: 82-87.
96. Voke J. Colour Vision Testing in Specific Industries and Professions. London: Keeler; 1980.
97. Voke J, Fletcher R. Defective Colour Vision: Fundamentals, Diagnosis and Management. London: Adam Hilger; 1985.
98. Noji J, Kandatsu A, Tamaki R, Kitahara K. Characteristics of the panel D-15 test in optic nerve diseases with congenital red-green color vision defects. In: Ohta Y, ed. Color Vision Deficiencies. Amstelveen: Kugler & Ghedini; 1990. p 225-232.
99. Collin HB. Recognition of acquired colour defects using the panel D-15. *Aust J Optom* 1966; 49: 342-347.
100. Bassi CJ, Galanis JC, Hoffman J, Comparison of the Farnsworth-Munsell 100-Hue, the Farnsworth D-15, and the L'Anthony [*sic*] D-15 desaturated color tests. *Arch Ophthalmol* 1993; 111: 639-641.

101. Smith DP. The assessment of acquired dyschromatopsias and clinical investigation of the acquired tritan defect in dominantly inherited juvenile optic atrophy. *Am J Optom Physiol Opt* 1972; 49: 574-588.
102. Bowman KJ. A method for quantitative scoring of the Farnsworth Panel D-15. *Acta Ophthalmol* 1982; 60: 907-916.
103. Dain SJ. Characteristics of random arrangements of D-15 type tests. In: Drum B, ed. Colour Vision Deficiencies. XI. Dordrecht: Kluwer; 1993. p 321-326.
104. Pinkers AJLG. Combined Panel D-15 and 100 hue recording. *Ophthalmologica* 1971; 163: 232-234.
105. Higgins KE, Knoblauch K. Validity of the Pinckers 100 hue version of the Panel D-15. *Am J Optom Physiol Opt* 1977; 54: 165-167.
106. Lanthony P. The desaturated panel D-15. *Docum Ophthalmol* 1978; 46: 185-189.
107. Bassi CJ, Galanis JC, Hoffman J. Comparison of the Farnsworth 100-Hue, the Farnsworth D 15 and the Lanthony D-15. *Arch Ophthalmol* 1993; 111: 639-641.
108. Lanthony P. Evaluation of desaturated Panel D-15. *J Fr Ophtalmol* 1994; 17: 15-21.
109. Geller AM. A table of color distance scores for quantitative scoring of the Lanthony Desaturated color vision test. *Neurotoxicol Teratol* 2001; 23: 265-267.
110. Giusti C. Lanthony 15-Hue desaturated test for screening of early color vision defects in uncomplicated juvenile diabetes. *Jap J Ophthalmol* 2001; 45: 607-611.
111. Adams AJ, Rodic R. Use of desaturated and saturated versions of the D-15 test on glaucoma and glaucoma-suspect patients. *Docum Ophthalmol Proc Ser* 1982; 33: 419-424.
112. Adams AJ, Rodic R, Husted R, Stamper R. Spectral sensitivity and color discrimination changes in glaucoma and glaucoma-suspect patients. *Invest Ophthalmol Vis Sci* 1982; 23: 516-524.
113. Birch J. A new panel test for tritan colour deficiency. In: Dickinson C, Murray I, Carden D, eds. John Dalton's Colour Vision Legacy. London: Taylor & Francis; 1997. p 309-316.
114. Dain SJ, Adams AJ. Evaluation of the Adams desaturated D-15 test with congenital color vision defects. In: Drum B, Moreland J, Serra A, eds. Colour Vision Deficiencies X. Dordrecht: Kluwer; 1991. p 125-133.
115. Dain SJ, Adams AJ. Comparison of the standard and Adams desaturated D-15 tests with congenital color vision deficiencies. *Ophthalmic Physiol Opt* 1990; 10: 40-45.
116. Hahn CS. Evaluation of congenital colour vision deficiencies. *Korean J Ophthalmol* 1991; 5: 26-29.
117. Lanthony P. The new color test. *Docum Ophthalmol* 1978; 46: 191-199.
118. Lanthony P. Quantitative study of the neutral zones in color vision defectiveness. *Mod Prob Ophthalmol* 1978; 19: 122-124.
119. Lanthony P. Lanthony's new color test. II Clinical evaluation. *Ophthalmologica* 1978; 177: 311-316.
120. Lanthony P. Clinical applications of the New Color Test. *Bull Soc Ophtalmol Franc* 1975; 75: 1055-1059.
121. Lanthony P. Lanthony's new color test. IV Neutral zone and neutral greys. *Ophthalmologica* 1982; 184: 51-57.
122. Dain SJ. Use of the Farnsworth-Munsell H-16 test as an identifier of congenital dichromats. *Optom Vis Sci* 1991; 68: 81.
123. Frisén L, Kalm H. Sahlgren's Saturation test for detecting and grading acquired dyschromatopsias. *Am J Ophthalmol* 1981; 92: 252-258.
124. Lindblom B, Wikholm M, Frisen L. Sahlgren's saturation test for acquired dyschromatopsia: Increased lightness enhances sensitivity. *Graefes Arch Clin Exp Ophthalmol* 1988; 226: 447-448.
125. Honson VJ, Dain SJ. The effects of size and analysis method on the performance of the Farnsworth-Munsell D-15 test. In: Drum B, Moreland J, Serra A, eds. Colour Vision Deficiencies X. Dordrech: Kluwer; 1991. p 29-36.
126. Hovis JK, Leat SJ, Epp K. The UWCDot colour vision test and low vision. *Ophthalmic Physiol Opt* 2003; 23: 125-131.
127. Roth MA. Le test 28 hue selon Farnsworth. *Bull Soc Ophtalmol Franc* 1966; 66: 231-238.
128. Ohta Y. Colour vision test by hue arrangement. *Colour Space* 1970; 58: 5-14.
129. Dain SJ. Assessment of the FM 100 Hue derivative tests. In: Verriest G, ed. Colour Vision Deficiencies V. Bristol: Adam Hilger; 1980. p 197-199.
130. Amos JF, Piantanida TP. The Roth 28-Hue test. *Am J Optom Physiol Opt* 1977; 54: 171-177.
131. Erb C, Adler M, Stübinger N, Wohlrab M, Thiel H-J. Evaluation of the desaturated Roth 28 Hue colour test—preliminary results. In: Cavonius CR, ed. Colour Vision Deficiencies XIII. Dordrecht: Kluwer Academic; 1997. p 323-329.
132. Erb C, Adler M, Stübinger N, Wohlrab M, Zrenner E, Thiel H-J. Colour vision in normal subjects tested by the colour arrangement test 'Roth 28-hue desaturated. *Vision Res* 1998; 38: 3467-3471.
133. Rayleigh Lord. Experiments on colour. *Nature* 1881; XXV: 64-66.
134. Krastel H, Gehrung H, Dax K, Rohrschneider K. Clinical application of the Heidelberg anomaloscope. In: Drum B, Moreland J, Serra A, eds. Colour Vision Deficiencies X. Dordrecht: Kluwer; 1991. p 135-149.
135. Birch J. Extreme anomalous trichromatism. In: Mollon J, Pokorny J, Knoblauch K, eds. Normal and Defective Colour Vision. Oxford, England: Oxford University Press; 2003. p 364-369.
136. Moreland JD. The effect of inert ocular pigments on anomaloscope matches and its reduction. *Mod Prob Ophthalmol* 1972; 11: 12-18.
137. Moreland JD Kerr J. Optimization of a Rayleigh-type equation for the detection of tritanomaly. *Vision Res* 1979; 19: 1369-1375.
138. Moreland JD. Analysis of variance in anomaloscope matches. *Docum Ophthalmol Proc Ser* 1984; 39: 111-121.
139. Roth A, Repiquet C, Renaud JC, Vienot JCh. The Besançon anomalometer. In: Verriest G, ed. Colour Vision Deficiencies V. Bristol: Adam Hilger; 1980. p 172-180.
140. Moreland JD. The clinical utility of anomaloscopy. In: Ohta Y, ed. Color Vision Deficiencies. Amstelveen: Kugler & Ghedini; 1990. p 127-144.
141. Roth A. The power of metameric color equations in testing color vision. In: Ohta Y, ed. Color Vision Deficiencies. Amstelveen: Kugler & Ghedini; 1990. p 181-190.
142. Pokorny J, Smith VC. Color matching as a clinical tool. Theory of modification by disease. In: Ohta Y, ed. Color Vision Deficiencies. Amstelveen: Kugler & Ghedini; 1990. p 255-268.
143. Estévez O, Spekreijse H, Van Dalen JTW, Verduynlunel HFE. The Oscar colour vision test: Theory and evaluation (objective screening of color anomalies and reductions). *Am J Optom Physiol Opt* 1983; 60: 892-901.
144. Cavonius CR, Kammann J. A clinical evaluation of the 'OSCAR' color vision set. In: Verriest G, ed. Colour Vision Deficiencies VII. The Hague: W Junk; 1984. p 275-279.
145. Zisman F, Seger KR, Adams AJ. Specificity evaluation of the OSCAR colour vision test. In: Verriest G, ed. Colour Vision Deficiencies VIII. The Hague: W Junk; 1987. p 171-176.
146. Verriest G, Uvijls A. About the OSCAR test. In: Verriest G, ed. Colour Vision Deficiencies VIII. The Hague: W Junk; 1987. p 177-181.
147. Verriest G, Uvijls A. Results of the OSCAR test in groups of normal and abnormal subjects. In: Drum B, Verriest G, eds. Colour Vision Deficiencies IX. Dordrecht: Kluwer; 1989. p 479-487.
148. Metha AB, Vingrys AJ. The C-100: A new dichotomiser of colour vision defectives. *Clin Exp Optom* 1992; 75: 114-123.
149. Fletcher R. A modified D-15 test. *Mod Prob Ophthalmol* 1972; 11: 22-24.
150. Fletcher R. Second edition of The City University test. In: Verriest G, ed. Colour Vision Deficiencies V. Bristol: Adam Hilger; 1980. p 195-196.
151. Honson VJ, Dain SJ. Analysis of the Mark II edition of The City University Colour Vision Test. *Am J Optom Physiol Opt* 1987; 64: 277-283.
152. Ohta Y, Kogure S, Izutsu Y, Miyamoto T,

Nagai I. Clinical analysis of colour vision deficiencies with The City University test. *Mod Prob Ophthalmol* 1978; 19: 126-130.
153. Verriest G, Caluwaerts MR. An evaluation of three new colour vision tests. *Mod Prob Ophthalmol* 1978; 19: 131-135.
154. Hill AR, Connolly JE, Dundas J. An evaluation of The City University Test. *Mod Prob Ophthalmol* 1978; 19: 136-141.
155. Birch J. The contribution of The City University test (1st and 2nd editions) in a clinical test laboratory. In: Verriest G, ed. Colour Vision Deficiencies VII. The Hague: W Junk; 1984. 193-198.
156. Chauhan BC, Block MT. City tests and information theory. *Ophthalmic Physiol Opt* 1986; 6: 157-163.
157. Zisman F, Adams AJ. Screening functional color vision anomalies: A comparison of The City University and AO-HRR tests on children. In: Verriest G, ed. Colour Vision Deficiencies VIII. The Hague: W Junk; 1987. 145-149.
158. Birch J. Clinical use of the City University Test, 2nd ed. *Ophthalmic Physiol Opt* 1997. 17: 466-472.
159. Oliphant D, Hovis JK. Comparison of the D-15 and City University (second) color vision tests. *Vision Res.* 1998; 38: 3461-3465.
160. Margrain TH, Birch J. Owen CG. Colour vision requirements of firefighters. *Occup Med (Oxford)* 1996; 46: 114-124.
161. Dain SJ, Riley JM, Steer A. The effect of colour vision test design on the tritan defect observed with short duration stimuli. In: Ohta Y, ed. Colour Vision Deficiencies. Amsterdam: Kugler & Ghedini; 1990. p 205-211.
162. Intersociety Color Council Colour Aptitude Test Committee. Color Aptitude: Philadelphia: Federation of Paint and Varnish Production Clubs. Test. 1953.
163. Dimmick FL. Specification and calibration of the 1953 edition of the Inter-Society Color Council Color Aptitude Test. *J Opt Soc Am* 1956; 46: 389-393.
164. Corbett HJ, Saxe JP. Examination of ISCC-Color Aptitude Test color differences. *J Opt Soc Am* 1959; 49: 1136-1136.
165. Anon. Correlation of results from color-matching aptitude-test scores. *J Coating Technol* 1986; 58: 41-47.
166. Boltz CL. A statute to Mr Trattles. London: Butterworth's Scientific Publications; 1952.
167. Cole BL, Vingrys AJ. A survey and evaluation of lantern test of color vision. *Am J Optom Physiol Opt* 1982; 59: 346-374.
168. Paulson HM. The performance of the Farnsworth Lantern at the Submarine Medical Research Laboratory and in the field from 195501965. Report No 466. US Naval Submarine Medical Center. Groton, Conn: Submarine Base; 1966.
169. Laxar K. Performance of the Farnsworth Lantern test as related to the type and degree of the color vision defect. Report No 504. US Naval Submarine Medical Center. Groton, Conn: Submarine Base; 1967.
170. Birch J, Dain SJ. Performance of red-green color deficient subjects on the Farnsworth Lantern (FaLant). *Aviat Space Environ Med* 1999; 70: 62-67.
171. Sie AW, Yap MK. The performance of color deficient individuals on airfield color tasks. *Aviat Space Environ Med* 2003; 74: 546-550.
172. Laxar KV. US Navy color vision standards revisited. NSMRL memo Report 98-01. Groton. Conn: Naval Submarine Research Laboratory; 1998.
173. Dain SJ, Honson VJ, Ang J. The effects of ambient conditions on the Farnsworth Lantern Test. *Aviat Space Environ Med* 1988; 59: 371-373.
174. Cole BL, Vingrys AJ. Who fails lantern tests? *Docum Ophthalmol* 1983; 55: 157-175.
175. Hackman RJ, Holtzman GL, Walter PE. Color vision testing in the US Naval Academy. *Milit Med* 1992; 157: 651-657.
176. Cole BL, Maddocks JD. Can clinical colour vision tests be used to predict the results of the Farnsworth lantern test? *Vision Res* 1998: 38: 3483-3485.
177. Board of Trade. Sight tests for seafarers. Report of the Committee to review the Board of Trade sight test standards for persons serving or intending to serve in the merchant navy or fishing fleet. Chair: J Naisby. Her Majesty's Stationery Office. 1970.
178. Holmes JG, Wright WD. A new colour-perception lantern. *Color Res Appl* 1982; 7: 82-88.
179. Vingrys AJ, Cole BL. Validation of the Holmes-Wright Lanterns for testing colour vision. *Ophthalmic Physiol Opt* 1983; 3: 137-152.
180. Birch J. Performance of red-green color deficient subjects on the Holmes-Wright lantern (type A) in photopic viewing. *Aviat Space Environ Med* 1999: 70: 897-901.
181. Hovis JK, Oliphant D. Validity of the Holmes-Wright lantern as a color vision test for the rail industry. *Vision Res* 1998; 38: 3487-3491.
182. Commission Internationale de l'Éclairage. International Recommendations for Colour Vision Requirements for Transport. Publication CIE 143-2001. CIE Central Bureau. Wien Austria.
183. Fletcher R. A modified lantern test. In: Drum B, Moreland J Serra A, eds. Colour Vision Deficiencies X. Dordrecht: Kluwer; 1991. p 111-113.
184. Hovis JK, Oliphant D. A lantern colour vision test for the rail industry. *Am J Ind Med* 2000; 38: 681-696.
185. Cole BL, Maddocks JD. Protans and PAPI: Recognition of a two colour code by persons with defective colour vision. In: Drum B, ed. Colour Vision Deficiencies XII. Dordrecht: Kluwer Academic Publishers; 1995. p 501-510.
186. Tanabe S, Hukami K, Yamade S, Ichikawa K, Tagai S. A new lantern using light-emitting diode lamps. In: Drum B, ed. Colour Vision Deficiencies XII. Dordrecht: Kluwer Academic Publishers; 1995. p 467-472.
187. Mäntyjärvi M, Karppa T, Karvonen P, Markkanen H, Myohanen T. Comparison of six colour vision tests for occupational screening. *Int Arch Occup Env Hlth* 1986; 58: 53-59.
188. Mertens HW, Milburn NJ. Performance of color-dependent air traffic control tasks as a function of color vision deficiency. *Aviat Space Environ Me.* 1996; 67: 919-927.
189. Mertens HW, Milburn NJ. Validity of clinical color vision tests for air traffic control. *Aviat Space Environ Med* 1998; 69: 666-674.
190. Mertens HW, Milburn NJ, Collins WE. Practical color vision tests for air traffic control applicants: en route center and terminal facilities. *Aviat Space Environ Med* 2000; 71: 1210-1217.
191. Dain SJ, Hughes LE. Survey of the colour vision demands in fire fighting. In: Mollon J, Pokorny J, Knoblauch K, eds. Normal and Defective Colour Vision. Oxford: Oxford University Press; 2003. p 347-353
192. Cole BL. The handicap of abnormal colour vision. *Clin Exp Optom* 2004; 87: 258-275.

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