# The Evolution of Colour Vision Testing

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## ABSTRACT

Colour vision testing forms an important part of the assessment of retinal pathology and congenital colour vision anomalies. Although the traditional Ishihara test and other pseudoisochromatic plates are relatively simple to use, some are not designed for the assessment of more complex acquired defects, and hue discrimination tests can be very time consuming to administer and analyse. This review outlines the theoretical development and historical evolution of colour vision tests, from the 19th until this early part of the 21st century. Based on these developments, speculation is made on how the tests will evolve in the future, with increasingly refined computer technology, and predicts that they will provide consistent and robust assessments of colour vision that will become routinely used in the clinical environment.

**Keywords:** colour vision testing, pseudoisochromatic plates, Farnsworth-Munsell 100-Hue, computer-assisted diagnosis, computerised colour vision tests.

## INTRODUCTION

Historically, the development of colour vision tests was driven by two major forces. The first was the need for vocational tests to ensure accurate colour vision in professions and industries such as electrical, textiles and the railway, navy, and armed forces. This was particularly fuelled by safety concerns following a series of accidents in the railway and shipping industries caused by the misinterpretation of coloured signals.[1] The second was to create accurate clinical tests to screen for congenital colour deficiencies and to diagnose acquired colour defects.

Despite the great advances in the development of colour vision tests since they were first created in the 1800s, there is no single colour test that can rapidly and accurately screen, diagnose and classify any colour vision defect. This means that selection from the colour vision test battery must be made carefully according to the type of defect and the level of information that is required. Therefore, it is imperative that clinicians have a firm understanding of the types of colour vision tests available and the colour deficiencies they are most appropriate to examine.

This review aims to describe the foundations and historical development of colour vision tests, the clinical tests that are currently available and recent advances in colour vision testing methods.

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## COLOUR VISION THEORIES

Colour vision deficiency was first described as a physiological failure of visual function by John Dalton in 1798.[2] Many theories on the mechanisms of colour vision and colour vision deficiency have since been proposed, each one advancing on the last.[3-11] Colour vision testing methods have tended to reflect the theory and technology of their time.

It was noted by several researchers in the 1700s that any one colour could be matched by the proportionate mixture of just three colours; red, yellow and blue. These were named the primary colours. This notion of trichromacy in colour vision became widely accepted, however, it was assumed to be a property of light rather than the physiology of sight.

In 1802, Thomas Young delivered his lecture 'On the Theory of Light and Colours' that presented the trichromatic theory. He hypothesised that "As it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles… it becomes necessary to suppose the number is limited, for instance, to the three principal colours, red, yellow and blue".[3] Several months later, Young was compelled to change his three principal colours to violet, red and green[4] after the experiments of William Wollaston[5], who observed that yellow could be obtained from a mixture of red and green, and therefore it could not be a primary colour.

Later, Young's trichromatism theory was revised by Hermann von Helmholtz[7] who conducted trichromatic colour matching experiments, finding that in some cases the mixture became

desaturated and could not be matched to the test colour, leading him to realise the spectral sensitivities of the retinal receptors must overlap. This was such an important finding that the Trichromacy Theory then became known as the Young-Helmholtz theory of colour vision.

In 1878, Ewald Hering[8] proposed a new theory that humans see four primary colours; red, blue, green and yellow and suggested that these colours were arranged in opponent pairs; red-green and blue-yellow. A few years later, Donders[9] (1881) proposed that it was feasible that Trichromacy may occur at one stage in the visual pathway and Opponency at another. These theories form the basis of modern colour vision models.

## HISTORICAL EVOLUTION OF COLUR VISION TESTS

Early vocational assessments of colour vision were made by an individual naming the colour of everyday objects, with their responses compared to those of an observer with normal colour vision[12] The first commercially available test, the Holmgren Wool Test (1875) was designed for examining train drivers[13] It consisted of many different coloured wool skeins that had to be matched to three large test skeins coloured red, green and purple. The colours of these test skeins were based on an erroneous proposition that the types of colour defect were distinct; red-blindness, green-blindness or violet-blindness[13] This severely impaired the accuracy of the Holmgren test, and the visual task itself led to errors[14]. A number of variations of this type of test were developed, the most common of these being the Edridge-Green Bead Test (1891)[15].

The next advance in vocational colour vision testing came in the early 1900s with the introduction of lantern tests designed to mimic the light signals used in rail and sea transport. These tests provided a fast method of detecting unsafe colour vision defects for such industries. The most popular lantern tests have been those devised by Edridge-Green (1891)[15], Farnsworth (1943)[16] and more recently Holmes and Wright (1975)[17]. Lantern tests are still in use in the transport, maritime, aviation and naval industries.

The Stilling test was the first clinical colour vision test to be developed and the first to utilise pseudoisochromatic principles. Pseudoisochromatic plates have their foundation in the Opponency Theory[8]. When considering cases of colour deficiency, discrimination of one colour in an opponent pair is compromised and as such, the colours of the pair appear isochromatic and will be confused. Therefore, Stilling performed colour matching experiments with two dichromatic subjects, one with a blue-yellow defect, and the other with a red-green defect, to determine the exact hues perceived as pseudoisochromatic. Their matches form the basis of pseudoisochromatic plate tests used today. The Stilling test was initially well accepted, however, it was eventually surpassed by the Ishihara pseudoisochromatic plates. The Ishihara remains the most commonly performed screening test for colour vision[18].

The pseudoisochromatic tests fulfilled the screening requirement for the detection of colour vision deficiency, however, they lacked the ability to grade the severity of colour defects. They were also unable to grade the degree of discrimination within subjects who had normal colour vision. Hue discrimination tests originally designed for vocational colour assessment[19] were able to measure these gradations in normal and abnormal observers, and have therefore become commonly used in clinical settings.

The Farnsworth-Munsell 100-Hue test (F-M 100) is the most widely used hue discrimination test. It was created by Dean Farnsworth in 1943 to detect those with superior colour vision for employment in industries requiring a demanding appreciation of colour[19]. It has since been found to be valuable in assessing acquired defects, particularly in monitoring their subtle progression[20].

Other hue discrimination tests based on the same principles as the F-M 100 have also been developed. The Farnsworth-Munsell Panel-D15 test is a shortened version of the F-M 100 used for a more rapid assessment. The test divides observers into two categories; those who pass with normal or mildly deficient colour vision, and those who fail with moderate or severe colour deficiency. Desaturated versions of the D15; the Adams[21] and Lanthony tests[22] are used to further discriminate those who pass the D15, giving a finer grading of severity

## CURRENT CLINICAL VISION TESTS (TABLE 1)

### PSEUDOISOCHROMATIC PLATE TESTS

Pseudoisochromatic colour vision tests have a long standing acceptance in research and clinical practice. These tests consist of plates with a central test figure such as a number, picture, symbol, or pattern that can be traced by an illiterate subject. The test shapes and background are composed of variably sized dots randomly placed. The test figure is delineated from the background by colour and can be readily detected by a person with normal colour vision. However, for people with abnormal colour perception, the plate testing their particular colour deficiency will appear isochromatic and therefore, the test figure will either be invisible or confused.

Originally, pseudoisochromatic plate colours were hand painted but this was superseded with the introduction of colour printing. The speed of this approach made pseudoisochromatic tests more broadly available and popular amongst clinicians.

The process of printing did pose some problems. Subsequent editions of the same test often vary in the colour properties of plates. In the case of the Ishihara test, small differences in colour and residual brightness cues between editions are apparent[23], although it does not appear to affect the sensitivity and specificity of the test[24]. In contrast, the third edition of the Hardy Rand Rittler test (HRR) was flawed because of visible differences in hue and saturation[25,26].

| Table 1: Comparison of Standard Clinical Colour Vision Tests | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Test Type** | **Test Name** | **Year of Developed** | **Reliability** | **Screening** | **Severity Diagnosis** | **Congenital Red-Green** | **Tritan** | **Acquired** | **Comments** | **Age Group** |
| **Pseudo-Isochromatic** | Ishihara | 1917 | Sensitivity 0.93 Specificity 0.98 [24] | ✓ | ✕ | ✓ | ✕ | ✕ | Illiterate plates | >=6 yrs [67] * |
| | Hardy Rand Rittler | 1954 | Sensitivity 1.0 Specificity 0.96 [36] (4th edition) | ✓ | ✓ | ✓ | ✓ | ✓ | Use of symbols makes it suitable for children. | >=3 yrs [67] * |
| | Matsubara | 1957 | Sensitivity 0.07 Specificity 0.90 [37] | ✓ | ✕ | ✓ | ✕ | ✕ | Designed for children Pictures- some are culturally specific to Japan and pose a problem for western populations | >=3 yrs [38] |
| | Colour Vision Testing Made Easy | Late 1990s | Sensitivity 0.90 Specificity 1.0 [39] | ✓ | ✕ | ✓ | ✕ | ✕ | Pictures and Matching Designed for children. | 5-7 yrs [39] † |
| **Hue Discrimination** | Farnsworth-Munsell 100-Hue | 1943 | Sensitivity 1.0 Specificity 0.83 [61] | ✕ | ✓ | ✓ | ✓ | ✓ | Very fine grading of colour discrimination, ideal to monitor acquired defects. | >=8 yrs [67] |
| | Farnsworth-Munsell Panel-D15 | 1947 | - | ✕ | ✕ | ✓ | ✓ | ✓ | Much faster to administer than FM 100. | >=8 yrs [67] |
| | Lanthony D15 | 1978 | - | ✕ | ✕ | ✓ | ✓ | ✓ | Used in combination with the original D15. Desaturated colours. | >=8 yrs [67] |
| | Adams Desaturated D15 | 1982 | - | ✕ | ✕ | ✓ | ✓ | ✓ | Used in combination with the original D15. Desaturated colours. | >=8 yrs [67] |
| | City University (2nd edition) | 1972 | Sensitivity 0.95 Specificity 0.83 [58] | ✓~ | ✕ | ✓ | ✓ | ✓ | 2nd Edition contains desaturated plates to detect mild defects. | >=4 yrs* # |

**\*** Originally designed exclusively for use in adults but has been shown to be useful in examining children also.

\# No verifiable data for appropriate age group is available in the literature, however, the City University test is readily used in the clinical setting for children >4 years of age.

† Verified for use in children of this age[38] but is designed also for use in younger children.

~ Not originally designed as a screening tool, but is commonly used as such.

## The Ishihara Test

The most commonly performed pseudoisochromatic plate test is the Ishihara, and several editions have been published. It is used as a quick and reliable[18] screening test for accurate identification of congenital red-green colour deficiencies[27]. Despite this, there are some short-comings of the test, arising predominantly through administration under non-optimal conditions and/or misinterpretation of results.

Appropriate illumination is essential for the correct and consistent display of colours in all colour vision tests. The majority of pseudoisochromatic plate manufacturers recommend that the test plates are well illuminated by daylight or by using a daylight globe with a colour temperature of close to 6740° Kelvin. Similarly, other testing parameters such as testing distance should also be kept consistent. The Ishihara test manufacturers recommend a testing distance of 75cm be used with the plates held at a right angle to the line of vision[27], however, this is rarely adhered to. Other testing distances suggested have been 2/3m and arms length[28].

The level of VA has been shown to affect Ishihara test performance and appropriate refractive correction should always be worn. A study by McCulley et al[29], using plus lenses to reduce the visual acuity in normally-sighted subjects showed that of three common colour vision tests; Ishihara, Farnsworth D15 and Hardy-Rand-Rittler (HRR), Ishihara was the most dependent on a good level of VA. Test performance was significantly affected with a VA level of less than 0.72 logMAR (≈ 6/30). The possibility misdiagnosis of patients with poor vision as having a colour defect needs to be considered.

Some eye care professionals incorrectly interpret any error on the Ishihara test plates as being indicative of a colour vision defect[30]. The pass/fail criteria recommended by the publishers in recent editions is that correct reading of 17 of the 20 screening plates can be regarded as denoting normal colour vision[18]. This is especially important to note, as the scripted font used in the Ishihara test has been shown to contribute significantly to misreadings by colour normal observers[31,32]. Failure to note this design characteristic can lead to the misclassification of individuals with normal trichromatic colour vision. If 12, or fewer plates are read correctly then the person can be said to have defective colour vision[18]. It is recommended that if between 12 and 17 plates are read correctly additional examination with other colour vision tests should be performed.

Finally, some eye practitioners may be unaware that Ishihara cannot be used as an all encompassing test for the detection of colour vision defects. As there are no tritan plates Ishihara is only suitable for examining red-green defects, and cannot detect tritan defects which are predominantly acquired. A further common misconception is that Ishihara may be used to test for acquired red-green defects[30]. This is a significant issue as the use of Ishihara to screen for acquired defects when disease or toxicity is suspected, and or record baseline data prior to commencing treatment known to cause retinal toxicity, may result in misdiagnosis and failure to undertake appropriate treatment.

### The Hardy Rand Rittler Test

The Hardy Rand Rittler test (HRR) is another common pseudoisochromatic test predominately used in the USA. It intended to be a single test to screen and diagnose both red-green (protan and deutan) and blue-yellow (tritan) colour defects. Unlike other pseudoisochromatic tests the background matrix of dots in the HRR are shades of grey varying in luminance rather than colour. The test figures are geometric symbols; a cross, a triangle or a circle which are coloured specifically to appear achromatic to either a protan, deutan or tritan observer. The colour of the test figure gradually increases in saturation over successive plates, effectively increasing the colour difference between the figure and background. This enables a diagnosis of mild, moderate or severe to be made.

The original version of the HRR received great acclaim, showing a very high sensitivity and specificity on repeated testing[33,34]. Unfortunately, the long awaited third edition showed visibly different colour saturation and as a result was not well received. The recent fourth edition more closely reproduces the colours of the original test[25], and studies have found its validity to be much improved on the inadequate intermediate editions[25,26,35].

### Pseudoisochromatic Plates for Children

The examination of colour vision in young children has still not been refined into a reliable and universal procedure. Quite often, Ishihara is used as the gold standard to screen for colour vision defects in school aged children. The HRR test is also useful for children and as it incorporates symbols and shapes, however, it is not always readily available outside the United States.

Other pseudoisochromatic test plates have been designed specifically for children, quite often using pictures or symbols as the test figure rather than a numeral. Some of the more widely available are Kojima-Matsubara[36,37] and the Colour Vision Testing Made Easy (CVTME)[38] test. None of these have successfully surpassed Ishihara as the 'gold standard' screening test, partly due to a lack of validation in the literature. They do, however, increase the age range that may be tested for colour vision deficiencies.

### HUE DISCRIMINATION TESTS

Hue discrimination tests are in relatively common use in clinical settings but unlike pseudoisochromatic plate tests they are not designed as a screening tool. They are specifically designed for detecting all types of colour deficiency and as such, can be used to examine both acquired and congenital, and both red-green and blue-yellow defects. Hue discrimination tests usually require the observer to place discs of varying hue into a sequence which progressively changes from a fixed colour at the beginning and end of the sequence being tested. Other tests require matching of closely related hues. Hue discrimination tests are rather more complex than pseudoisochromatic plates, and quite often give a more comprehensive assessment of a patient's level of colour vision.

Also, unlike pseudoisochromatic plates, hue discrimination tests do not pre-suppose the type of colour confusions that might be present[19]. This makes hue discrimination tests useful in the assessment of acquired colour deficiencies[20], and as such, are essential for examining colour vision in cases with pathology. The number of errors made can often be used to determine the severity of the defect and monitor subtle progression. This characteristic also makes these tests valuable in assessing the colour discrimination aptitude of observers with normal colour vision. This is predominately used vocationally to distinguish those with superior discrimination for occupations requiring a demanding appreciation of colour.

### The Farnsworth-Munsell 100-Hue

The F-M 100 is based on the Munsell System of Colours[39], developed by Albert Henry Munsell in the early 1900s. In this system, each colour is given a unique coding according to three characteristics: hue, value and chroma. Hue refers to the dominant wavelength colour, value to the relative lightness, and chroma refers to the colour saturation. Munsell designated five principle colours; Red, Yellow, Green, Blue and Purple and a range of colours intermediate to these, Red-Yellow, Yellow-Green, Green-Blue, and Blue-Purple.

The principal hues are described by their first letter, that is, R for red, Y for yellow and so on. Each hue step intermediate to the principle hues is assigned a number from 1 to 10. The value was also allocated a number between 1 and 10 where 1 describes darkest and 10 the lightest. Similarly, chroma was numbered from 0 which is neutral grey, to 15, which is the most vivid colour. Therefore, a complete colour notation could be written as 4B5/5, which indicates a number 4 blue hue, with a Munsell value of 5 and a chroma of 5.

The colours used in the Farnsworth-Munsell 100-Hue test (F-M 100) form a hue circle of perceptually equal hue steps ranging across the entire visible spectrum whilst maintaining a constant Value/Chroma level of 5/5. The original series of 100 Hues was established by Nickerson and Granville[40] using of a set of experimental Munsell papers prior to being incorporated into the F-M 100. Although researchers had experimented with hue scales prior to this[41-45] none had formed a series which differed only in Hue, while remaining constant in Chroma and that had encompassed the full range of visible colours.

While the original series consisted of 100 hues, Farnsworth found that each step around the hue circle was not quite equal in terms of difficulty[19] and certain steps were particularly prone to causing errors by observers with normal colour vision. As a result 15 caps were removed, leaving a total of 85 hues. Farnsworth's writings on the construction of the F-M 100 do not indicate which colours were removed or where they may fall on the hue circle[19,46]. The impact of this on the validity of the F-M 100 can only be speculated.

It is known, however, that the measured change in hue between each of the F-M 100 caps is not equal throughout the hue circle. The caps that are closest in hue spacing are located in the section confused by tritans (between caps 80 to 85, 1 to 8 and 32 to 52). This variation in hue gradation can lead observers with normal colour vision to make increased errors in this area[47]. Therefore, a slight tritan pattern can be an artefact of the test and must be taken into consideration when interpreting the results. This can also make it difficult to differentiate between an observer with normal trichromatic colour vision and a person with anomalous trichromacy. This is all ready problematic, as anomalous trichromacy is not characterised by a single area of colour confusion[47], rather, it is characterised by minor and generalised mistakes, much like that of colour normal observers with moderate to low discrimination ability.

The final way in which the current F-M 100 colours differ from those described by Nickerson and Granville, is that while the experimental papers were said to have a constant Value and chroma of 5, Farnsworth's writings indicate that this may not be the case for the F-M 100[46]. The likely effect of areas of de-saturation in the hue circle is to increase the errors made by observers with normal colour vision in these areas. Regardless of these fundamental inaccuracies of design, the F-M 100 remains the most valuable clinical test for acquired deficiencies.

Unfortunately, the F-M 100 has some drawbacks, occurring predominately through errors in recording and administration. The recording process, involving arithmetical calculation and graphing of results is both laborious, time consuming, and prone to errors. This has caused clinicians to resort to other less arduous methods of testing colour vision. Another common error results from the examiner's misinterpretation of error scores. This is most often due to ignorance when it comes to the normative values, and the fluctuation of error scores in both the normal and colour deficient population according to age[48-50], macular pigment[51,52], pupil size[52], familiarity with the test[53] and level of colour discrimination[19]. As such, these normative values must be kept in mind when examining error scores on the F-M 100.

Incorrect lighting, coupled with the degradation of colour through sunlight and handling[54], and colour variance already apparent between individual tests can produce erroneous display of the coloured caps. These problems with administration effectively alter the value of caps and allow the patient to discriminate based on these brightness cues rather than hue[55].

**Other Hue Discrimination Tests**

Farnsworth also developed other, more concise hue discrimination tests using the F-M 100 colours. The most popular has been the Farnsworth-Munsell Panel D-15 (D-15), which was designed for vocational use in the Electronics industry[19]. Other hue discrimination tests have been designed based on the D-15, with some slight changes in colour properties, particularly value. Some such tests are the Lanthony and Adams de-saturated tests. The City University Test is primarily designed for use in children and has the advantage of being able to detect acquired colour deficiencies. The test is produced in book form with a number of plates consisting of a central test colour surrounded by 4 variably coloured dots. The central colour is matched to the peripheral one which is the most similar in hue.

Unfortunately, studies have shown that while the rate of failure for the D-15 and the City University are similar, only 60-70% of subjects with known colour vision anomalies fail both tests[56,57]. As such, the results cannot be used interchangeably as originally intended. A further discrepancy between the two tests is that while City University is less sensitive to protanopic defects, the D15 is less sensitive to detecting deuteranopia[56].

## COMPUTERISED COLOUR VISION TESTS

Computer technology, particularly the resolution of colour monitors, graphics display, and storage capacity, has greatly evolved in recent years and computers have become a necessity in everyday life, both at home and in the workplace. Computerisation of colour vision testing has been seen as a way to overcome some of the difficulties in the administration and recording of colour vision tests by making the tests more repeatable and robust for clinical use. This occurs by controlling colour variance between tests, lighting errors and examiner error in calculating and recording results. Additionally, electronic storage of data will assist with the

retrieval of records, allowing rapid comparison of results over time. This is thought to enhance the monitoring of disease progression in acquired deficiencies. The widespread distribution of sophisticated computer technology, and its control of human error and variance in testing conditions, will mean that computerisation is an inevitable next step to improve current testing methods.

There are, however, presently some limitations to computerised colour vision testing. There can be great variation in colour when displayed on different types of computer monitors such as those using Cathode Ray Tubes (CRT) or Liquid Crystal Displays (LCD). There are also potential differences in the resolution of the screens, available colour settings and the amount of drift over time that has occured in these settings. Typically, CRT screens are more suitable for the accurate display of colour, however, they are known to degrade with time and have become largely obsolete with the introduction of newer technology. LCD monitors are widely available but colour settings can drift requiring frequent calibration. A general issue with computers is that while they are very efficient for the storage of results, there is always the possibility of data corruption, loss of data and vulnerability to viruses. Finally, there remains the issue of the discipline required to perform frequent monitor calibration and data back up.

The development of scientifically-based computerised colour vision tests began in the 1980s, however, these tests used technology that was expensive and therefore more appropriate to research than clinical use. Currently, with increasingly advanced computer technology and public availability, there has been an influx of newly developed computerised tests (Table 2). Unfortunately, many of these tests have not yet been validated, and this field remains in its preliminary stages. Additionally, a lack of standardised test procedures for administration of the computerised tests such as, screen type, test distance, room illumination levels and recommendations for monitor calibration is likely to affect the robustness in clinical practice. Numerous colour vision tests have also flooded the internet resulting in the possibility of mass self-screening for colour vision deficiencies. Although in theory this should increase the awareness and detection of colour vision defects, many of these tests have been developed and presented as games and their validity is questionable.

## PSEUDOISOCHROMATIC PRINCIPLES

### Colour Assessment and Diagnosis (CAD) Test City University

The web-based Colour Assessment and Diagnosis (CAD) Test, developed by City University in London[58], uses pseudoisochromatic principles, presenting a moving coloured square test figure against a neutral grey background[58] The coloured square varies in hue throughout the 90 second test duration. A colour vision defect is detected if at any time the test figure disappears, having become indistinguishable from the background. Random luminance masking of the background and test figure is used to ensure only chromatic, and not luminance differences are used to distinguish the test figure[59]. The CAD test has been found reliable in identifying protanopia and deuteranopia, but its effectiveness in detecting anomalous trichromacy has not yet been tested[60].

### Cambridge Colour Test (CCT)

The Cambridge Colour Test (CCT)[61] (Figure 1 part a) also uses pseudoisochromatic principles. Each plate is made up of randomly generated dots which vary in luminance

| Table 2: Comparison of Computerised Colour Vision Tests (Unpublished Data) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Test Type** | **Test Name** | **Reliability** | **Screening** | **Severity Diagnosis** | **Congenital Red-Green** | **Tritan** | **Acquired** | **Comments** |
| **Pseudo-Isochromatic** | Colour Assessment and Diagnosis Test (CAD) [61] | Sensitivity 0.93 Specificity 1 [61] | ✓ | ✗ | ✓ | ✗ | ✗ | Uses a moving square as the test figure. Background is composed of squares of varying luminance. |
| | Cambridge Colour Test [62, 63] | – | ✓ | ✓ | ✓ | ✓ | ✓ | Presentation of test figure within background dot matrix as in Ishihara and Stilling tests. Uses Landholt C as test figure. |
| **Hue Discrimination** | Save Sight Institute Computerised FM 100 (SSI FM100) | Sensitivity 0.93 Specificity 0.89 * | ✗ | ✓ | ✓ | ✓ | ✓ | Based on the Farnsworth-Munsell 100-Hue with identical presentation, size of caps and spacing of the hue circle. |
| | Portal Colour Sort Test (PCST)[64] | – | ✗ | ✗ | ✓ | ✓ | ✓ | The PCST uses the principles of the Farnsworth tests however uses 18 caps to give a fast assessment of colour discrimination. |
| | Seohan 85 Hue Test [66] | – | ✗ | ✓ | ✓ | ✓ | ✓ | Based on the FM 100 however caps are displayed as squares. Like the FM 100 there are 85 caps separated into 4 segments. |

and size so that the test figure, a coloured Landholt C, is distinguished by chromatic cues only. To determine the severity of the colour defect, the C is presented at various levels of Chroma (saturation) using a staircase method along each of the axes for protan, deutan and tritan classification. The CCT test is designed not only to rapidly detect defects, but also to give a more detailed assessment particularly in the case of acquired defects. The CCT has been found valid in assessing all colour vision defects[62].

## HUE DISCRIMINATION PRINICIPLES

### Save Sight Institute Computerised Farnsworth-Munsell 100-Hue Test (SSI F-M 100)

The SSI F-M 100 (Figure 1 part b) was designed to replicate the F-M 100 test while improving scoring speed, and eliminating colour degradation. The program contains 85 hue caps that are identical to the F-M 100 in hue, spacing and size. The original F-M 100 is presented on a black background but the SSI F-M 100 uses a charcoal background to produce effective contrast while maintaining the impression of depth of the caps. The SSI F-M 100 test is also organised and presented as 4 'boxes'.

At the commencement of each box, the caps are randomly presented on the lower half of the screen. The observer is required to move the caps up into position in the tray on the upper half of the screen and to place them in order, relative to the fixed caps at the beginning and end of the test box. As each box is completed the score is calculated by the program and graphed according to the Farnsworth scoring method; that is familiar to clinicians[19]. The results may be saved and printed out as required. It is able to be run on the 'Windows' platform on any computer containing a suitable graphics card and uses a simple 'drag and drop' procedure for the ordering of the caps. This test is still in the research and development stage and is not currently available commercially.

### Portal Colour Sort Test (PCST)

The Portal colour sort test (PCST) is also based on the F-M 100.63 The test consists of 4 screens corresponding to the 4 boxes of the F-M 100 test; however, each section has only seven movable colour caps, described as chips. The coloured chips are derived from a colour circle of red-green-blue with each chip positioned at 10 degree intervals. The chips have a saturation (Chroma) and brightness (Value) of 60% with a small amount of random variation between chips. The computer provides automated scoring and plotting on a graph that has a similar format to the F-M 100. A study by Melamud et al[64] found that despite the PSCT test having a smaller number of chips with which to grade colour defects, the results obtained correlated well with the F-M 100 when examining congenital colour vision defects. Assessment of acquired defects has not yet been undertaken.

### Seohan 85 Hue Test

The Seohan 85 Hue Test (Figure 1 part c), developed in Korea is also based largely on the F-M 100 test, having 4 separate components and a total of 85 hues that cover the red, green, yellow and blue spectra[65]. It is designed to be displayed on a calibrated computer screen in a darkened room and the results are computed and displayed on a graph similar to the F-M 100. An evaluation of the test determined that statistical analysis of the section error scores could be used to differentiate between congenital and acquired colour vision defects[65].
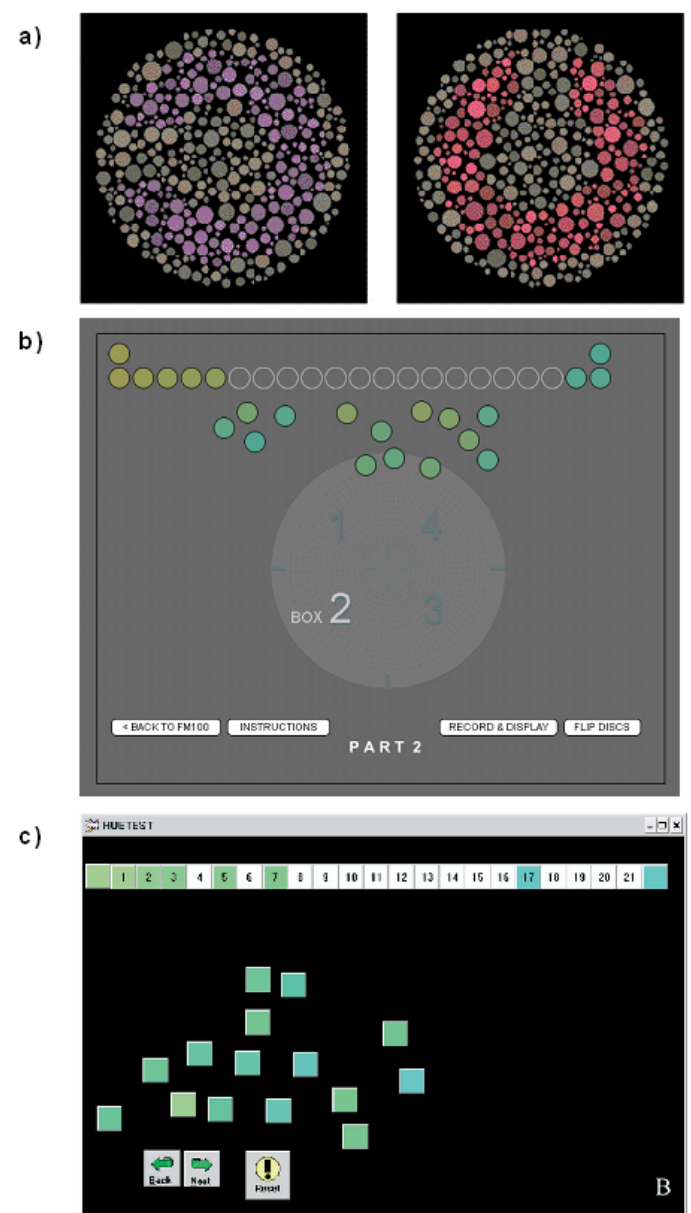


**Figure 1.** Examples of some computerised colour vision tests. a) Two plates from the Cambridge Colour Test (CCT)[61] b) The appearance of box 2 on the Save Sight Institute computerised Farnsworth-Munsell 100-Hue. c) Box 2 of the Seohan[85] Hue Test[65]

## CONCLUSION

Colour vision testing methods have greatly evolved since their emergence in the 1800s. The current standard clinical tests use either Pseudoisochromatic plates or Hue discrimination, however, each of these methods has possible pitfalls for clinicians in administration, recording and interpretation. With the widespread use of high resolution colour monitors and high capacity computers, computerisation of colour vision tests is an inevitable and valuable next step in the evolution of colour vision testing. However, standardisation of these computerised tests is essential to ensure their compatibility with current clinical standards. Continued investigation into their validity and reliability, will inevitably result in consistent and robust computerised colour vision tests. If such robust tests are then coupled with simple and clear administrative instructions and techniques, and an overall user-friendly interface, they are likely to find acceptance amongst eye practitioners and become widely incorporated into the clinical environment in the future.

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