Safety Regulation Group

# PAPER 2006/04

# Minimum Colour Vision Requirements for Professional Flight Crew - Part 1

## The Use of Colour Signals and the Assessment of Colour Vision Requirements in Aviation

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# Executive summary

## 1 Introduction

The UK Civil Aviation Authority (CAA) is currently reviewing the colour vision requirements for professional flight crew. Concern has been expressed that, although flight crew must be able to discriminate between colours because their work involves the recognition of various colour codes, both on the flight deck and externally, it is not certain if the present requirements and testing procedures are appropriate for the tasks that pilots need to carry out. The International Civil Aviation Organisation (ICAO) provisions state that 'The applicant shall be required to demonstrate the ability to perceive readily those colours the perception of which is necessary for the safe performance of duties' (ICAO International Standards and Recommended Practices, Annex 1, 2001), whereas the present standards for the Joint Aviation Authorities' (JAA) Member States (JAR-FCL 3 Section 1, 2002) require the passing of a screening test and, if this is failed, a secondary test.

A project designed to assess whether these current tests and the standards they set are appropriate for modern aviation has been undertaken by the Applied Vision Research Centre (AVRC) at City University, under sponsorship from UK CAA. In addition to investigating the relative importance of colour in the aviation environment through visual task analysis, the project also aims to develop a new test and to establish standard norms for chromatic sensitivity that can be used to quantify the severity of colour vision loss. The pass/fail criteria will be based on the characterisation of the colours used in colour-critical aviation tasks that were identified in the visual task analysis that was undertaken for the project by QinetiQ, a specialised research organisation based at Farnborough.

## 2 Colour vision deficiencies and current tests

### 2.1 Congenital colour vision deficiency

Information is coded in the retinal image as spatial modulation of either intensity or spectral content. Colour deficient observers, in general, cannot make use of some of this information. The extent to which a colour deficient observer can still make use of chromatic information depends on the extent and type of their deficiency. Colour vision deficiency is mostly congenital, and is fairly common, affecting almost 8% of men and 0.4% of women. It is inherited through the female line, though most females are only carriers. There are several types of congenital colour deficiency and these can vary widely in severity amongst individuals. Broadly, colour deficiency is either red/green or blue/yellow, but red/green deficiency is the most prevalent. Colour deficiency normally causes a reduction in chromatic sensitivity (i.e., the affected person cannot discriminate between certain colour differences) so that some colours that look different to colour normals look the same to people with defective colour vision and are said to be confused. However, the severity of the deficiency can vary from very mild, when colour discrimination is not significantly different to that of colour normals and is virtually unnoticeable in everyday life, to very severe, when visual performance can be impaired significantly. Although anyone with a colour deficiency is commonly called 'colour blind', it is extremely rare for someone to have no colour vision at all. The type and severity of colour vision deficiency that a person inherits remains unchanged throughout life, although aging can cause a systematic loss of chromatic sensitivity in all subjects (Knoblauch, et al., 2001).

There are three different types of light receptors, or cones (Marks et al, 1964; Brown and Wald, 1964; Bowmaker and Dartnall, 1980; Dartnall et al, 1983), in the retina that provide colour vision. Due to the wavelength regions that they are active in these cones are referred to as L-cones (long-wave, red region), M-cones (medium-wave, green region) and S-cones (short-wave, blue region). For red/green deficiencies the L- or M-cones are either missing (dichromats), the most severe deficiency, or are different to normal (anomalous trichromats), the degree of which abnormality dictates how severe the deficiency is. Depending on whether it is the L- or the M- receptors that are affected, the deficiency is either red (protan) or green (deutan). However, this does not mean that red and green are the only colours that are confused, as a range of colours, depending on the type and severity of the deficiency, are affected. People with a red deficiency also have reduced luminance efficiency for red colours so see them as quite dark.

### 2.2 JAA accepted colour vision tests

The current colour vision screening test for the JAA is the Ishihara isochromatic plate test (Birch, 1997), a series of numbers outlined by different coloured dots. This is the mostly widely accepted screening test for red/green colour deficiency and uses camouflage to exploit the colour confusions of colour deficient observers. Dots or patches of colour that vary in size and lightness make up the individual elements of the designs in such a way that a different number emerges from the background for people with normal colour vision to that seen by colour deficient people. The colours contained in the number and background are designed so that all the dots appear 'falsely of the same colour' (pseudoisochromatic) to colour deficients. The outline of the figure is broken up and its shape concealed by the dot matrix. The first 15 plates of the 24-plate version is the screening test stipulated by JAR, with no errors as the pass criteria.

If the screening is failed then either a lantern test or the Nagel anomaloscope test has to be taken within the JAA. Each State uses their own preferred test of these. Lantern tests are vocational tests that were designed for aviation, most of them several decades ago. The three lanterns recommended by the JAA are the Holmes-Wright A (Birch, 1999), the Spectrolux and the Beyne (Rui 1956). The first two show a sequence of vertically separated pairs of coloured lights to the examinee, who is seated a set distance away from the lantern. There are three colours: red, green and white. The Beyne lantern shows only a single colour at a time and has five colours: red, green, white, yellow and blue. For all the lanterns the examinee has to correctly name the colours of the lights being shown to them. It is quite common for colour deficients to confuse the green and the white particularly, so naming them incorrectly. It is also possible for some to confuse all the other colours.

The Nagel anomaloscope (Birch 1983) is a more complex and expensive optical instrument and is only used in a small number of JAA member states for aviation testing, though is currently accepted as the 'gold standard' for colour vision testing in general. This instrument is based on colour matching.

The examinee has to look down a viewfinder at a circle that is split in half by a horizontal line. The top half of the circle consists of red and green light that can be mixed together in different proportions by turning a scaled knob on the side of the instrument. The bottom half of the circle is yellow light, the brightness of which can be altered by turning another scaled knob. The examinee has to turn the knobs until the two halves of the circle look exactly the same in both colour and brightness, so it looks like one uniform circle. All people with normal colour vision will call the two halves of the circle a match over a small range of settings for the mixture of the red and green top half; the setting for the brightness of the yellow bottom half is fairly consistently the same for all normals for all matches. However, for colour deficient observers, the scale settings depend on what type of deficiency the examinee has. Compared to an observer with normal colour vision, more red is needed in the top half of the circle by anomalous red deficient observers and more green by those that have an anomalous green deficiency; neither groups of anomalous deficient observers match the circle with the same red/green mixture settings as normal observers. Generally, the range of the red/green colour mixture over which a match is accepted shows the severity of the deficiency - the larger the range the more severe the deficiency as fewer different colours can be distinguished.

Examinees with the most severe deficiency, so one type of light receptor is missing from their retinae (dichromats), will see both halves of the circle as matching in colour for the whole range of the settings of the red/green mixture top half; pure green through equal mixture of red and green to pure red all look exactly the same as the lower, yellow half of the circle. To pass this test for the JAA a matching range of 4 scale units or less on the red/green mixture scale is needed.

## 3 New colour vision test

### 3.1 The need for a new test in aviation

From an investigation into the JAA approved colour vision tests, we discovered that several aspects of the tests could be improved.

- The Ishihara plates are excellent for screening red-green deficiency, but although the pass criterion within the JAA is standardised to no mistakes, outside JAA this can vary from 2 (Canada, Australia) to 6 (USA) or less mistakes, out of 15 plates, being allowed as a pass. The result of this test is also very much up to the examiner, as hesitation in reading the numbers, or misreadings as opposed to mistakes (the numbers are in a style which is not easily read by everyone), may or may not be taken into account. This test also does not screen for blue-yellow loss, which can affect even colour normals from about 50 years old onwards.
- Due to the variety of lantern tests, different results can be obtained on each one by the same person. The design of each lantern varies with the number, intensity, size and colour of lights, so have different testing criteria. The testing protocol for the same lanterns are also not standardised between the Member States. In addition, there are other lantern tests that are used outside the JAA. Colour naming is not an ideal colour vision testing method, as even colour normals can disagree on the naming of a given colour. There are also other cues on these lanterns, apart from colour vision that can be used by examinees, such as the brightness of the lights. Colour normal subjects can fail these lanterns, particularly the Beyne.
- The Nagel anomaloscope is not very widely available and some models are not made any more. The test can take quite a long time and it needs to be administered by an experienced examiner who knows how to interpret the results; some subjects produce unusual results, especially when under stress. Again, although there are some guidelines, the results seem to have no standardised method of interpretation and the position of the match on the red/green scale along with the range of matches do not always relate well to the deficiency of colour discrimination (Wright, 1946). Some protanomalous subjects passed this test and about 50% of normal subjects failed.

This international (and sometimes national) diversity in colour vision testing methods and outcomes illustrates the necessity to have an objective and accurate test, relevant to aviation, which can be widely used so the same standards are known to be applied. The aim is to identify those subjects that have chromatic sensitivity outside the normal range. In addition, the test should provide a direct measure of chromatic sensitivity loss and direct classification of the type of colour deficiency involved. This information, coupled with the results of a visual task analysis carried out, should then make it possible to identify objectively the kind of visual tasks for which the applicant's colour vision may not be adequate.

### 3.2 CAD test

A new computer-based colour assessment and diagnosis (CAD) test has been developed. The design of the test is based on studies of camouflage which have shown that colour deficient people, have, for example, difficulty finding objects of certain colours in everyday life when those objects are defined by colour but lie in a variegated background where brightness is varying randomly, for example fruit in trees. This is because only colour vision can be used in this situation to identify the objects, and luminance vision, which distinguishes varying brightness, does not help with identification because of the variegated background. However, this background does not hinder the identification of coloured objects by people with normal colour vision. The use of dynamic luminance contrast noise in the background of a stimulus masks the detection of luminance contrast information without affecting the subject's ability to detect colour information (Barbur et al., 1994).

The new computer test simulates this dynamic luminance contrast noise background to mask the detection of luminance contrast information in the test target and isolate the use of colour information (Barbur et al., 1993). The examinee briefly sees a coloured stimulus moving across the centre of the computer screen and has to press a button that indicates the direction that this stimulus moved in. The direction of movement will not be possible to identify if the colour is below the examinee's chromatic detection threshold or is one of the colours that they confuse if they are colour deficient, as they will not see the stimulus. In this situation the examinee is told to randomly press any button. The colour intensity of the stimulus is changed, depending on whether the subject responded correctly or not, until the threshold of detection for this colour is found. Several different coloured stimuli are examined in a random order. This method yields thresholds for detection of all colour information

This test is quick and easy to use, device-independent and easy to interpret. A full assessment of chromatic sensitivity is made which is quantified with reference to the internationally agreed x,y colour reference system (CIE Proceedings, 1931). The test screens for normal colour vision, quantifies loss of chromatic sensitivity and classifies and grades colour deficiency. These functions can be achieved in less than 15 minutes, and if only red-green deficiency is investigated the CAD test takes only six minutes; a whole battery of clinical tests can take 40 to 60 minutes and produce data that are often difficult to interpret. Unlike the Nagel anomaloscope, an expert examiner is not needed to carry out the test. The results are easy to interpret by comparison with the template that defines the average normal trichromat, or, alternatively, against any set minimum occupational colour sensitivity standard. No colour naming is involved. The procedures employed to measure chromatic detection thresholds are tolerant of subject indecision and lapses in concentration.

### 3.3 Conclusion

Many documents and papers over the last twenty years, including ICAO publications, have stated the need for new colour vision tests that are more appropriate to the tasks that pilots carry out. Many publications emphasise the importance of objective tests. It is clear that colour naming and decision making draws in further elements of guessing and assessed judgements rather than certainty of seeing and recognising a colour. The naming of coloured objects is often variable and subject dependant. This observation supports the culture argument that it does not matter if a mildly colour deficient person does not see the same colour as a 'normal' person, as long as they can clearly distinguish between colours.

The purpose and aim of this project is to define and assess the colours used in aviation and their importance. This has resulted in a description of visual tasks and target configurations that involve colour and are considered important. Typical illuminants, light levels, stimulus sizes, luminance contrasts and colour differences that describe best a number of aviation visual tasks and environments have been measured and will be analysed.

Experimental findings and current information on the use of colour in aviation will be used to establish minimum colour vision requirements for pilots that are specific to the visual tasks investigated. The computer-based program is being optimised for testing colour sensitivity in pilots. There will be a quick screening test. For the few subjects that fail or are judged borderline from the results of the first test, then a second program will measure the subject's chromatic sensitivity for stimulus conditions that are considered important experimentally. The results from this will then make it possible to judge whether the subject's performance meets the minimum colour vision requirements that yield normal visual performance in the tasks investigated.

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# Abbreviations

| | |
|---|---|
| AGL | Aeronautical Ground Lighting |
| AME | Authorised Medical Examiner (JAA) |
| AMJ | Advisory Material Joint (JAR) |
| AMS | Aeromedical Section (JAA) |
| AO HRR | American Optical (Hardy, Rand and Rittler) |
| ASL | Aviation Signal Light |
| ATCOs | Air Traffic Control Officers |
| AVRC | Applied Vision Research Centre (City University) |
| CAA | Civil Aviation Authority |
| CAD | Colour Assessment and Diagnosis test |
| CIE | Commission Internationale de l'Eclairage |
| CRT | Cathode ray tube |
| CU | City University |
| CV | Colour vision |
| EFIS | Electronic Flight Instrument Systems |
| FAA | Federal Aviation Authority |
| FCL | Flight Crew Licensing (JAR) |
| F-M | Farnsworth-Munsell |
| ICAO | International Civil Aviation Organisation |
| ISRP | International Standards and Recommended Practices (ICAO) |
| JAA | Joint Aviation Authorities |
| JAR | Joint Aviation Requirements |
| L-cones | Long-wave cones |
| LC | Luminance contrast |
| LLW | Low-level white lighting |
| M-cones | Medium-wave cones |
| MED | Medical |
| NRC-NAS | National Research Council-National Academy of Science |
| PAPI | Precision Approach Path Indicator |
| S-cones | Short-wave cones |
| SAE ARP | Society for Automotive Engineers Aerospace Recommended Practice |

| | |
|---|---|
| SI | Système International d'Unités (International System of Units) |
| UK | United Kingdom |

# Nomenclature

| | |
|---|---|
| ° | degrees |
| cd $m^{-2}$ | candelas per square metre |
| $\lambda$ | wavelength (lambda) |
| $\lambda$m | maximum (peak) wavelength of V($\lambda$) |
| $\lambda$'m | maximum (peak) wavelength of V'($\lambda$) |
| ($\lambda$) | spectral |
| % | percent |
| 2' arc | 2 minutes of arc |
| mm | millimetres (1 mm=$10^{-3}$ of a metre) |
| nm | nanometres (1 nm=$10^{-9}$ of a metre) |
| $p_e$ | excitation purity |
| s | second (time) |
| $\mu$ | micro=x$10^{-6}$ |
| V($\lambda$) | Standard photopic luminous efficiency, (for high ambient illumination) (CIE, 1924) |
| V'($\lambda$) | Standard scotopic luminous efficiency, (when very low light levels are in |

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# 1 The use of colour signals and the assessment of colour vision sensitivity in aviation

## 1.1 Introduction

Colour perception is an important dimension of visual processing that provides additional information on the physical properties of the environment. Colour signals can play an important role in the coding and segmentation of visual images and are being increasingly used in aviation (section 4). Technological improvements in colour displays have made it possible to use a range of colour combinations to improve visual performance for many different tasks. Colour is used for lights, signs, flight deck instruments and in air traffic and other control applications. In these situations colour, in addition to enhancing conspicuity (Barbur and Forsyth, 1990), is used for the coding, grouping and segmentation of packets of information, which can improve significantly the processing and interpretation of visual information. The conspicuity of objects can be increased significantly by addition of colour, though luminance contrast is undoubtedly the most important parameter. The actual benefits of colour vision are, however, often difficult to assess, largely because of redundancy in the coding of visual information.

The colour vision requirements for professional flight crew (section 5) are currently under review. Concern has been expressed that, although flight crew must discriminate colours because their work involves the recognition of various colour codes, it is not certain if the present requirements and testing procedures are completely appropriate for the tasks that are carried out in their profession.

The International Civil Aviation Organisation (ICAO) provisions state (ICAO International Standards and Recommended Practices, Annex 1, 2001) that 'The applicant shall be required to demonstrate the ability to perceive readily those colours the perception of which is necessary for the safe performance of duties'. These provisions are very much open to interpretation as, although types of colour vision tests are suggested to demonstrate that this requirement is met, no tests or testing protocol are specified. This has left each country to use their own preferred tests and their own protocol. Different tests often examine different aspects of colour vision so the result for one person can vary from one test to another. This has led to applicants having their colour vision tested in different countries in an attempt to find a test they can pass. It is sometimes possible for a pilot to find employment in a country where they have failed a colour vision test (and been rejected) by operating aircraft registered in another country which applies a colour vision test the pilot has been able to pass. In addition to the above confusion, it is not certain which, if any, of the wide variety of colour vision tests (section 6) currently used in aviation are appropriate for the profession, as a recent task analysis of how colour is used in current airline operations has not been carried out.

Colour vision deficiency (section 3) is mostly congenital, and is fairly common, affecting almost 8% of men and 0.4% of women. There are several types of congenital colour deficiency and these can vary widely in severity amongst individuals. The most prevalent congenital deficiency affects the red/green chromatic channel. Colour deficiency normally causes a reduction in chromatic sensitivity (i.e., the ability to discriminate some colour differences). However, the severity of the deficiency can vary from very mild, when colour discrimination is not much different from that of colour normals and is virtually unnoticeable in everyday life, to very severe, when visual performance can be greatly impaired. Although anyone with a colour deficiency is commonly called 'colour blind', it is extremely rare for someone to have no colour vision at all. The type and severity of colour vision deficiency that a person inherits remains invariant throughout life, although aging can cause a gradual loss of chromatic sensitivity (Knoblauch, et al., 2001).

To test for colour deficiency, regulatory bodies in different countries use a screening test. Subjects that pass this test are assumed to have normal colour vision, and those that fail are identified as needing further testing. If the further tests are passed, the applicant is regarded as colour 'safe' and a medical certificate is issued. However, if these tests are failed, the applicant's colour deficiency is considered unacceptable, i.e. colour 'unsafe' and a medical certificate is denied. However a colour 'unsafe' applicant may be granted restricted certification, e.g. with limitations to daylight flying only. Such a limitation is normally only possible for private pilots, as commercial airline pilots almost invariably have to work at night. Some authorities also allow appeals for further testing and issue waivers to fly professionally under certain restrictions.

The screening colour vision test is usually based on a pseudoisochromatic plate test (section 6.3), such as the 'Ishihara' test. These plates show figures (usually numbers) formed by coloured dots on multi-coloured backgrounds. The plates are designed so that people with a colour deficiency, when asked to read the numbers, see different figures emerge from the background from those with normal colour vision. These tests do not, however, quantify the subject's loss of chromatic discrimination and provide only an approximate measure of the severity of deficiency.

The further testing carried out on those that fail the screening is usually done using an occupational test. This shows the ability of someone to, for example, name correctly certain coloured lights, as in lantern tests (section 6.5) or place colours in a correct colour order, as in hue discrimination tests (section 6.4). However, in all these tests the subject can make use of other cues, such as luminance contrast, in addition to colour vision. It is also relatively easy to guess the colours of lanterns correctly, so some subjects can pass whilst others with the same type and severity of deficiency may fail.

Unfortunately, there are a number of different tests similar to the Ishihara plates (that often give different results) and even if the same test is used, the testing procedure as well as the pass/fail requirements may vary from one regulatory body to another. An additional problem exists with some tests in that it may be possible to learn the correct responses and pass the test by cheating. The Aviation Signal Lights test and many lantern tests are available which all have slightly different test criteria, so it could depend on which test an applicant undergoes as to whether they pass or fail. It is also not certain if these tests are failing people who do have the 'ability to perceive readily those colours the perception of which is necessary for the safe performance of duties' (ICAO International Standards and Recommended Practices, Annex 1, 2001) or, alternatively, passing some whose ability is not adequate. The rarity of aircraft accidents where colour vision deficiency has been shown to play a part supports the view that stringent colour vision standards, as expected by some regulatory authorities, may result in unnecessary rejection of some applicants.

The current situation is clearly unsatisfactory and some effort is needed to determine what colours need to be discriminated by a pilot to ensure flight safety and to develop a test (or tests) capable of measuring the actual loss of chromatic sensitivity in applicants with defective colour vision. This information and precise knowledge of the use of colour signals could be used to set more task-based pass/fail criteria for colour vision based on aviation-related visual tasks. Piloting an aircraft on a modern flight deck with mostly digital instruments may require different colour vision pass/fail criteria from that needed for older aircraft, with analogue instruments, since the chromatic sensitivity requirements will depend on the nature of the visual task.

A project designed to assess the colour vision requirements of professional flight crew has been undertaken by the Applied Vision Research Centre (AVRC) at City University (under sponsorship from UK CAA). In addition to investigating the relative importance of colour in the aviation environment through visual task analysis, the project also aims to develop a new test (section 8) and to establish standard norms for chromatic sensitivity that can be used to quantify the severity of colour vision loss. The pass/fail criteria will be based on the results of the task analysis that is being undertaken by QinetiQ, a specialised research organisation based at Farnborough.

# 2 Normal colour vision

## 2.1 Background information

The retina of the human eye (Hill, 1987) contains the photoreceptors consisting of light sensitive pigments (photopigments) that absorb photons of light and channel nerve impulses to the brain. There are two classes of photoreceptors, rods and cones. Rods function in scotopic, i.e. very low, light levels, cones operate in photopic, i.e. normal daylight, levels and there is an overlap with both receptors working to a certain extent in the intermediate, mesopic, light levels (Walkey et al, 2001). Rods are not colour sensitive or sensitive to detail, whereas cones provide both the ability to see fine detail and colour vision.

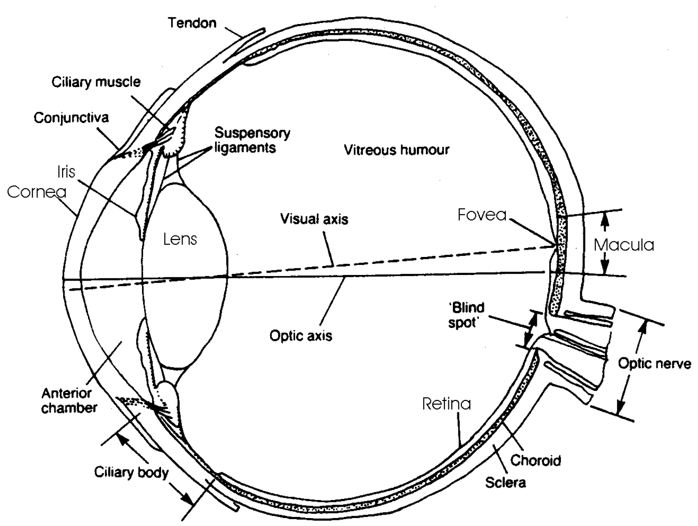



**Figure 1** Horizontal section of the human eye (Hill, 1987)

### 2.1.1 Cone photopigments

There are three types of cone photopigments (Marks et al, 1964; Brown and Wald, 1964; Bowmaker and Dartnall, 1980; Dartnall et al, 1983), and these are not equally sensitive to light of all wavelengths, having a maximum absorbance in different parts of the visible spectrum, with a considerable spectral overlap (Figure 2). The types of cones have traditionally been referred to as 'red', 'green' and 'blue'; but the maximum absorbance values, or peak wavelength sensitivities, of the photopigments lie in the yellow-green (approximately 570 nm (1nm=10-9 of a metre)), green (approximately 542 nm) and blue (approximately 442 nm) parts of the spectrum; it is therefore more appropriate to call them long-wave (L-cones), medium-wave (M-cones) and short-wave (S-cones) sensitive photopigments.

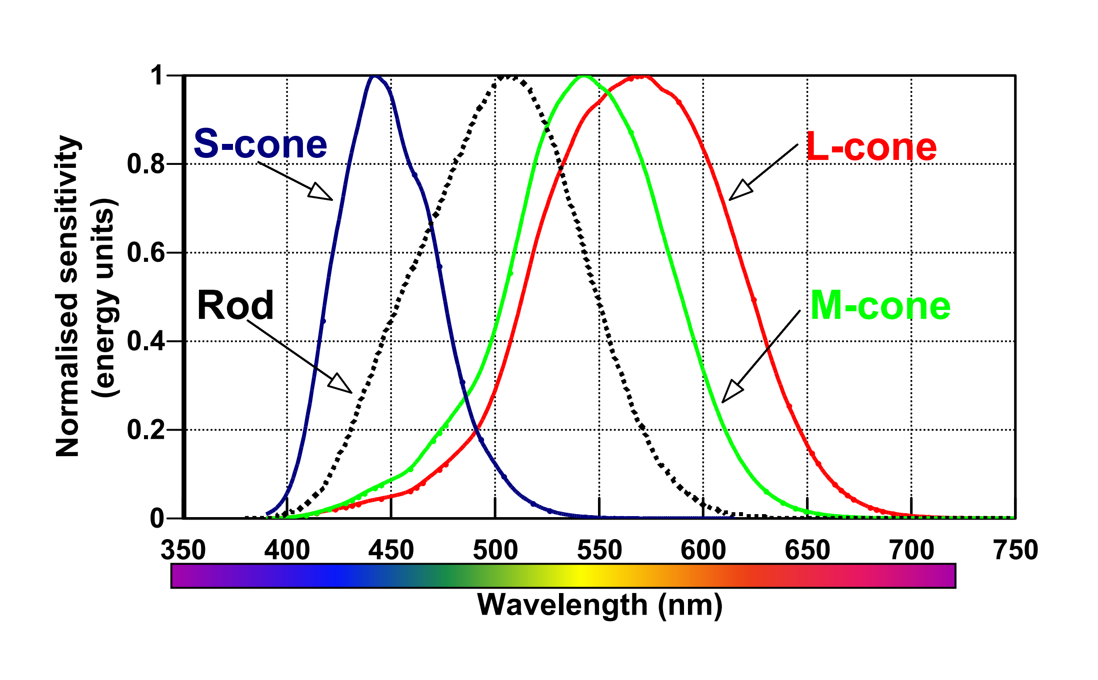



**Figure 2** Normalised spectral sensitivity of the four receptor types found in the human retina (from Stockman et al, 1999; Stockman and Sharpe, 2000).

The three cone classes are distributed more or less randomly in the retina (Mollon and Bowmaker, 1992) and the retinal densities of L-, M- and S-cones can vary significantly from subject to subject (Nerger and Cicerone, 1992). The mean L:M:S cone densities are taken to be in the ratio of about 40:20:1 (Kremers et al., 2000; Walraven and Bouman, 1966). Colour vision is limited to stimuli seen within about 40° of the visual axis (Hurvich, 1981); outside this area vision is virtually monochromatic and used mainly for the detection of movement. The ability to see both colour and fine detail gradually increases within the 40° on either side of the eye's axis as the axis is approached. The central region of maximum resolution in the retina, the fovea (Figs. 1 and 3), subtends a visual angle of about 1.5°. Approximately the central 1° of the fovea, termed the foveola, contains only L- and M-cone receptors. The probability of absorbance of a given wavelength of light at any point on the retina therefore varies according to the relative distribution of the cone types. In all areas of the retina, the probability of absorbance is least in the short wavelength region of the spectrum.

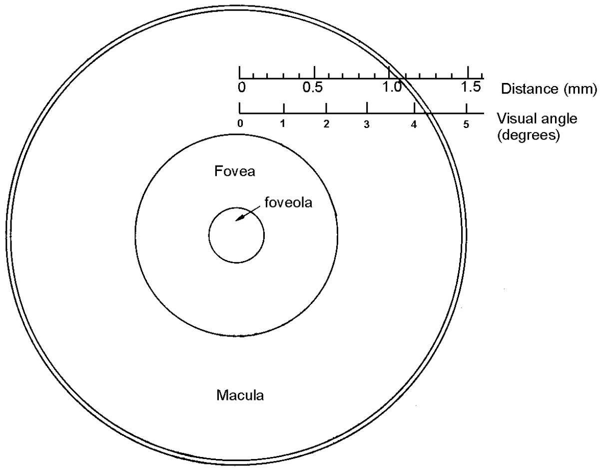



**Figure 3** Schematic diagram of the macular region of the human eye.

### 2.1.2 Visual signal transmission

The molecules of the photopigments in the retina are excited when light is absorbed, causing a signal to be generated and transmitted along nerve fibres to the brain. The exact process of this signal transmission is not completely understood. It is, however, known that there are not four different types of signal, one for each type of receptor (rods and three types of cones), but that different combinations of these signals are transmitted along nerve fibres (Mollon (1982)).

The following simple scheme (Figure 4) is adapted from Hunt (1998), who suggests that such a scheme 'can be regarded as a plausible framework for incorporating some of the salient features of what is believed to take place.' It is most likely that photoreceptor signals are combined to form three channels - the achromatic channel and two colour difference channels. The achromatic signal is composed of inputs from the rods and all three cone types. The cone part of this signal reflects the different abundance of each cone type, L, M and S (see section 2.1.1) so the whole signal is represented as:

$2L+M+S/20+r=A$

where r is the rod receptor contribution that varies significantly with ambient light level, stimulus size and location in the visual field.

The two colour difference signals are composed of the three possible basic difference signals:

$L-M=C1$

$M-S=C2$

$S-L=C3$

When these are added up they equal zero, so do not need to all be transmitted separately. Hunt suggests that the signals transmitted resemble:

$C1=L-M$

and

$C2-C3=M-S-(S-L)=L+M-2S$

These two colour difference signals are broadly referred to as an opponent system of 'red minus green' and 'yellow minus blue', where L+M is labelled as yellow. The ratio of the signal C1 to that of C2-C3, from this system can be used to indicate hue (see section 2.2.2) and the strength of these two signals to indicate colourfulness (see section 2.2.3). For achromatic 'colours', white, grey and black, the signals from each cone type are equal so the colour difference signals C1, C2 and C3 would be zero (as would be the colourfulness).

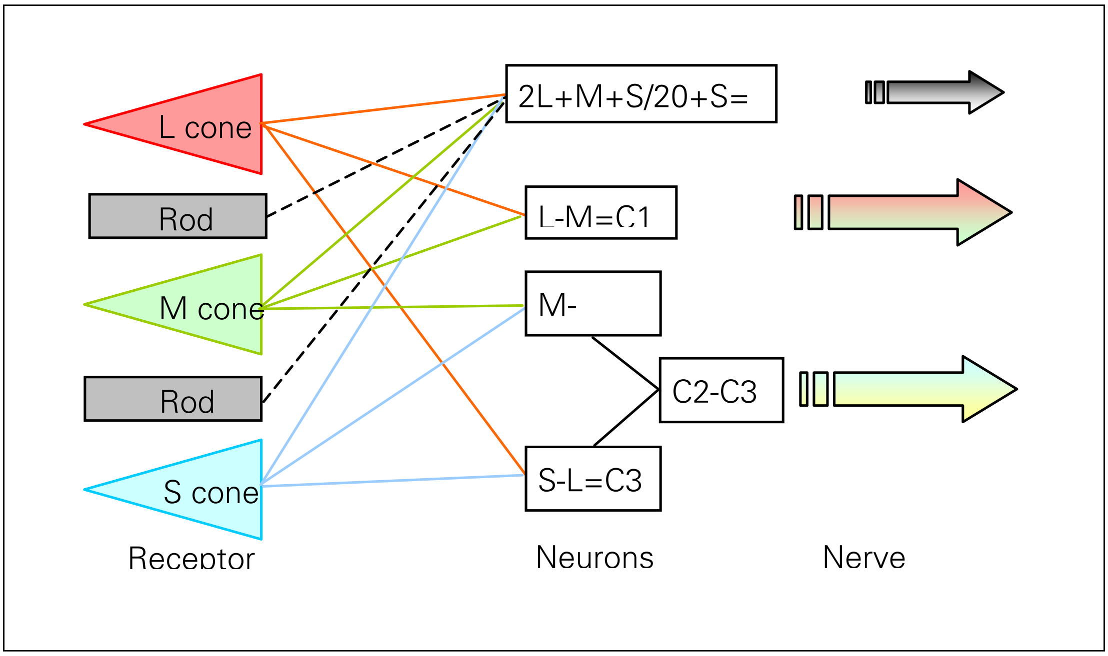



**Figure 4** Greatly oversimplified and hypothetical diagrammatic representation of possible types of connections between some retinal receptors and some nerve fibres (Hunt, 1998).

### 2.1.3 Variations in normal colour vision

Variations in both normal and defective colour vision can be caused by selective absorption of short wavelengths in the crystalline lens and by the presence of macular pigment (Figs. 1, 3 and 5). A progressive yellowing of the lens occurs with age, so absorbing more short wavelength light, which has a significant effect on hue discrimination ability and short-wavelength sensitivity thresholds after about 55 years of age (Lakowski, 1962; Weale, 1960, 1963). This is not immediately noticeable to the casual observer due to the phenomenon of colour constancy (see section 2.5.3). The macula, in the central retina (Figs. 1, 3 and 5), contains a non-photosensitive yellow pigment that has an absorption peak near 460 nm (Figure 5). The role of this pigment is uncertain, but it may serve to reduce light scatter. Inter-subject variation of pigment concentration can be very large (Wald, 1949; Brown and Wald, 1963; Stiles, 1953; De Vries et al., 1953; Naylor and Stanworth, 1954; Ruddock, 1963). Macular pigment is therefore a major source of variation in threshold short-wavelength sensitivity between 450 and 490 nm, in people of all ages (Figure 5).

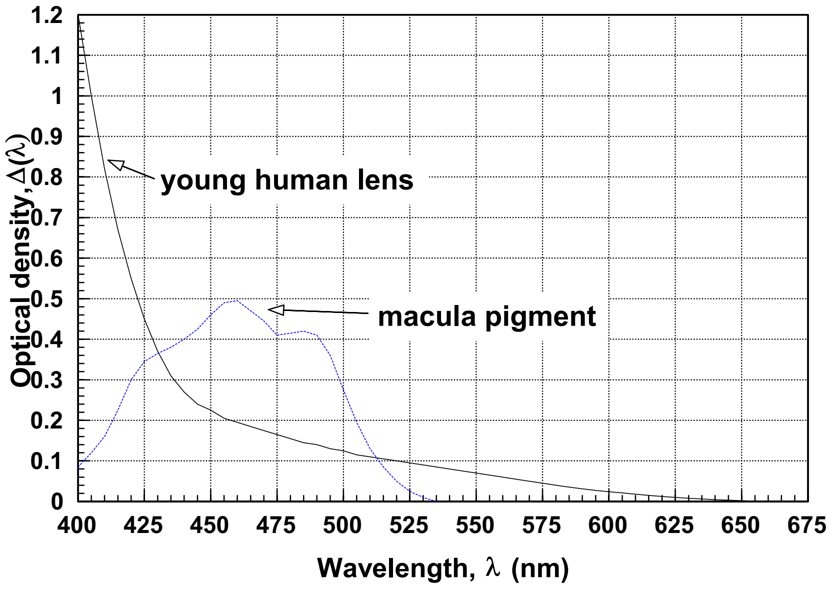



**Figure 5** Graph showing the average optical density of the young human eye lens (completely open pupil) and of the macular pigment covering the fovea, as functions of wavelength. (Wyszecki and Styles, 2000).

### 2.1.4 Relative luminous efficiency

The sensitivity, or spectral response, of the human eye is not constant over the visible spectrum but varies with wavelength, location on the retina, state of light adaptation, etc. When employing the same stimulus conditions, one also finds significant inter-subject variation. There are, however, two internationally agreed curves accepted as depicting this response for a standard, or typical observer, one in light-adapted conditions and the other for very low light levels. These graphs have been derived using several independent experimental methods. The curves represent the Commission Internationale de l'Eclairage (CIE, the international lighting commission) standard photopic luminous efficiency, V(λ) (for high ambient illumination) (CIE, 1924) and the CIE standard scotopic luminous efficiency, V'(λ) (when very low light levels are involved) (CIE, 1951) (see Figure 6). Although the two curves are similar in shape, the V(λ) curve peaks at about 555 nm, whereas the V'(λ) curve peaks at about 507 nm.

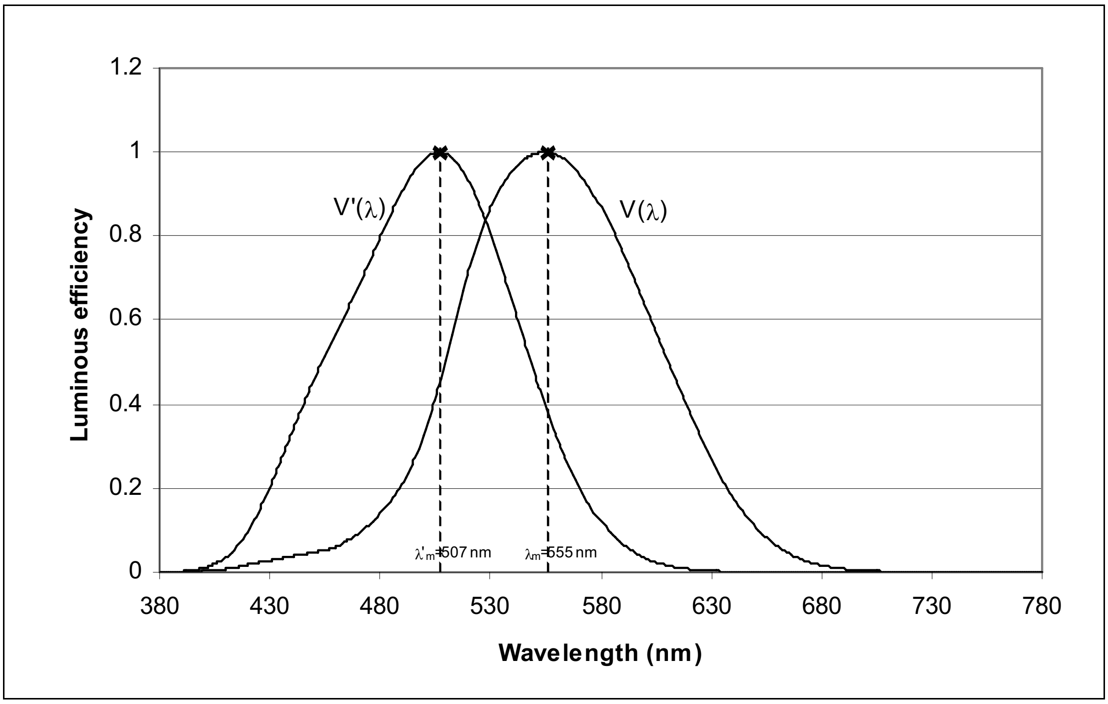



**Figure 6** Spectral luminous efficiency functions V(λ) and V'(λ) defining the standard photopic and standard scotopic observer, respectively. Each function is normalised to have a maximum value of unity which occurs at about λm=555 nm for V(λ) and at about λ'm=507 nm for V'(λ) (data for V(λ) from CIE, 1924 and data for V'(l) from CIE, 1951).

## 2.2 Perceived attributes of colour

### 2.2.1 Introduction

Colour can be described as the perceived effect caused by variations in the composition of the light emitted, transmitted, or reflected by objects. Without light there is no colour. The perception of the colour of an object depends on:

1) the colour of the light source;

2) 2.the way the object reflects, transmits and absorbs the available light;

3) 3.the eyes and brain of the person looking at the object.

Colour can be self-luminous, for example yellow street lamps or fireworks, when the light source itself is the colour. However, more often the colour is associated with objects that reflect or transmit light emitted by a source. The colour of the source affects the perceived colour of the object, for example, a red bus appears dark brown or black under yellow street lighting. If an object is illuminated with white light and the surface absorbs all of the colours of the visible spectrum apart from red, which it reflects, then the object will appear red. Similarly, a red filter only transmits red light, but absorbs the rest of the visible spectrum.

So, to classify colour, taking into account the above factors, light source, object and observer (a 'standard normal observer' (see section 2.1.4) is assumed at the moment), colour perception may be described in terms of only three properties, though it is dependant upon many more than three physical stimulus parameters. The three basic perceptual attributes of self-luminous colour (such as light sources) are hue (section 2.2.2), saturation (section 2.2.3) and brightness (section 2.2.4), and these are principally related to the stimulus physical dimensions of dominant wavelength (section 2.3.3), excitation purity (section 2.3.3) and luminance, respectively. However, changes in one stimulus variable may affect the other two colour attributes. A further complication, showing the lack of a simple relationship between the physical properties of a stimulus and perception, is the fact that the perceived colour of a stimulus depends on the context in which it is viewed, for example the background colour (see section 2.5).

As stated above, colours are also perceived when light is reflected from or transmitted through objects that are not self-luminous. The attributes of the perceived colour are then determined by both the nature of the incident radiation (e.g. sunlight or artificial light) and the spectral reflective properties of the pigments in the object. These attributes are hue (section 2.2.2), saturation (section 2.2.3) and lightness (section 2.2.4), and the physical correlates are similar to those of self-luminous colours (Wright, 1946).

### 2.2.2 Hue

All colour sensations can be described by combinations of four psychologically unique sensations, or colour names: blue, green, yellow and red (see section 2.1.2) (Boynton et al., 1964). 'Hue' is the visual sensation according to which an area appears to be similar to one, or to proportions of two, of these perceived unique colours. The four unique colours are naturally organised into two opposing pairs, blue-yellow and red-green. Hues do not appear 'yellowish-blue' or 'reddish-green'; however, complex hue percepts, such as yellow-green, blue-green, red-yellow and red-blue, do occur in nature (see Table 1), with certain blends of pairs of these unique hues producing different named colours such as orange (red-yellow).

A person with normal colour vision can distinguish between about 150-200 variations of hue in the visible spectrum (Wright, 1946). Figure 7 shows the main bands of colour defined by the wavelengths of electromagnetic radiation, showing which colours appear, and in which order, when white light (e.g. natural sunlight) is split by a prism, or as in a rainbow. In reality, each colour merges into the next so there is really no exact boundary. The visible spectrum, or light, for the human eye is between about 380 and 780 nm. Discrimination varies with spectral region (see section 2.4.2).

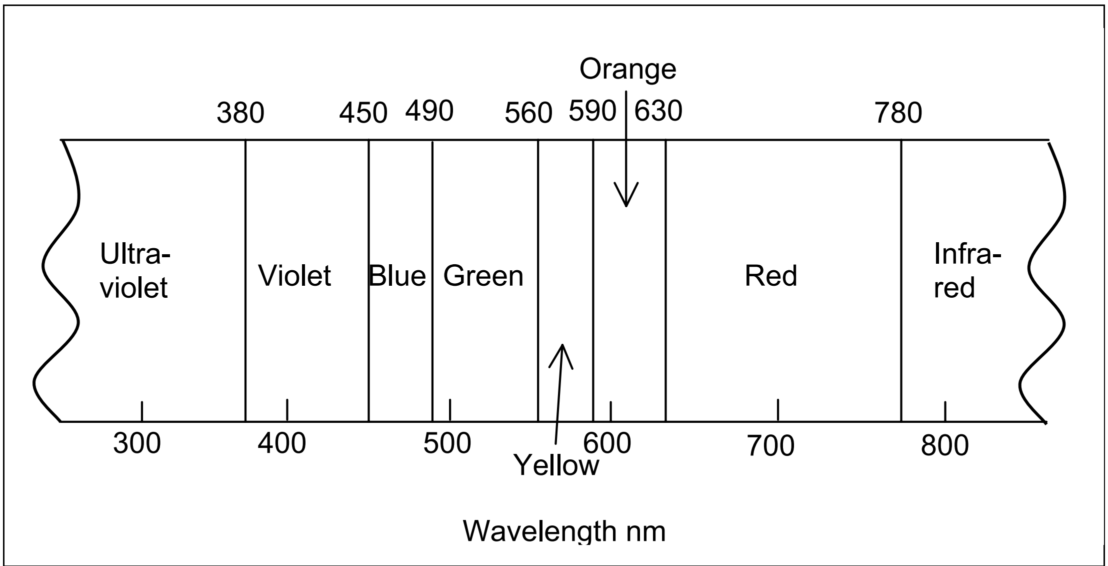



**Figure 7** The colour names usually given to the main regions of the spectrum.

A spectral hue consists of just one wavelength. There are also non-spectral hues. Purple cannot be produced by the presentation of a single wavelength, but only when light from both the long- (red) and short-wavelength (blue) portions of the spectrum are simultaneously present. A "white" is seen when all the spectral wavelengths are simultaneously present, as in sunlight.

In situations when colour is perceived as light reflected from objects, hues arise for objects that reflect the illuminant more in one spectral region than another. If the illuminant is reflected evenly by an object in all spectral regions, the object will appear achromatic (white, grey or black).

### 2.2.3 Saturation and chroma

'Colourfulness' is the attribute of a visual sensation according to which an area appears to exhibit more or less of its hue, and 'saturation' is the colourfulness of an area judged in proportion to its brightness. The term saturation is used to signify the relative white content of a stimulus perceived as having a particular hue, as whiteness can coexist with any of the hues and white does not seem to be a colour in the sense of the four unique hues (section 2.2.2). Across the saturation scale colours vary in paleness, or their white content, with the spectral hues being completely saturated colours (no white content at all) and white, completely unsaturated (no hue content at all). The spectral hues themselves are seen to be comparatively different in saturation, with spectral blues and reds appearing generally more saturated than spectral greens and yellows. (see section 2.4.3).

Saturation is applicable to both related colours (that is, colours perceived to belong to areas seen in relation to other colours e.g. all colours produced by objects reflecting light), and unrelated colours (that is, colours perceived to belong to areas seen in isolation from other colours e.g. light sources). This is because the brightness of an object changes with a change in lighting condition, and saturation is judged in proportion to the change in brightness.

Chroma is the colourfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting. Chroma varies from strong to weak and is only applicable to related colours.

### 2.2.4 Brightness and lightness

'Brightness' is the attribute of a visual sensation according to which an area appears to exhibit more or less light, varying from bright to dim.

If the level of lighting of an object changes, such as going from sunshine into shade, the brightness of that object changes. However, 'lightness' is a term used to describe the brightness of objects relative to that of a similarly illuminated white. The lightness of the object, therefore, remains constant and does not change with different lighting conditions. As the attribute of lightness is defined with reference to a similarly illuminated area, it only applies to related colours, e.g. colours produced by objects reflecting light, and not to unrelated colours, e.g. self-luminous colours such as light sources.

## 2.3 Colour matching and chromaticity

### 2.3.1 Colour matching

A certain colour of light can be produced in many ways. A yellow, for example, can be produced with monochromatic radiation of about 590 nm or by the additive mixture of two monochromatic radiations of wavelengths 545 nm (appearing yellowish-green) and 670 nm (appearing red with a slight tinge of yellow). A human observer would not be able to tell how this yellow stimulus was produced (in terms of its spectral composition) just by looking at it.

In the same way it is impossible to describe exactly the sensation produced by light of any particular spectral quality, but it is possible to evaluate a colour in terms of certain standard or primary stimuli. In practice, a normal observer can duplicate the effect of any colour stimulus by combining the light from three primary sources in the proper proportions. This mixture of lights will therefore look exactly the same as the original colour. These mixtures of light are called metameric matches as they look exactly the same (match), but do not have the same spectral composition (have not been produced the same way). Colours that look exactly the same (match) and are also physically identical to one another (have identical spectral compositions) are called isomeric matches.

To make a metameric match, the primary colours are taken from the long, medium and short parts of the spectrum so are usually red, green and blue. For a normal observer, for each set of primaries used, there is just one value for each primary colour which, when the three are combined, will match the given colour, in hue, saturation and brightness. However, the amount of each of the three primaries needed for the match does depend on the field of view of the colours; the given colour and the combination of primaries can look as though they match to an observer with a small field of view, but if a larger area is looked at then they may not appear to match anymore. The fact that colours can be matched using three matching stimuli in the mixture in this way is due to the fact that there are only three spectrally different types of receptor in the retina (see section 2.1.1). Whatever the physical properties of a colour, light mixtures that cause the same proportional stimulation of the three receptors will result in the same sensations.

The amounts of each primary needed are described as tristimulus values. These values depend on the primaries selected and for the same set of primaries the amounts needed for a match can vary slightly from person to person. To avoid such difficulties, the Commission Internationale de l'Eclairage (CIE), established a "standard" system of colour measurement and specification. This system defines the colour matching properties of the hypothetical 'CIE 1931 Standard Colorimetric Observer' (CIE, 1931). The CIE colour-matching functions, $\bar{x}(\lambda)$,$\bar{y}(\lambda)$,$\bar{z}(\lambda)$, define the amounts of a set of three primaries, designated X, Y, Z (the tristimulus values), needed to match any spectral colour for a 2° field of view (the field of view needs to be stated as the retina varies considerably in its properties from one part to another (section 2.1.1)).

When these functions were set up, the primaries were chosen so that the $\bar{y}(\lambda)$ function is exactly the same shape as the $V(\lambda)$ function (see section 2.1.4), so that the luminance of a colour is indicated directly by the value of Y. This means that the luminance difference between two colours can be compared, as well as the chromaticity difference, just using these three values. As luminance is an approximate correlate of brightness, the Y value is also a correlation with the perceptual attribute of brightness (see section 2.2.4).

As the X and Z tristimulus values do not correlate to any perceptual attributes, other measures have been derived from them that do provide such correlates. The relative magnitudes of the tristimulus values are related to important colour attributes. Therefore, chromaticity co-ordinates can be calculated based on relative tristimulus values: $x=X/(X+Y+Z)$, $y=Y/(X+Y+Z)$ and $z= Z/(X+Y+Z)$.

### 2.3.2 **Chromaticity**

It is convenient and useful to illustrate the relationship of various colours one to another by representing them graphically. Chromaticity co-ordinates can be easily plotted on a two-dimensional graph. From the way that x, y, and z are calculated, it is clear that $x+y+z=1$, so if, for example, x and y are known then z can be easily deduced from $1-x-y$. It is usual, therefore, to plot x, and y co-ordinates on a graph which is referred to as the x,y chromaticity diagram. In the CIE 1931 x,y chromaticity diagram

(Figure 8) a curved line, called the spectral locus, shows where the spectral hues (section 2.2.2) lie. The wavelengths are indicated in nanometres (nm) along the curve.

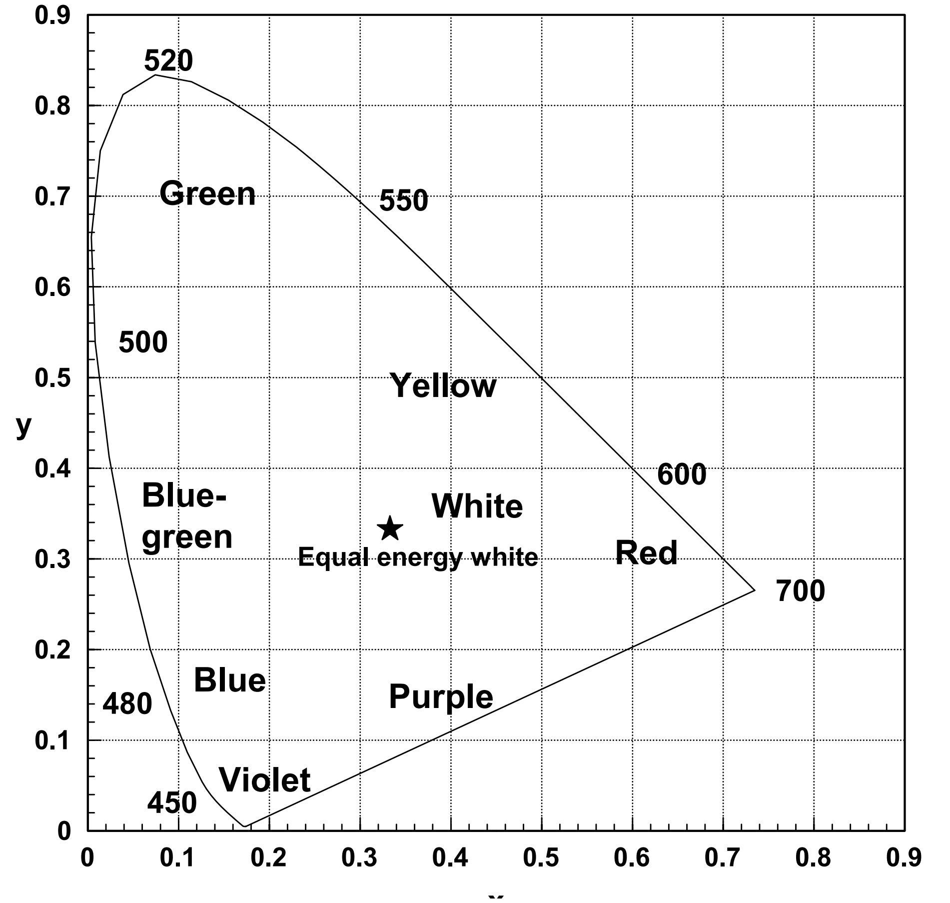



**Figure 8** The CIE x,y chromaticity diagram (1931). x, y, and z are equal to each other at the equal energy white. The numbers along the curve are spectral wavelengths in nm.

A fundamental property of the chromaticity diagram is that if two colour stimuli are additively mixed together, then the point representing the mixture is located in the diagram by a point that lies on the line joining the two points representing the two original colours. Therefore, the two ends of the spectral locus are always shown joined by a straight line that represents mixtures from the two ends of the spectrum; this is known as the purple boundary as these colours are a mixture of red and blue (see section 2.2.2). The chromaticities of all desaturated colours can be plotted on this diagram within the area enclosed by the spectral locus and the purple boundary; this is because the spectral locus consists of a continuously convex boundary so that all mixtures of wavelengths must lie inside it. White is located around the centre of the diagram.

The chromaticity diagram represents a continuous gradation of stimuli from spectral hues (on the locus) to whites (in the centre). Therefore, if a line is drawn on the diagram between a point A near the centre (see Figure 9) and a point B on the spectral locus, then this represents colours that can be matched by additive mixtures of the white A and light of the particular wavelength that B is. If the mixture forms a fairly saturated hue, consisting mainly of the spectral colour, B, then the corresponding point on the diagram will be near the spectral locus. If the opposite is the case and the mixture is pale, consisting mainly of the white, A, then the corresponding point will lie near A in the centre of the diagram. However, chromaticity diagrams only show the proportions of the tristimulus values; this means that colours with tristimulus values having the same ratios but with different brightness or lightness levels will still be depicted at the same point in the diagram.

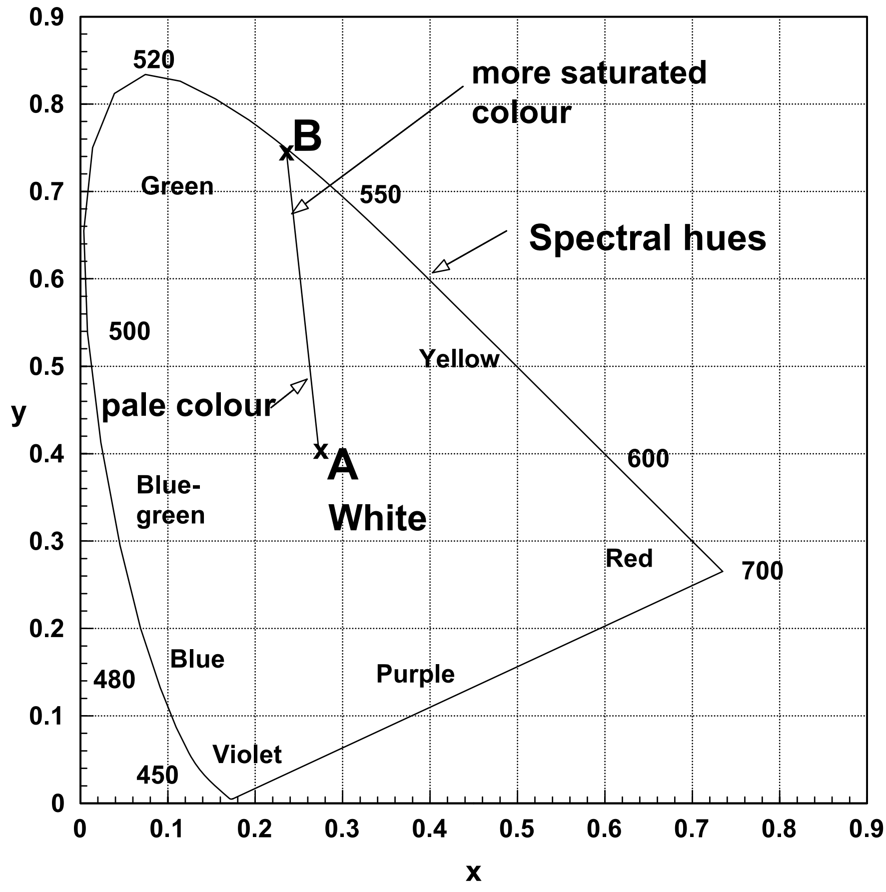



**Figure 9** The CIE x,y chromaticity diagram (1931) illustrating more saturated and pale colours.

### 2.3.3 Dominant wavelength and excitation purity

It was established in section 2.2.1 that the three basic perceptual attributes of colour are hue (section 2.2.2), saturation (section 2.2.3) and brightness (section 2.2.4), and that these approximately correlate to the stimulus dimensions of dominant wavelength, excitation purity and luminance, respectively. Two of these stimulus dimensions can be obtained graphically using the chromaticity diagram.

Luminance levels of stimuli cannot be established from the chromaticity diagram, as colours with the same saturated hue but different brightness levels cannot be distinguished, as mentioned in section 2.3.2. However, dominant wavelength and excitation purity can be established from the chromaticity diagram.

In Figure 10 the point C on the chromaticity diagram is the white light source illuminating samples P1 and P2. Source C is a CIE standard illuminant representing daylight. If a line is drawn from Source C, through P1 to the spectral locus at D1, it can be seen that the colour P1 can be matched by an additive mixture of the colour, D1 and the white, C. The wavelength on the spectral locus corresponding to D1 is therefore called the 'dominant wavelength' of the colour P1, relative to the white point, C.

It is not so easy to establish the dominant wavelength of the sample P2 as the point D2 is on the purple boundary so has no corresponding wavelength. For this example, the line CP2 is extended in the opposite direction to meet the spectral locus at point D2c (Figure 10). The corresponding wavelength at this point is called the 'complementary wavelength' of the colour P2, relative to the white point, C. Dominant (and complimentary) wavelength approximately correlates with the hue of a colour.

'Purity' is a measure of the proportions of the monochromatic stimulus (or stimulus whose chromaticity is a point on the purple boundary) and of the specified achromatic stimulus that, when additively mixed, match the colour stimulus considered. 'Excitation purity' is specifically a quantity defined by the ratio of the length of the lines joining the specified achromatic stimulus and the colour stimulus considered, and the specified achromatic stimulus and the monochromatic stimulus (through the colour stimulus considered) on the chromaticity diagram. In the examples shown in Figure 10, excitation purity, pe, is defined as:

$p_e$ = CP1/CD1 or CP2/CD2

If the excitation purity has a value of nearly one then the colour considered is highly saturated and will tend to be near the spectral locus (see Figure 9) or purple boundary; conversely if the excitation purity value is near zero, then the colour will tend to be pale and the chromaticity point is near the specified achromatic stimulus. Excitation purity approximately correlates with the saturation of a colour.

As chromaticity diagrams in the CIE system do not account for luminance then two colour stimuli having the same dominant wavelength and excitation purity but different luminances will plot at the same point.

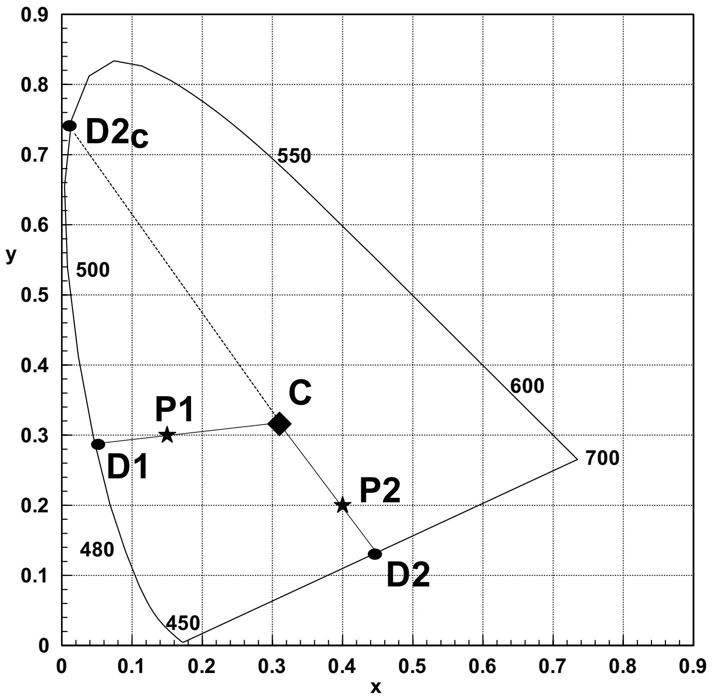



**Figure 10** The derivation on the chromaticity x,y diagram of the dominant wavelength at D1 and excitation purity, CP1/CD1, of the colour P1, relative to the source, C; also, the derivation of the complementary wavelength at D2c and excitation purity, CP2/CD2, of the colour P2, relative to the source, C.

## 2.4 Chromatic Discrimination

As was stated in section 2.2, the human eye is able to discriminate between many different colours. This discriminative ability has been defined using many methods.

### 2.4.1 Wavelength discrimination

Wavelength discrimination capacity is defined by the smallest change in wavelength that can be detected at a particular wavelength value. To depict this a graph is plotted (see Figure 11) of just noticeable wavelength difference against wavelength. There are three minima on this curve located in the long, medium and short wavelength parts of the spectrum (Judd, 1932; Wright and Pitt, 1934). These are the values at which sensitivity to changes in wavelength is greatest and are in spectral regions where two cone pigments are being stimulated differentially and the dominant sensitivity is changing from one photopigment to another. Their presence is due, in part, to the existence of the three types of retinal cone receptors that have different spectral absorption characteristics.

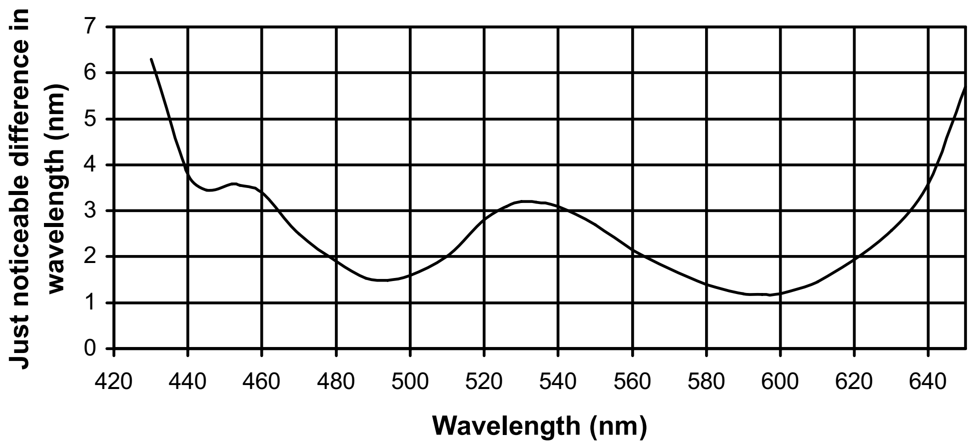



**Figure 11** Wavelength discrimination for normal colour vision (Wright, 1946). The ability to detect small changes varies throughout the spectrum.

### 2.4.2 Saturation discrimination

Saturation discrimination measures the minimum quantity of a given wavelength that must be added to white light for the change in appearance to be detected. Deciding when an object no longer appears white, but contains just a hint of colour, is one of the more difficult perceptual judgements to make. A pronounced minimum in the results is found at approximately 570 nm (Figure 12).

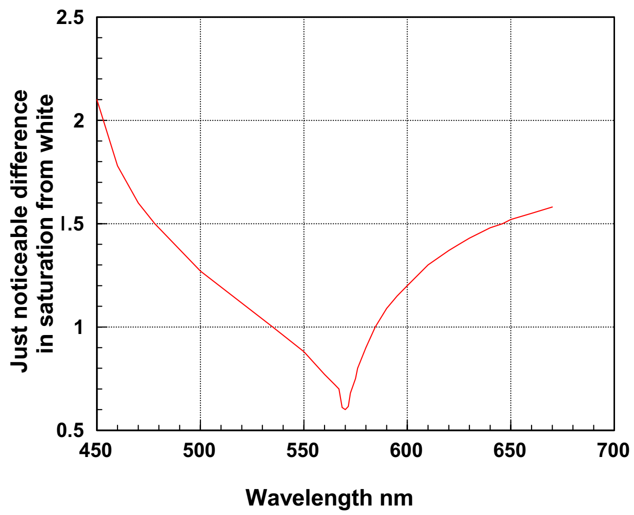



**Figure 12** Saturation discrimination from pure white against wavelength for normal colour vision (from Wright, 1946).

### 2.4.3 **Chromaticity discrimination**

As explained in section 2.3.2, a fundamental property of the CIE x,y chromaticity diagram is that additive mixtures of two colours always lie on a straight line joining their co-ordinates, and the exact specification depends on the relative amounts used in the match (Figure 10). The threshold difference between two discriminable colours can therefore be expressed as a chromaticity difference and plotted in the CIE x,y chromaticity diagram.

Just noticeable difference thresholds for normal chromatic discrimination, for non-spectral colours, have been derived and are represented in a series of ellipses in the CIE 1931 x,y chromaticity diagram (MacAdam, 1942) (Figure 13). Provided that no luminance contrast exists, colours that have x,y, chromaticity co-ordinates within an ellipse look the same to normal observers. Discrimination ellipses provide tolerance limits for colour specification and colour reproduction.

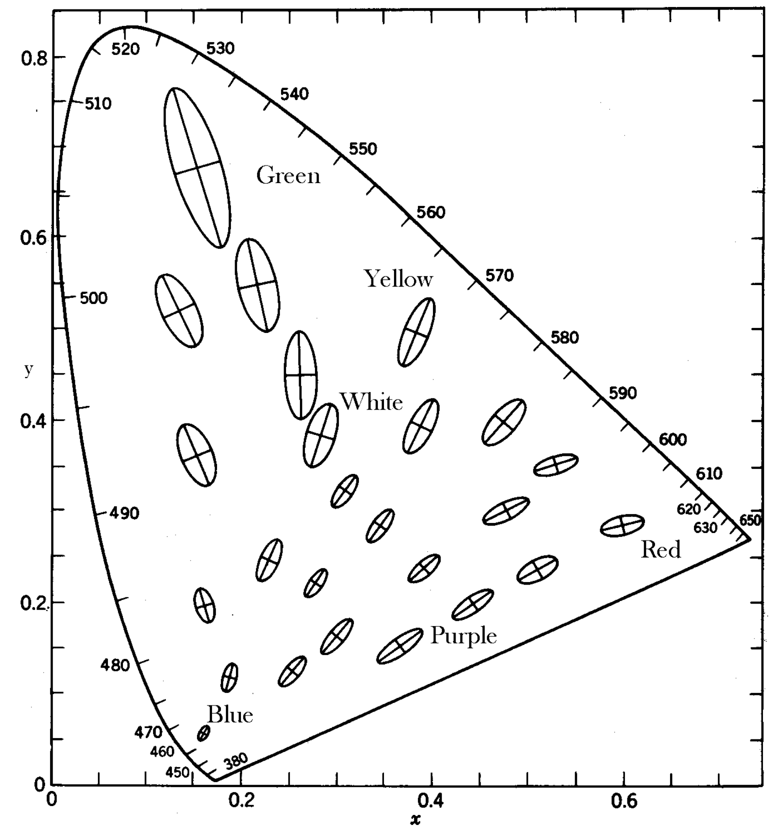



**Figure 13** MacAdam (1942) discrimination ellipses for normal colour vision plotted in CIE 1931 x,y chromaticity diagram. The axes of the plotted ellipses are 10 times their actual lengths. Colours which have x,y chromaticity co-ordinates within an ellipse cannot be discriminated and appear to be the same. Variations in the size of ellipses show that numerical differences in the 1931 CIE system of colour measurement do not represent equal perceptual differences (from Wyszecki and Stiles, 2000).

As can be seen in the absorption spectra in Figure 2, the short-wave photopigment has no sensitivity to wavelengths longer than about 520 nm so only two colour matching variables are required to match wavelengths in the long-wave portion of the spectrum. This is a very useful phenomenon to make use of in testing colour vision as it is a relatively complicated process to match a colour using the mixture of three other colours. This enables people with normal colour vision to make a precise colour match fairly easily by adding suitable proportions of red and green wavelengths (Figure 15) to obtain an intermediate yellow wavelength (a Rayleigh match). Subjects with a red/green colour deficiency (see section 3.2) will use different proportions of red and green to match the yellow; dichromats (see section 3.1.2) will match the yellow with all combinations of red and green as they have only one functioning cone at these wavelengths (see section 3.4.1). This is therefore an important tool for classifying red/green colour deficiency (see section 6.6 Anomaloscopes).

## 2.5 Colour in context

### Introduction

Visual perception of colour involves a complex series of events and is affected by many variables such as:

- level of ambient illumination
- stimulus brightness, saturation
- the influence of adjacent colours, stimulus size, shape, texture and duration
- visual fatigue and afterimages
- the integrity of the visual system (as affected by age, disease and drug usage).

### 2.5.1 Chromatic induction

The perceived hue of a stimulus can be affected by the presence of other colours in the field of view. This chromatic induction (Walraven, J., 1976) can be a problem for colour-coded displays, as colours may look different depending on the colour of surrounding objects; green-coloured symbols, for example, may appear quite yellowish when surrounded by a blue background. The luminance contrast between colours can make a difference, for example, orange may look brown when on a white background. In a lantern test, a particular colour might be perceived differently depending on which other colour is shown simultaneously. Such effects are connected to the properties of colour constancy mechanisms.

### 2.5.2 Colour constancy

Colour is often used as an aid to recognition of an object. It is therefore important that the perceived colour of objects remains invariant, irrespective of how objects are illuminated. There is a wide range of possible lighting conditions, from bright, white daylight, to dim, coloured, artificial lighting. The visual system can however adapt to certain changes in the level and colour of the illuminant so as to achieve colour constancy (Jameson and Hurvich, 1989) - recognising objects as having nearly the same colour in many conditions. The extraction of chromatic signals involves a number of complex processes that make the use of colour robust and efficient over a large range of lighting conditions. Unlike a colour camera that works well only when "balanced" for a given illuminant, rapid and complex computations that are likely to involve the primary visual cortex in the brain (Barbur et al., 2002) ensure that the perceived colour of objects remains relatively unaffected, even with large changes of illuminant.

However, colour constancy is only approximate and considerable changes can occur. The following examples (Hunt, 1998) illustrate some situations when significant departures from colour constancy do occur:

As the illumination level falls:

1. There is a progressive reduction in brightness and colourfulness.

2. Below about 0.1 lux, complete loss of colour vision occurs.

As the colour of the illumination becomes increasingly different from average daylight:

3. There is progressive loss of colour compensation (for example, objects look yellower in candle light).

4. There are obvious changes in most colours (for example, in many purples).

5. There are large changes in most colours if the illuminant contains only some parts of the spectrum (for example, with low-pressure sodium street lights, which contain only yellow light).

As the field size is reduced:

6. There is progressive reduction in adaptation (for example, with projected films, or with pictures printed on coloured papers).

# 3 Congenital colour deficiency

## 3.1 Introduction

Colour deficient individuals can discriminate fewer spectral hues than those with normal colour vision. Further, the relative luminous efficiency of the eye is altered and colour matching is abnormal, which results in colour confusions so that some colours that appear different to colour normals look the same to people with defective colour vision.

Congenital colour deficiency (Birch, 2001) is the most common type of deficiency and is caused by inherited photopigment abnormalities. The exact causes of these abnormalities is not certain but they probably arise when the spectral sensitivity of one of the three photopigment groups differs significantly from that of the normal, or when one or two of the three photopigment groups are absent. These different types of colour deficiency are classified according to the number of photopigments present and hence the number of colour matching variables required to match all the spectral hues (Table 1). Visual acuity and all other visual functions are not affected by congenital colour deficiency. The deficiency is binocular, symmetrical and does not change over time.

| Number of colour matching variables | Number of cone pigments | Type | Denomination | Occurrence[1]% of population | | Hue discrimination |
|---|---|---|---|---|---|---|
| | | | | Men | Women | |
| 1 | None | Mono-chromat | Typical (rod) monochromat | 0.003 | 0.002 | None |
| 1 | One | Mono-chromat | Atypical, incomplete (cone) monochromat | Very rare | Very rare | Limited ability in mesopic viewing conditions |
| 2 | Two | Dichromat | a)Protanope<br>b)Deuteranope<br>c)Tritanope | 1<br>1.1<br>0.002 | 0.02<br>0.01<br>0.001 | Severely impaired |
| 3 | Three | Anomalous trichromat | a)Protanomalous<br>b)Deuteranomalous<br>c)Tritanomalous | 1<br>4.9<br>Rare | 0.02<br>0.38<br>Rare | Continuous range from slight to severe impairment |

**Table 1** Classification of congenital colour deficiency (adapted from Birch, 2001).

1. from Hunt, 1998 - estimates based on various surveys.

There are three distinct classifications, monochromatism, dichromatism and anomalous trichromatism, and these themselves are subdivided according to the photopigment that is missing or abnormal.

### 3.1.1 Monochromatism

Monochromats do not see any colour, only lightness differences in the environment. They are able to match all spectral wavelengths using one colour-matching variable. There are two types: typical (rod) monochromats who have no functioning cone receptors and atypical (cone) monochromats who have a single cone type. Both types are rare.

### 3.1.2 Dichromatism

Dichromats have one class of cone photopigment missing. Therefore, they only require two colour-matching variables to match all the spectral hues (as opposed to three required by normal trichromats; see sections 2.3 and 3.4). There are three types of dichromatism depending on which of the three normal pigment types is functionally absent. Protanopes and deuteranopes lack the L- and M-cones respectively whereas tritanopes lack the S-cone. As can be seen in Table 1, the most common forms of dichromatism are deuteranopes and protanopes. Very few females have this deficiency.

### 3.1.3 Anomalous trichromatism

Anomalous trichromats have all three classes of cone receptor but one class has abnormal spectral sensitivity. Protanomalous, deuteranomalous and tritanomalous trichromatism refers to the presence of abnormal L-, M- and S-cones, respectively. Three colour matching variables are required to match all spectral hues (as for normal trichromats; see sections 2.3 and 3.4). The range of severity in protanomalous and deuteranomalous trichromatism is continuous but the spectral sensitivity of the abnormal cones varies individually. Individual variation has been found in the genes encoding the anomalous photopigments (Nathans et al., 1986; Merbs and Nathans, 1992; Asenjo et al., 1994; Neitz and Neitz, 1994) and in the wavelength of peak sensitivity of individuals' cone photopigments (Pokorny et al., 1973; Walraven, P.L., 1976; Pokorny and Smith, 1977; Alpern, 1979; Shevell and He, 1997). As can be seen in Table 1, deuteranomalous trichromatism is the most common form of both anomalous trichromatism and overall congenital deficiency in men (4.9%) and women (0.38%); tritanomalous trichromatism is rare.

## 3.2 Red/green deficiencies

For types of colour deficiency involving either absence (dichromatism) or abnormality (anomalous trichromatism) of the same photopigment group the group terms 'protan', 'deutan' and 'tritan', from Greek words meaning first, second and third, are used. The term red/green colour deficiency collectively describes protan and deutan defects and these will be concentrated on in this report, as they are the only deficiencies that are really prevalent.

Red/green defects share a common mode of inheritance and similar colour confusions in the red-yellow-green range (section 3.4). Dichromats and severe anomalous trichromats confuse saturated colours whereas slight anomalous trichromats only confuse dark and/or pale, de-saturated colours.

The fact that red/green deficiency is much more prevalent in men than women is because the defect is genetically based and the transmission from one generation to the next depends on the gene carried on the X chromosome. Females have two X chromosomes and males an X and a Y. A colour vision defect only becomes apparent when the full compliment of X chromosomes is affected. Therefore, a female with one normal and one defective X chromosome will not exhibit defects herself, but acts as a carrier and has a 50% chance of passing the defective chromosome onto each child. A male inherits the X chromosome from the mother and a female one each from the mother and father. Females that exhibit colour deficiency only occur when the father is deficient and the mother is either deficient, or a carrier and passed the deficient chromosome, rather than the normal one, on to the daughter. This is an uncommon occurrence as approximately only 1 in 200 females has any type of congenital colour vision deficiency.

### 3.3 Relative luminous efficiency

Any change in the absorbance spectra of the cone photopigments (Pokorny et al., 1973; Walraven, P.L., 1976; Pokorny and Smith, 1977; Alpern, 1979; Shevell and He, 1997) results in a change of the photopic spectral sensitivity of the visual system. The relative luminous efficiency, the sensitivity of the eye to different wavelengths in an equal energy spectrum, shows that the wavelength of maximum sensitivity is different in protan and deutan defects from that of a normal. The maximum is at about 535 nm for protans, with a marked reduction in sensitivity for long wavelengths, and at about 560 nm for deutans, compared to about 555 nm for normal observers (see V($\lambda$) curve, Figure 6, section 2.1.4).

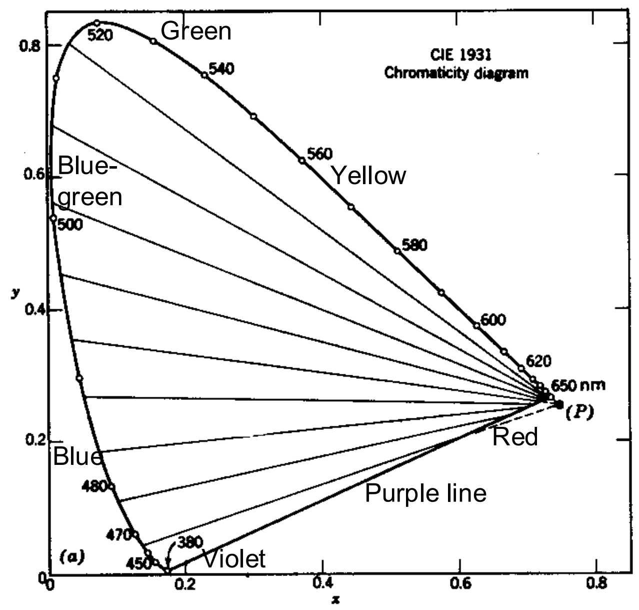
In protanopia, the absence of the long-wavelength-sensitive cones means that the photopic spectral sensitivity response is based upon the absorption characteristics of just the S- and M-cones. Considerable reduction in sensitivity to longer wavelengths results and this means that stimuli typically perceived, as bright red to the normal trichromat will appear very dull and dark to the protanope. The peak sensitivity shifts along the wavelength axis since the photopic luminous efficiency curve is a function of the combined absorbance spectra of the cones. Additionally, the weighting of the L:M cones for a normal colour vision subject is 2:1 (see section 2.1.1) so when the L-cones are missing then this can have quite an effect on the luminance sensitivity and it also shifts the peak of the luminous efficiency curve. However, the curve for deuteranopes is derived from the absorbance spectra of the S- and L-cones so, due to the similarity of the shapes of the spectra for the L- and M-cones on the short wavelength side of their peaks, its peak sensitivity and overall shape is not that different from that of the normal trichromat.

### 3.4 Colour matching and chromaticity

#### Dichromatism

A dichromat accepts the colour matches (see section 2.3.1) of the normal subject, but certain colours that are easily distinguished by normal trichromats will appear identical to dichromats (if there is no luminance contrast), and are therefore confused. These can be represented in the CIE 1931 x,y chromaticity diagram (see section 2.3 and Figure 8), as the MacAdam ellipses for normal trichromats are (Figure 13), but the major axis of each discrimination ellipse extends the full length or width of the chromaticity diagram and is typically depicted as a line. These lines are known either as isochromatic lines as they describe the locus of chromaticities which all appear as the same colour (Figure 14), or simply as confusion lines as they show the colours that are confused by dichromats.

a)




b)

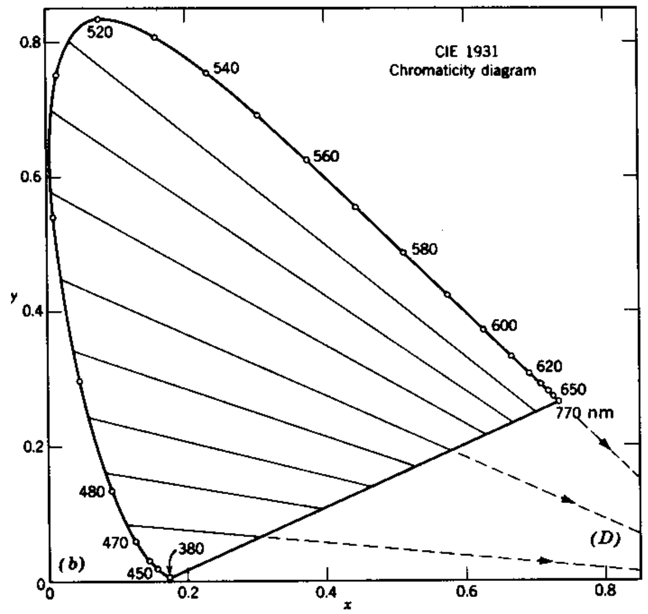



**Figure 14** CIE 1931 x,y chromaticity diagrams showing a) protanopic chromaticity confusions; b) deuteranopic chromaticity confusions. Colours represented along a line are seen as identical if no luminance contrast is present. Isochromatic lines for anomalous trichromats are similar to those of the corresponding dichromat but are shorter and do not include the full range of chromaticities. Isochromatic lines for each of the three types of congenital dichromat converge to a point that in the CIE x,y system of measurement lies outside the chromaticity diagram. The points (P), (D) are the convergence points for protanopic confusions and deuteranopic confusions respectively(Judd, 1944), the chromaticity points of the primaries associated with dichromatic vision (from Judd and Wyszecki, 1975).

The convergence of isochromatic lines for dichromatic vision shows the loss of a fundamental mechanism. However, there are individual variations in colour matching functions and in the location of the dichromatic convergence point due to differences in the macular pigment density in the eye. This variation is greatest in deuteranopes (Judd, 1944; Nimeroff, 1970; Morland and Ruddock, 1993).

**Anomalous trichromatism**

Anomalous trichromats do not accept colour matches made by normal trichromats or, necessarily, those of other anomalous trichromats in the same category. There is considerable variability amongst observers. Colour confusions do not include the complete range of chromaticities found in dichromatic vision. Isochromatic zones become a series of discrimination ellipses with the long axis of each of which has the same angle as the corresponding dichromat's isochromatic zone (Birch, 1973). The long axis of the ellipse varies in length and position depending on the extent of the photopigment abnormality and hence the severity of the colour deficiency.

**Spectral neutral point and neutral colours**

All monochromatic (single wavelength) lights are chromatic (coloured) for the normal observer, so they differ in appearance to what would be called white. However, protanopes and deuteranopes are able to match a mid-spectrum wavelength (i.e. a blue-green colour to a normal observer), a white and a non-spectral mixture colour (appearing purple to a normal observer), represented on the purple boundary on the chromaticity diagram, and so see all of these as the same "colour".

The spectral wavelength that matches equal energy white (Figure 8) (the white that consists of an equal mixture of the three primaries, see section 2.3.1) is called the spectral neutral point. This can be found on the CIE 1931 x,y chromaticity diagram as the point where the isochromatic line going through the equal energy white intersects the spectral locus. Wyszecki and Stiles (2000) calculated the theoretical equal energy neutral points of protanopes and deuteranopes to be 494 and 499 nm, respectively. However, these values vary depending on the definition of the white light and with the differences in the macular pigment density in the eye between observers. Neutral points are about the same for anomalous trichromats as those of the corresponding dichromat.

As long as there is no perceived luminance difference, all "colours" with x,y chromaticity co-ordinates along the isochromatic line though the neutral point will look the same as each other and the same as neutral grey, i.e. achromatic, and are referred to as neutral colours. These neutral colours are often used in pseudo-isochromatic colour vision tests (see section 6.3).

**Rayleigh match**

For both protanopes and deuteranopes, isochromatic zones coincide with the straight portion of the spectral locus of the CIE 1931 x,y chromaticity diagram (Figure 15) for wavelengths greater than 520 nm. Dichromats only have one cone type working in this region (see Figure 2 showing normal spectra) so an additive mixture of wavelengths in this spectral range always produces a fully saturated intermediate wavelength. This characteristic explains the effectiveness of a Rayleigh match for identifying and diagnosing types of red/green colour deficiency (see section 2.3 and section 6.6 on anomaloscopes). Provided that luminance differences can be equated, dichromats are able to match any red and green mixture ratio with an intermediate yellow wavelength.

The straight portion of the spectral locus of the CIE 1931 x,y chromaticity diagram for wavelengths greater than 520 nm is also useful for identifying and diagnosing anomalous red/green colour deficiency. Anomalous trichromats (as do normal trichromats) only have two cone types working in this region (see Figure 2 showing normal spectra). The proportions of red and green wavelengths to match a spectral yellow are abnormal in anomalous trichromatism as the sensitivity of either the 'red' sensitive (L-cones) or 'green' sensitive (M-cones) photopigment groups is altered. Protanomalous trichromats require significantly more red and deuteranomalous trichromats significantly more green compared with normal values. The extent of the abnormality and hence the severity of colour deficiency is shown by the range of matching red/green mixture ratios (see section 6.6 Anomaloscopes).

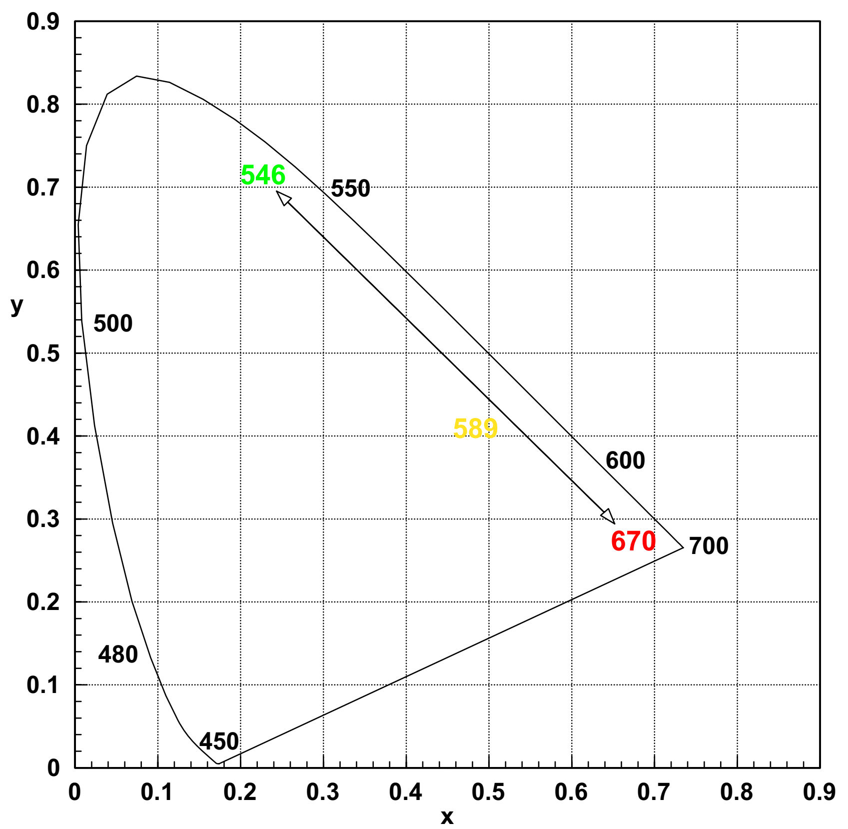



**Figure 15** The CIE x,y chromaticity diagram showing the Raleigh match, as used by the Nagel anomaloscope (see section 6.6). Different types and severities of colour vision deficiencies can be diagnosed, depending on the mixture of the red (670 nm) and green (546 nm) wavelengths perceived to match the yellow (589) wavelength (All wavelengths are given in nm).

**Isochromatic zones and clinical tests for colour deficiency**

If there is no perceived luminance contrast, pigment colours with x,y chromaticity co-ordinates within isochromatic zones look the same to colour deficient people and are confused (section 3.4.1). Isochromatic colours are therefore used in tests to identify colour deficiency and also to grade its severity, which is achieved by using ramped colour difference, or saturation, steps. Neutral colours (section 3.4.3) are employed to classify protan, deutan and tritan deficiency. Table 2 shows the principal colour confusions of these three groups.

| Colour confusion | Type of colour deficiency | | |
|---|---|---|---|
| | Protan | Deutan | Tritan |
| Red/orange/yellow/green | ● | ● | |
| Brown/green | ● | ● | |
| Threshold saturation discrimination: green/white | ● | ● | |
| Threshold saturation discrimination: red/white | ● | ● | |
| Blue-green/grey/red-purple | ● | | |
| Green/grey /blue-purple | | ● | |
| Red/black | ● | | |
| Green/black | | ● | |
| Violet/yellow-green | | | ● |
| Red/red-purple | | | ● |
| Dark blue/black | | | ● |
| Yellow/white | | | ● |

**Table 2** Colours matched and confused by colour-deficient people if no luminance contrast exists (from Birch, 2001).

3.5 **Chromatic discrimination**

**Wavelength discrimination**

In normal colour vision about 150 spectral hues (Wright, 1946) are distinguishable (section 2.2.2), whereas it has been estimated (Pitt, 1935) that there are about 30 distinguishable spectral hues in protanopia and about 17 in deuteranopia. The discrimination of wavelength is a function of the different spectral absorption characteristics (see Figure 2, section 2.1 for normal spectral absorption characteristics) of the three cone receptor types. The smaller the difference in absorbance spectra between two spectrally adjacent cone photopigments, the poorer will be the wavelength discrimination in that region of the spectrum. The wavelength discrimination for protanopes and deuteranopes is similar (Figure 16). Optimum hue discrimination is at about 495 nm with no colour differences able to be distinguished in wavelengths greater than 540 nm as only a single cone photopigment type predominates. In this spectral region there are no comparative response functions and therefore there can be no wavelength discrimination. In anomalous trichromacy, the mean wavelength separation is smaller between adjacent anomalous and normal photopigments than between the L- and M-cones in the normal trichromat. There is considerable variation in hue discrimination between that for dichromats and normals (Figure 16).

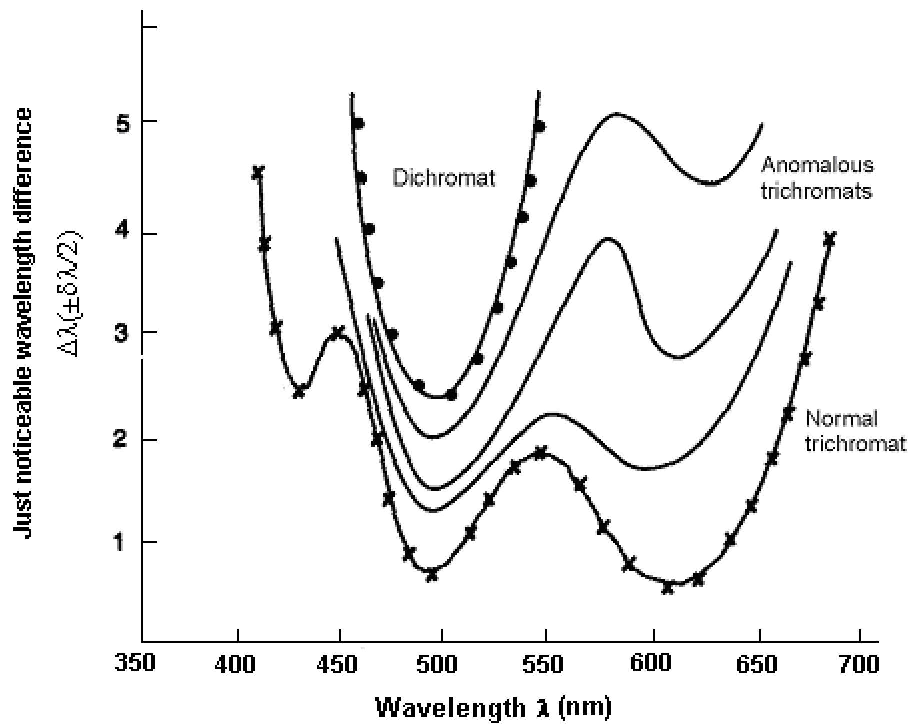



**Figure 16** Wavelength discrimination in congenital colour deficiency. A series of curves, which are intermediate between that of the normal trichromat and the corresponding dichromat (Pitt, 1935), is found in both protanomalous (data of McKeon and Wright, 1940, adapted from Wright, 1946) and deuteranomalous (data of Nelson, 1938, adapted from Wright, 1946) trichromatism showing that a continuum of severity occurs in these classes of colour deficiency (from Birch, 2001).

**Saturation discrimination**

For both dichromats and anomalous trichromats saturation discrimination is reduced at all wavelengths, and the normal minimum at 570 nm is absent. Differences in saturation discrimination, within specific isochromatic zones, are exploited in some colour vision tests.

# 4 The use of colour signals

## 4.1 Introduction

Colour occupies an increasingly important place in our everyday life. In the natural world the diversity of colour is functional as well as interesting. The ability to recognise different colours helps animals to communicate and move around safely in a complex visual environment. The colour vision of different species has evolved to suit their habitat and lifestyle. Colour is used in nature by flowers to attract pollinating birds and insects, by animals as part of courtship to attract a mate and as camouflage, to either hide from predators or from potential prey until ready to strike. Bright colours are used as a warning, for example by poisonous berries and insects, so animals know not to eat them, benefiting both.

Humans use colour for recognition and communication. Just as in nature, colour is used to attract attention, for identification and for camouflage.

Colour coding is a process by which different colours are used to represent different categories of information, e.g. the widely acknowledged international code of a red signal means 'stop' or 'danger' and a green signal means 'proceed' or 'safe'. Colour coding is used in business and industry as well as in recreational activities. It conveys information either connotatively or denotatively. Connotative or non-redundant codes provide specific information through colour recognition alone, such as coloured light signals, or for identifying electrical wiring or the contents of a gas bottle. Denotative codes combine colour with other coding dimensions such that two or more codes correlate with one another to provide information, such as text, shape difference, or relative position. Colour is referred to as 'redundant' in this case, but information may be retrieved quicker using the colour code.

Colour has been found superior for improving the visual interface for conditions where:

- Isolated elements that form some functional group must be located and tracked in a complex array (e.g., air traffic control)
- Multiple coherent elements need to be organised functionally
- Attention should be focused on critical elements, although nothing can be ignored
- Level of display complexity exceeds human memory capacity
- Accuracy of information transfer is critical and rapid response to changing information is needed

## 4.2 The use of colour in aviation

### External colour

Until relatively recently, essentially only the colours of red, green and white were utilised in aviation, with aircraft lights, and beacons and flares used for illumination outside the cockpit and coloured instruments and warning lights used inside it. These were very particular types of stimulation, of relatively short display time. External to the cockpit, navigational aids in aviation still remain consistent with the traditional red/green/white navigation lights based on those used by other modes of transportation (Ivan et al., 2001). Great variability exists worldwide in the configuration and types of lighting used, but virtually all runway lighting systems are strongly based on red, green and white lights (See Table 3). Aeronautical ground lighting provides flight crew with position, height and alignment information, particularly in adverse weather conditions and at night.

| Lighting system (purpose of light fitting) | Definition | Colour | Country |
|---|---|---|---|
| **High intensity Approach light system** | Provides alignment, roll guidance and limited distance-to-go information in low visibility. | Red/White<br>Red/White/Flash | Europe<br>USA/Canada |
| **Low intensity Approach lights** | Provide alignment, roll guidance and limited distance-to-go information at night | Red/White | Europe |
| **Precision Approach Path Indicator (PAPI)** | Provides visual approach slope guidance using combination of coloured lights - colour and position coded. Provides flight crew with information on the achieved approach angle and gives clearance over approach obstacles. | Red/white<br>Red/white | Europe<br>USA/Canada |
| **Visual Approach Slope Indicator** | | Red/white | USA/Canada |
| **Threshold lights** | Indicate the start of the available landing distance. | Green<br>White | Europe<br>USA/Canada |
| **Touchdown Zone (TDZ) lights** | Additional lighting consisting of 2 rows of barrettes symmetrically disposed either side of the runway centreline. Improve texture and perspective. | White<br>White | Europe<br>USA/Canada |
| **Runway edge lights** | Define the usable extent of the runway - located along the edges of the runway as 2 parallel rows of lights equidistant from the runway centreline. | White<br>White/Last 2000' Amber | Europe<br>USA/Canada |
| **Runway centreline lights** | Provided in addition to edge lighting for low visibility conditions. Colour coded to warn of approaching end of runway. | White: alternate Red/White: Red | Europe and USA/Canada |
| **Runway end lights** | Mark the extremity of the runway that is available for manoeuvring. | Departure=Red<br>Approach=Green | Europe and USA/Canada |
| **Taxiway centreline lights** | Provide centreline guidance on taxiways and aprons and when entering or vacating a runway. | Green<br>Green | Europe<br>USA/Canada |
| **Taxiway edge lights** | Indicate the edge of the taxiway; usually installed where no centreline lights. | Blue<br>Blue | Europe<br>USA/Canada |
| **Taxiway hold lights or stop-bars** | Intended to help protect the runway against inadvertent incursions. Unidirectional row of single lights across the taxiway. | Red | Europe |

**Table 3** A few examples of the use of aeronautical ground lighting in different countries (UK CAA, 2000; UK CAA, 2001; Ivan et al., 2001).

The CIE have recently produced a technical report on 'International Recommendations for Colour Vision Requirements for Transport' (CIE 143, 2001). In it they have detailed some of the uses of colour in aviation:

*'Aircraft have red, green and white navigation lights, the same colour code as that used on ships, with red indicating the port side, green starboard and white for the stern light. This code enables pilots to determine the direction of travel of another aircraft in their airspace but pilots may not use this code, except possibly at smaller airports when several planes are holding close circuit under visual flight rules.*

*Aircraft are equipped with a hazard warning beacon to enable detection of another aircraft in the same airspace. The light may be red or white and is usually flashed and of high intensity. Recognition of the colour is not important: detection of the high intensity flashed signal is sufficient.*

*Airports are identified by a green flashing beacon (a yellow light at water aerodromes) and the approaches to runways at important airports are delineated by arrays of red lights.*

*High ground and obstructions around airports are marked by red lights, which need to be distinguished from extraneous lights. Recognition of the red colour provides more certain identification of these lights.*

*In the event of failure of radio communication, the traffic control tower will communicate with aircraft by means of a signal gun using red, green and white colours, but this is rarely used.*

*The descent guide path to a runway is delineated by means of coloured signal lights, the most common of which is PAPI (Precision Approach Path Indicator). PAPI is an array of four signal lights each projecting a red beam in the lower field and a white beam in the upper field. The signal beams are directed so that two appear red and two white when the aircraft is on the correct approach path for landing. The number of white signals increases if the approach is too high and the number of red signals increases if the approach is too low. This signal system offers no visual redundancy: there is no alternative to recognising the red and white signals in order to determine visually whether a landing approach is on the correct descent path.*

*There is an alternative approach path indicator, T -VASIS, which is not as commonly used, but does offer redundancy. A row of lights extends above or below a horizontal bar of lights forming a - or T to indicate respectively a high or low approach. While this system does not require colour recognition, when the approach is too low all the signal lights in the T turn red to signal a dangerously low approach.*

*Runways are delineated by white lights with the threshold designated by a row of green lights and the end by a row of red lights. The runway centre line lights are alternating red and white for the last 900 m and red for the last 300 m. Red signal lights are also used to denote barriers beyond which aircraft should not proceed. Blue and green signal lights are used to delineate run-offs and taxiways.'*

### Internal colour

In the cockpits of older aircraft there is a relative lack of colour, but in the modern aircraft there is an increasing use of colour. Colour is today widely used on the instrument panels of most aircraft, particularly on visual displays. Aircraft are now equipped with sophisticated Electronic Flight Instrument Systems (EFIS). These use fairly complex, differently coloured symbologies, displaying a variety of alpha numerical and analogue data for flight management and control. The data are usually polychromatic (more than eight colours, each of which can be displayed at different light intensities) with varied graphics, ranging from very small areas (alphanumerical, scale graduations) to larger areas (backgrounds, sky, ground).

The use of colour on visual displays is effective in improving performance on search and identify tasks in which both identification and / or location of specific information is important. Colour is, for example, more effective than shape, size, or alphanumerics when certain types of information need to be grouped together and located quickly within a display (Society for Automotive Engineers Aerospace Recommended Practice - SAE ARP4032, 1998).

Colour has been shown to be a practical means of drawing attention to specific information when applied within appropriate constraints. A specific colour maintains its attention-getting value only if it is used sparingly and consistently. The choice of colour also needs to be made carefully as it may be difficult to discriminate between any two similar-appearing colours, such as yellow and amber. This is especially true when displayed on a multi-colour CRT under high ambient lighting - a quite common condition on a flight deck (SAE ARP4032, 1998). Similar-appearing colours, if used either successively or simultaneously on the same display, may lead to a loss of attention-getting value as well as colour confusions.

Colour can be used for the purpose of de-cluttering. If information is grouped or organised by colour then it is transmitted more efficiently, but only if the number of colours used for this purpose is limited. The use of more than six symbol colours (SAE ARP4032, 1998) may degrade performance on search, identification and coding tasks due both to poorer discriminability (especially under high ambient light) and a loss of organisational value (the ability for the addition of colour to give systematic arrangement). The number of colours employed is particularly important since the use of too many colours makes colour coding ineffective (Barbur et al, 1991). If applied correctly, colour can enhance the contrast between items or areas, as compared to luminance contrast alone. Luminance contrast has been shown to be the most important factor in the legibility of alphanumeric and graphic symbols, but the proper use of colour can enhance the legibility. This can be achieved through the use of symbol and background colours that are widely spaced on the CIE 1931 x,y chromaticity diagram (see Figure 8, section 2.3). The addition of chromatic contrast may not yield any significant improvement in legibility or visual search if luminance contrast is already sufficiently high (e.g. > 30%) (Barbur and Forsyth, 1990).

**Colour-coding**

A simple connotative code is accepted worldwide: red means stop, danger or hazard; yellow or amber is associated with warning or caution; and green means safety, engaged or proceed. This basic code is used in aviation, and was, until relatively recently, about the only colour coding used.

Colour is effective as a coding scheme, particularly for qualitative information. Colour-coding schemes can facilitate processing of the displayed information and can be an aid in the pilot's cognitive tasks (Mejdal et al., 2001). For instance, colour has proved effective where a great deal of information must be presented in a dense format (Kopala, 1979). Where more than a small number of coding categories exist, other coding schemes, such as alphanumerics, are more efficient for the transmission of the information. The use of colour may still enhance information transmission, however, if the separate categories can be logically divided into several major divisions with a different colour code. This is referred to as partial redundancy and has been shown to enhance search performance.

It has been shown that colour coding enhances the speed and accuracy with which information is extracted from aviation displays (Christ, 1975; Luder, 1984; Macdonald and Cole, 1988).

Maps also benefit from the broad categorisation powers of colour. Specifically, *'colour can be used to separate and contrast different elements in a display that cannot be separated properly by space - thereby improving symbol visibility. In this capacity,* *colour serves as an attention cue for the operator'* (Stokes and Wickens, 1988). '*One of the best demonstrated uses of colour coding is for search tasks where colour serves as a primary or redundant cue*' (Christ, 1975).

**Colour redundancy**

Colour redundancy has several advantages: a faster and more accurate response is achieved as different cues are processed in parallel; some people with colour deficiencies are able to interpret colour-coded displays (SAE ARP4032, 1998); it may reduce the impact of individual electron gun failures in the CRT; also, in situations such as high ambient lighting conditions, redundancy can help to ensure the accurate transmission of information where colours alone may be difficult to distinguish even for persons with normal colour vision.

The UK CAA has carried out tests (Hallworth, 2001) in which it was found that under some conditions pilots can react quicker to audio signals than to flashing lights. Therefore, all Warning and Caution lights are accompanied by an audio warning - a fire bell for red fire warning lights, and chimes for others. For some instruments this audio signal is verbal advice, which can change as the situation changes or the pilot reacts to it. For some there are also "attention getters" - generally red and amber lights, one of each on each side of the cockpit, at about eye height; these illuminate and sometimes flash so they can be seen first and then the pilot can look for the specific light detailing the problem.

4.3 **Illumination of the cockpit**

As detailed in section 2.2.1, the illumination of the cockpit can affect the perception of the colours used. The cockpit will normally be lit with natural daylight, the quality and 'colour' of which can vary with altitude and weather conditions. Internal illumination can also be added. Any variation in these lighting conditions will not affect the appearance of the instrument colours too much due to colour constancy (section 2.5.3), as long as the lights are essentially 'white' (even ordinary tungsten light is not pure white, but it is essentially white).

However, it is still considered by some that red lighting is the best illumination for night flying. Red illumination will change the perception of the colours on the flight deck so making the possibility of the wrong interpretation of information more possible. Red light is only needed if the night vision (rod) system must come on in seconds. But this is mainly important if the light outside is really dim (at most a crescent moon in a clear sky) and it is necessary to see details outside. This is not necessary whilst flying, as the only details that need to be seen from a modern aircraft are usually lights or illuminated objects, so the night vision system is not used to see these. As so many colours are used on a modern flight deck it is not worth the near-loss of colour vision under red lights, to be able to see the occasional non-illuminated feature outside, which will be detected by the modern instruments inside if it needs to be 'seen' anyway.

The more appropriate way of being significantly dark adapted but still being able to perform visual tasks is to dim the internal lighting, or just rely on the dimmed displays and instrument lights, with little other overhead lighting. A report has been carried out in the USA on the use of low level white lighting (LLW), instead of the traditional red, in the control rooms in submarines (Kobus and Luria, 1985; Luria et al., 1986). LLW was judged by the officers and men to be more desirable than red light. Claims were made that the low level white lighting made things easily visible and reduced the incidence of headaches. Handwriting tasks seemed easier to perform in the white light. Locating and activating non-illuminated switches and controls were easier tasks under white light. Colour coding was preserved on the CRT displays; CRT displays could be maintained at a lower level of luminance than under red lighting (where the colour coding at lower luminances was harder to discern). Personnel "felt better" working in the low level white lighting than in red lighting.

## 4.4 Colour standards in aviation

The benefits of colour as an attention getter, information grouper and value assigner are lost if too many colours or improper colour combinations are used (Murch and Taylor, 1986). The only cockpit instrument colours for which official JAA guidance exists are as set out in the Joint Aviation Requirements JAR-25 (Section 3, AMJ 25-11). This states that three main colours are used for lights: red for warning, amber for caution and green (or white) for advisory and safe operation signals. It then states that the advisory colour can be any colour that is contrasting to red and amber and that any other colour contrasting sufficiently to the above colours can be used for other lights.

JAR 25 Advisory Material Joint (AMJ 25-11), Section 3, which is on information separation, states that there is no colour standardisation now because there has not been any historically. However, it has been acknowledged that, if left unrestricted then there will soon be few common areas of colour selection. To avoid significant safety implications from information transfer problems colours are being recommended based on current-day common usage. If reasonably justified, deviations may be approved.

There are several reports (Silverstein et al., 1985; Murch and Taylor, 1986; Walrath and Hunter, 1990; Fadden and Jacobsen, 1987; Wentz et al., 1998; SAE ARP4032, 1998) that give recommendations and suggestions, especially for the design of displays, and it is suggested that acknowledged guidelines for display design are followed. However, the use of computer monitors in an office situation, and the use of displays in aviation differ considerably in factors such as lighting conditions and length of use.

ICAO does have some colour specifications for aerodromes (Figs. 17 to 20) (ICAO ISRP Annex 14, 1999) and aircraft lights (Figure 21) (ICAO Airworthiness Manual Vol II, 2001; ICAO ISRP Annex 8, 2001). However, although a colour is stated for each light, marking, sign or panel, a range is usually specified for each named colour (see Figs 17-21). The following notes are given in the Airworthiness Manual (Vol II, 2001; ICAO ISRP Annex 8, 2001) about the colours of aircraft lights:

*'Note 1.- It is not possible to establish specifications for colours such that there is no possibility of confusion. For reasonably certain recognition, it is important that the eye illumination be well above the threshold of perception, that the colour not be greatly modified by selective atmospheric attenuations and that the observer's colour vision be adequate. There is also a risk of confusion of colour at an extremely high level of eye illumination such as may be obtained from a high-intensity source at very close range. Experience indicates that satisfactory recognition can be achieved if due attention is given to these factors.*

*Note 2.- The chromaticities are expressed in terms of the standard observer and coordinate system adopted by the International Commission on Illumination (CIE) (see section 2.3.2).*

*Note 3.- The chromaticity boundaries defined below (Figure 21) are those recommended by the International Commission on Illumination (CIE) in its publication 2.2, dated 1975.'* (This CIE document has since been updated to CIE standard S004/E-2001, in which some of the recommended boundaries have slightly changed).

The UK CAA also has a document, called CAP 168 - Licensing of Aerodromes (UK CAA, 2001), of which Chapters 6 and 7 give information on Aeronautical Ground

Lighting (AGL) and Aerodrome Signals, Signs and Markings. This document gives details such as position, intensity, colour, angle and spread of lights. Chromaticity details of the lights are given, in addition to the diagrams shown below (Figs. 17 to 20). It also provides a certain amount of guidance on discrimination between lights, such as:

*'If there is a requirement to discriminate yellow and white from each other, they should be displayed in close proximity of time or space as, for example, by being flashed successively from the same beacon.'*

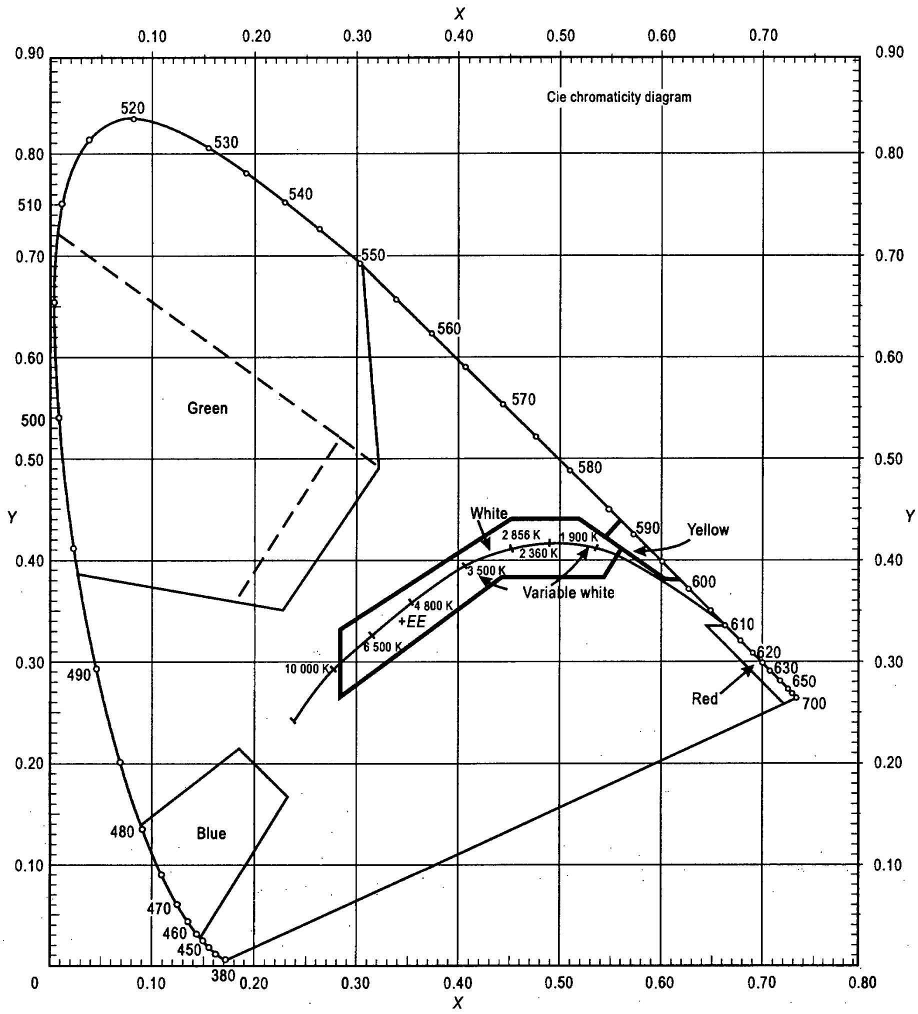



**Figure 17** ICAO approved colours for aeronautical ground lights at aerodromes (ICAO ISRP Annex 14, 1999).

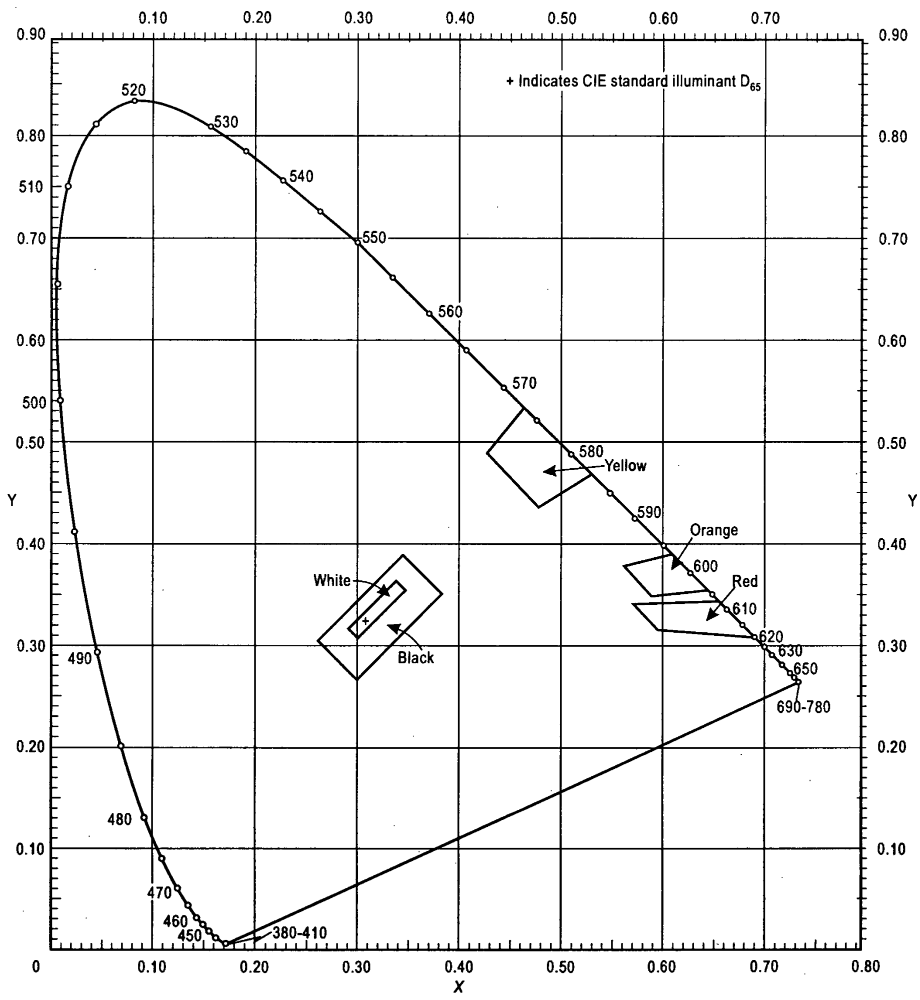



**Figure 18** ICAO approved ordinary colours for markings and externally illuminated signs and panels at aerodromes (ICAO ISRP Annex 14, 1999).

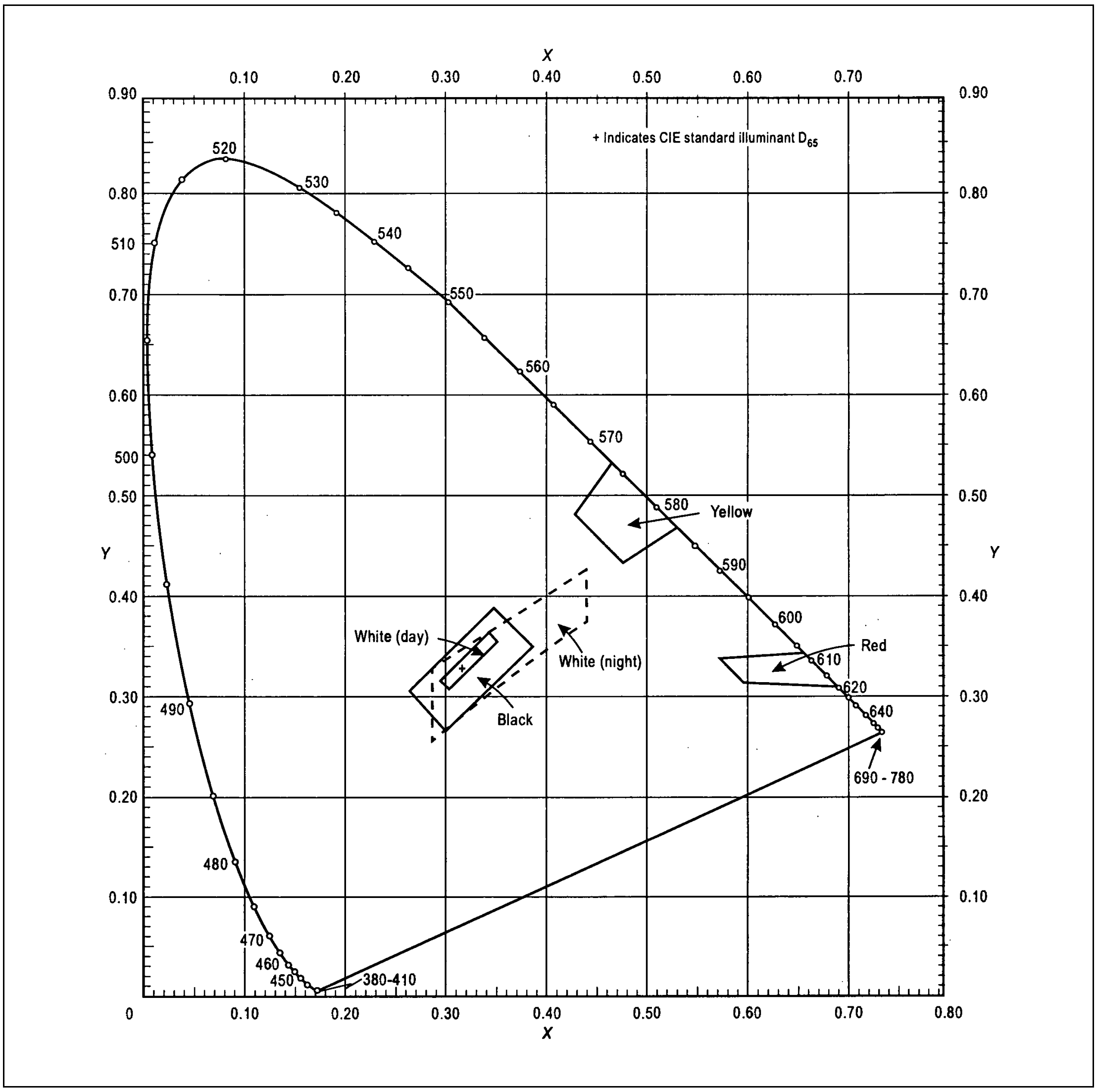



**Figure 19** ICAO approved colours of transilluminated (internally illuminated) signs and panels at aerodromes (ICAO ISRP Annex 14, 1999).

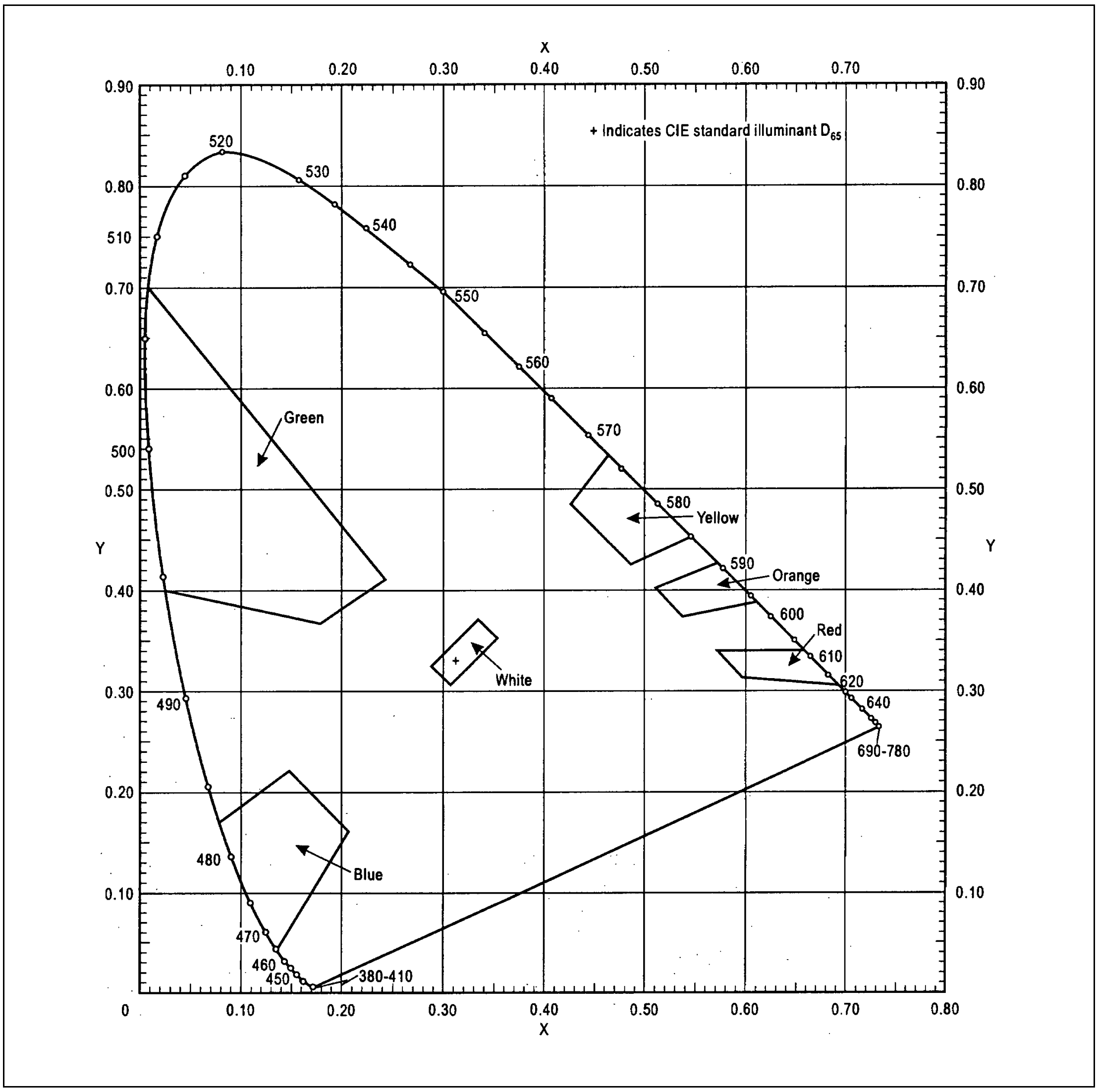



**Figure 20** ICAO approved colours of retro-reflective materials for markings, signs and panels at aerodromes (ICAO ISRP Annex 14, 1999).

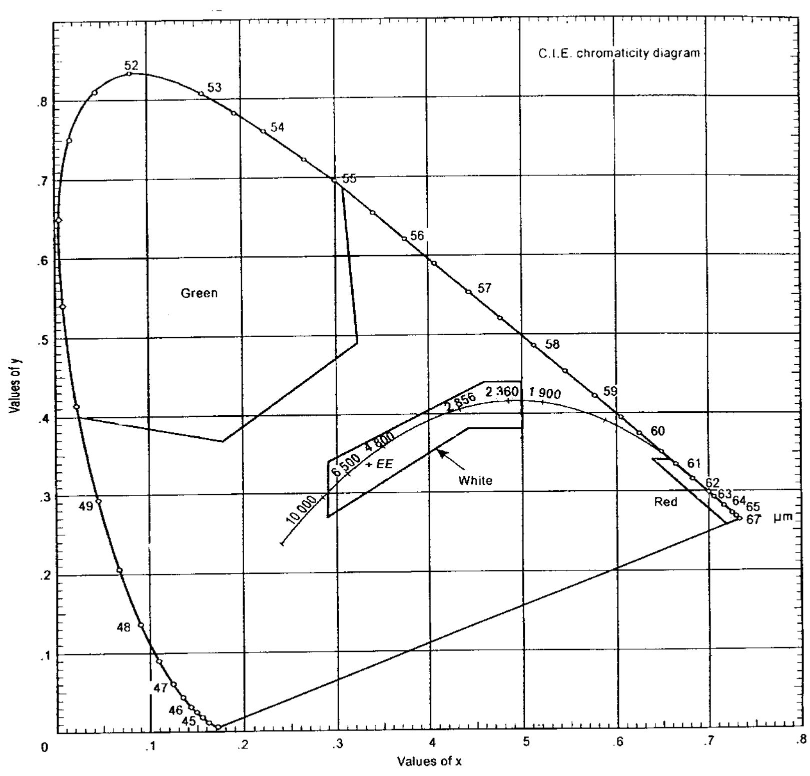



**Figure 21** Exterior aircraft light colours (ICAO Airworthiness Manual Vol II, 2001).
Note: EE=equal energy point
1 900 to 6 500 co-ordinates of significant colour temperatures of a radiating black body.

# 5 Current colour vision requirements in aviation

### Introduction

The colour vision requirements for aviation, as for other standards, are set by the International Civil Aviation Organisation (ICAO). These are then interpreted and applied by each of the individual contracting states. In Europe, for harmonisation purposes, the 38 members of the Joint Aviation Authorities (JAA) have agreed to apply the same standards.

## 5.1 ICAO colour vision requirements

### 5.1.1 ICAO International Standards and Recommended Practices

The ICAO requirements place emphasis on the need for the applicant to be able to perceive the colours needed to perform their duties safely (ICAO ISRP Annex 1, 2001):

*'6.2.4 Colour perception requirements*

*Contracting States shall use such methods of examination as will guarantee reliable testing of colour perception.*

*6.2.4.1 The applicant shall be required to demonstrate the ability to perceive readily those colours the perception of which is necessary for the safe performance of duties.*

*6.2.4.2 The applicant shall be tested for the ability to correctly identify a series of pseudo isochromatic plates in daylight or in artificial light of the same colour temperature such as that provided by CIE standard illuminants C or D65 as specified by the International Commission on Illumination (CIE).*

*6.2.4.3 An applicant obtaining a satisfactory result as prescribed by the Licensing Authority shall be assessed as fit. An applicant failing to obtain a satisfactory result in such a test shall be assessed as unfit unless able to readily distinguish the colours used in air navigation and correctly identify aviation coloured lights. Applicants who fail to meet these criteria shall be assessed as unfit except for Class 2 assessment with the following restriction: valid daytime only.*

*Note - Guidance on suitable methods of assessing colour vision is contained in the [ICAO, 1985] Manual of Civil Aviation Medicine (Doc 8984).*

*6.2.4.3.1 Recommendation. - Sunglasses worn during the exercise of the privileges of the licence or rating held should be non-polarising and of a neutral grey tint.*

*Another section in the same Annex states that if the applicant does not pass the appropriate tests, they can still be assessed fit for flight under certain circumstances:*

*1.2.4 Medical fitness*

*1.2.4.8 If the medical Standards prescribed in Chapter 6 for a particular licence are not met, the appropriate Medical Assessment shall not be issued or renewed unless the following conditions are fulfilled:*

*a) accredited medical conclusion indicates that in special circumstances the applicant's failure to meet any requirement, whether numerical or otherwise, is such that exercise of the privileges of the licence applied for is not likely to jeopardise flight safety;*

*b) relevant ability, skill and experience of the applicant and operational conditions have been given due consideration; and* *c) the licence is endorsed with any special limitation or limitations when the safe performance of the licence holder's duties is dependent on compliance with such limitation or limitations.'*

### 5.1.2 ICAO Manual of Civil Aviation Medicine

The ICAO Manual (ICAO Doc 8984, 1985) acknowledges that the requirements set in Annex 1 (ICAO ISRP Annex 1, 2001) are open to interpretation by contracting states as there is at present no defined line between the type and severity of colour deficiency that is safe for flying and that which is not. This is because this definition is extremely difficult to set due to the varied and increasing number of tasks for flight crew that involve colour, and the fact that no present colour vision test can define the exact colour vision properties of a person with a deficiency.

*'Chapter 10 Ophthalmology*

*There are all grades of colour vision defect from subtle to severe and the question which arises is how much of a colour vision defect can be allowed before an individual must be considered unable to operate safely in the aviation environment.*

*The section of Annex I dealing with colour perception states that the applicant shall be required to demonstrate ability to perceive readily those colours the perception of which is necessary for the safe performance of his duties. Precise physical and physiological criteria cannot be given because of the large number of variables in different viewing situations.*

*Simple practical tests such as the ability to name correctly signal flare or signal light colours give information only about the specific test situation and are of limited value.'*

Several tests are mentioned as possible for use and it is suggested that the instructions for each test are adhered to. Chapter 2 of the Manual states how to incorporate a certain amount of flexibility in the colour vision tests.

*Chapter 2 Medical requirements*

*Sample procedures for evaluation of borderline licensing cases*

*'Defective colour vision*

*An applicant might be assessed as fit if able to demonstrate:*

*a) Ability to distinguish colours used on aviation charts, including coloured print in various sizes, conventional markings in several colours from an inverted map at a distance of 3 metres.*

*b) Ability to read flight instruments, especially those with coloured markings, coloured lights in the cockpit, especially marker beacon lights, warning lights, and lights of varying intensities and hues.*

*c) Ability to recognise terrain and obstructions. While in flight, the applicant should be asked to select several emergency landing fields, preferably under somewhat marginal conditions, and describe their surfaces, e.g. sod, stubble, ploughed field. The applicant should be asked to identify obstructions such as ditches, fences, terraces, low spots, rocks, stumps and especially any grey, tan or brown objects in green fields.*

*d) In addition, applicants for privileges to fly at night should be tested at twilight or at night to determine their ability to see coloured lights of other aircraft in the vicinity; runway approach lights; airport boundary lights; taxiway lights; red warning lights on TV towers, high buildings, stacks, etc.; conventional signal lights from the tower and all colour signal lights normally used in air traffic control as described below.'*

These tests for borderline cases are not very good for testing colour vision as they are not using a controlled consistent environment and the test could depend on the luck of the day and the situation. Just because the pilot completes the task set, does not mean that he will be safe in all situations as in these tasks he is using other cues apart from just his colour vision. This may not be fair for the pilot and does not necessarily guarantee that he can 'perceive readily those colours the perception of which is necessary for the safe performance of duties' (ICAO ISRP Annex 1, 2001).

This project aims to address these difficulties in colour vision assessment, by investigating how colour is used by flight crew, then from this defining a line for safe colour deficiency, and developing a colour vision test that will define which side of this line a candidate's colour vision is. This should make standards more uniform, applicable and reliable.

## 5.2 Joint Aviation Authorities (JAA) colour vision requirements

### 5.2.1 Joint Aviation Requirements

The JAA regulations, Joint Aviation Requirements-Flight Crew Licensing, Part 3 (Medical) (JAR-FCL 3 Section 1, 2002) are slightly more specific than the ICAO regulations in the types of tests that are to be used and what the protocol and pass/ fail criteria are for these.

*'JAR-FCL 3.225 Colour perception*

*(a) Normal colour perception is defined as the ability to pass Ishihara's test or to pass Nagel's anomaloscope as a normal trichromat (see paragraph I Appendix 14 to Subpart B).*

*(b) An applicant shall have normal perception of colours or be colour safe. Applicants who fail Ishihara's test shall be assessed as colour safe if they pass extensive testing with methods acceptable to the AMS (anomaloscopy or colour lanterns - see paragraph 2 Appendix 14 to Subpart B).*

*(c) An applicant who fails the acceptable colour perception tests is to be considered colour unsafe and shall be assessed as unfit.'*

Appendix 14 to subpart B (JAR-FCL 3, 2002) gives the basic protocol for each specific colour vision test. It also shows that there is still a fair degree of flexibility in the type of test used, as, although three options are suggested for the lantern test, it also allows for any lantern acceptable to the JAA-FCL Medical Sub-committee (AMS) to be used:

*'Colour perception*

*(See JAR-FCL 3.225 and 3.345)*

*1 The Ishihara test (24 plate version) is to be considered passed if the first 15 plates are identified without error, without uncertainty or hesitation (less than 3 seconds per plate). The plates shall be presented randomly. For lighting conditions see the JAA Manual of Civil Aviation Medicine [JAR-FCL 3, 2002].*

*2 Those failing the Ishihara test shall be examined either by:*

*a) Anomaloscopy (Nagel or equivalent). This test is considered passed if the colour match is trichromatic and the matching range is 4 scale units or less, or by*

*b) Lantern testing. This test is considered passed if the applicant passes without error a test with lanterns acceptable to the AMS such as Holmes Wright, Beynes [sic], or Spectrolux.'*

The Ishihara pass criteria for JAA is very demanding and it is likely to fail a few people with normal colour vision, as it does not allow for misreadings (see section 6.3.1 on Ishihara plates). In addition, the use of the shorter 24-plate test, as opposed to the full 38-plate test, also means that many of the Ishihara plates that more consistently identify colour normals and colour deficients correctly are not used (see section 6.3.1). There is the back-up of the follow-on anomaloscopy (see section 6.6) or lantern test (see section 6.5). However, there is a chance that these tests could also fail some applicants with normal colour vision, depending on the test and the testing criteria used. The Beyne lantern (section 6.5.3), which is of French origin, particularly has been found to do this (unpublished data from City University, 2002) when testing is carried out according to the City University protocol (see section 6.5.3.1).

The limiting of the colour matching range for a pass on the Nagel anomaloscope (see section 6.6) to four scale units or less also seems too small as a large number of normal trichromats do exceed this range, and anomalous trichromats can have a range of only 2 or 3 units The position of the range on the scale is therefore important. In addition, only trichromats (both normal and anomalous) will achieve a range of 4 or less as dichromats will always match the whole range (0 - 73 scale units for the Nagel), so it does not need to state that the colour match should be trichromatic to pass. However, the Appendix 14 could be interpreted as limiting the passing of the test to 'normal' trichromats with a range of 4 or less, as the section (a) of '*JAR-FCL 3.225 Colour perception* does say the applicant should *pass Nagel's anomaloscope as a normal trichromate*. This section (a), though, is referring to screening (it refers to *'paragraph I Appendix 14 to Subpart B'* which is about screening with the Ishihara plates), so is suggesting the Nagel anomaloscope as an alternative to the Ishihara plates to pass those with normal colour vision. The normal trichromat as measured on a Nagel anomaloscope is not defined, though, either in Appendix 14 or in the JAR manual (see section 6.6.2). The manual also does not mention restricting the pass only to normal trichromats, but only to a range of 4 or less as a secondary test. The Ishihara plates (section 6.3.1) are so effective for screening, however, and cheaper, quicker and easier to use, that the Nagel anomaloscope, which is no longer manufactured, does not need to be used for this purpose, only as a possible secondary test.

Follow up colour vision tests are carried out for renewal of medical certificates depending on age: 5-yearly to age 40, then 2-yearly to age 65 (JAR-FCL 3 Section 2, 2000). However, Ishihara plates (section 6.3.1) are used for this, unless a change from the initial assessment is found, so any blue/yellow deficiencies will not be picked up. These are the deficiencies that tend to be brought on with age (section 2.1.3) and also occur with acquired deficiency (section 7). However, for the latter, associated with any colour vision defect there are also likely to be other symptoms, such as other visual defects, that will tend to be noticed before an acquired colour vision deficiency might pose a flight safety hazard.

### 5.2.2 UK CAA colour vision testing procedure

The UK CAA Medical Division adheres to the JAR procedures set out in the previous section.

The UK CAA has set out their procedures for colour vision testing (Chorley et al, 1999):

*'The CAA uses three classifications for colour vision: CP2 (normal), CP3 (safe) and CP4 (unsafe). Colour vision assessment is carried out with the Ishihara plates (24 plate version tested in daylight or artificial light of the same colour temperature). For CP2 classification, the patient must make no errors. A patient who fails the Ishihara*

*test is then assessed with the Holmes-Wright lantern, which must be passed for the colour vision to be classed as safe (CP3).*

*The Holmes-Wright lantern consists of two lights in a vertical plane, which the subject must name correctly at a distance of 6 m in a normally lit room. Although each colour will have different hues on different presentations, the subject must identify both lights on each presentation of red, green or white. There are nine presentations on each run and, if the subject names all lights correctly, then no further runs need to be used; presentations are made in different orders to prevent learning. Any mistakes, and a further two runs are made where, if any further mistakes are made, the subject is dark adapted and one further run is carried out in darkness. If the Holmes-Wright test is passed at any stage, the patient is classed as CP3 - safe. If any mistakes are made after dark adapting, the patient will be classed as CP4 - unsafe.*

*Patients who fail the lantern test may still fly but only with a restricted Class 2 which would allow them to fly only during daylight hours within the Joint Aviation Authorities' flight information regions using aerodromes where air traffic control is provided by means of radio communication.'*

# 6 Conventional colour vision tests

## 6.1 The design of colour vision tests

The design of colour vision tests is based on the characteristic colour confusions found in protan, deutan and tritan defects (Pitt, 1935; Wright, 1952) (see section 3). Variations in colour matching ability (section 3.4) and chromatic discrimination thresholds (section 3.5) are exploited. Colour deficient people, for example, have difficulty finding an object in everyday life when that object is defined by colour but lies in a variegated background where lightness is varying randomly, such as fruit in trees. This fact has been used to design colour vision tests since 1877 when Stilling (Stilling, 1877) constructed pseudoisochromatic plates with figures which, when read, could distinguish colour-deficient people from normals. These plates were made up of a target and field, both of which were broken into many small patches, each with its own contour and of varying lightness. Thus, neither edge artefacts, nor luminance differences could be used as a cue for discrimination of the target against the field. These principles have been incorporated into all subsequent sets of pseudoisochromatic plates (Regan et al., 1994).

It is possible to illustrate the design principles of most colour vision tests by reference to the characteristic isoconfusion lines of colour vision deficiencies as represented in the CIE 1931 x,y chromaticity diagram (Figure 14, section 3.4). In these diagrams it is possible to select pairs of stimuli whose chromaticities will be discriminated by individuals with normal colour vision yet appear indistinguishable to either a protan, deutan or tritan colour defective.

Colour vision tests (Birch, 2001) are designed to perform different functions. People with abnormal colour vision can be identified using screening tests; some tests classify protan, deutan and tritan colour deficiency; the severity of colour deficiency is estimated using grading tests; practical colour matching ability, hue discrimination and colour recognition are examined using vocational tests (see Table 4).

A wide variety of practical tests are available and can be split into groups that differ both in design principles and method of administration. One group is based largely on the principle of colour confusion and tends to be the simplest to use. The majority of such tests are known as pseudo-isochromatic tests as they employ stimuli that may be described as falsely appearing of the same colour. These are usually presented in book form and the verbal identification of a coloured figure (of specified chromaticity viewed against a background of different, but carefully selected, chromaticity) is required. More sophisticated judgement is needed for both hue discrimination tests, designed principally to assess colour discrimination, and red/green colour matching tests, based on the principles of matching a reference stimulus by a mixture of light intensities from two spectral primaries. Other tests are more specialised, designed to measure specific aspects of colour vision and overall performance, such as judgements of colour difference and colour memory.

| | Pseudoiso-chromatic plates | Hue discrimination | Lanterns | Spectral anomalo-scope |
|---|---|---|---|---|
| **Visual task** | Identification of a figure | Arrangement of hues in sequence | Colour naming | Precise colour matching |
| **Function** | | | | |
| **Screening (identifying)** | ●●● | — | Some capability | ●●● |
| **Classifying (protan, deutan and tritan)** | ●● | ●● | — | ●●● |
| **Grading severity** | † | ●● | Some capability | ●●● |
| **Diagnosis (dichromat/ anomalous trichromat)** | — | — | — | ●●● |
| **Occupational suitability** | — | ●●● | ●●● | — |

**Table 4** Different types of colour vision tests and their principal functions (from Birch, 2001).
●●● =excellent capability in this category
●● =partially effective in this category
— =no capability in this category
† =Some plate series grade severity

### 6.2 Test Batteries

Current colour vision tests vary in sensitivity and specificity and employ response criteria that make the results difficult to generalise. In order to provide a detailed description of a person's colour vision, the use of several different tests is often required. This is known as a test battery. The tests selected depend on the priorities of the examination. To determine occupational suitability it is common to use screening, grading and classifying tests. It is not always required to make an exact diagnosis of the type of colour deficiency, so sometimes a single efficient screening test is all that is needed to identify red/green colour deficiency. The tests included in a battery may be limited by the availability, location, cost, and the time available.

The JAR Manual's (JAR-FCL 3 Section 2, 2000) opinion on colour vision testing procedure is that:

*'The mere qualitative diagnosis of the colour vision deficiency is not sufficient, because the colour discrimination varies considerably between individuals with the same type of defect.*

*A practical colour vision test certainly has the highest validity but only for the conditions present at the test. It has been the practice of some countries to waive applicants with simple deuteranomaly who readily pass lantern tests. In some cases, a practical test with a signal gun has been decisive. Even individuals with rather outspoken defects may pass this test which does not signify whether the applicant normally perceives other less conspicuous signals.*

*In order to assess the fitness of an applicant with a colour vision deficiency with regard to a possible waiver, it is necessary to have at hand the results of a battery of colour vision tests. As many different aspects of colour vision as possible should be examined.'*

| Test | Type of test | Version | Test used for: |
|---|---|---|---|
| The Ishihara plates | Pseudoisochromatic plates | 38-plate test (first 25 used) | Screening |
| The AO HRR plates | Pseudoisochromatic plates | (2nd ed.) | Grading and classifying |
| The Farnsworth D15 test | Hue discrimination | | Grading and classifying |
| The CU test | Hue discrimination | (2nd ed.) | Grading and classifying |
| Nagel anomaloscope | Spectral anomaloscope | | Grading, classifying and diagnosis |
| Holmes-Wright lantern | Lantern | Type A | Suitability for occupation |
| Spectrolux lantern | Lantern | | Suitability for occupation |
| Tritest L3 Luneau France (Beyne) lantern | Lantern | Aviation lantern | Suitability for occupation |

**Table 5** Test battery used at City University. All of this battery is used for this study.

<table>
<tr><th colspan="2">Test</th><th colspan="2">Pass</th></tr>
<tr><td colspan="2">Ishihara plates (24 plate version)</td><td colspan="2">0 mistakes</td></tr>
<tr><td colspan="4">If fail Ishihara plates then:</td></tr>
<tr><th>Test</th><th>Pass</th><th>If any mistakes</th><th>Then if any mistakes</th></tr>
<tr><td>Holmes-Wright A lantern9 vertical pairs of lightsRed, green, white</td><td>0 mistakes in first run in lighted room</td><td>2 more runs in lighted room. Pass if no mistakes in both runs</td><td>1 run in dark after dark adaptation. Pass if no mistakes</td></tr>
<tr><td colspan="4">and:</td></tr>
<tr><th>Test</th><th colspan="2">Conditions</th><th>Pass</th></tr>
<tr><td>Tritest L3 Luneau France (Beyne) lanternSingle lightsRed, green, white, blue, yellow</td><td colspan="2">1 run of 5 single lights1 second exposure time3 min arcdim room</td><td>0 mistakes</td></tr>
</table>

**Table 6** Tests used by UK CAA for Class 1 medical.

## 6.3 Pseudoisochromatic plates

Pseudoisochromatic plates (Birch et al, 1979) are the most widely accepted screening test for red/green colour deficiency and use colour camouflage to exploit isochromatic colour confusions (see section 3.4). Spots or patches of colour that vary in size and lightness make up the individual elements of the designs in such a way that a different figure emerges from the background for people with normal colour vision to that seen by colour deficient people. The colours contained in the figure and background are within isochromatic zones (see section 3.4.5), so that all the spots appear 'falsely of the same colour' (pseudoisochromatic) to colour deficients. The outline of the figure is broken up and its shape concealed by the dot matrix. Isochromatic zones for protans and deutans are similar in the orange, yellow and yellow-green area of the chromaticity diagram, so these are the usual colours used for the spots on screening plates for identifying red/green colour deficiency.

There are three different types of design of pseudoisochromatic plates: vanishing, hidden figure and transformation. A series of plates is always used, sometimes only based on one of these types of design (e.g. American Optical Company (Hardy, Rand and Rittler) (AO HRR) (second edition) plates, section 6.3.2), but some tests include a mixture of all three types (e.g. Ishihara, section 6.3.1). All pseudoisochromatic tests contain vanishing camouflage patterns, and these are the easiest to design. With these a figure is seen by colour normals but not by colour deficients; the reverse of this, the hidden figure design, is harder to design so is not always so effective. More complex patterns are contained in transformation plates, with careful placement of the colour dots giving an apparent transformation of the perceived figure; normal trichromats see one figure and colour deficient people see a different figure in the same design. Positive evidence of colour deficiency is given by transformation designs whereas vanishing designs give negative evidence.

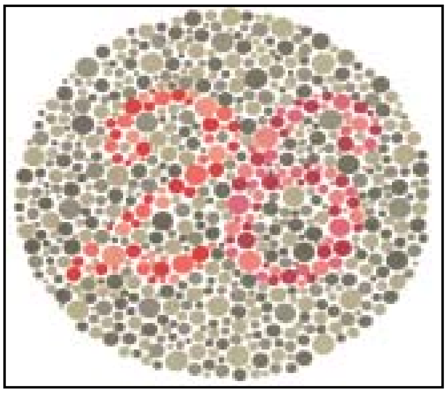


**Figure 22** Example of a classification vanishing design pseudoisochromatic plate from the Ishihara plate test (section 6.3.1). Deutans tend to see only the left-hand figure (2) and protans tend to see only the right-hand figure (6) (see Table 7).

In order to be effective, pseudoisochromatic plates must be carefully designed. The selected colours must have chromaticities within appropriate isochromatic zones with reference to the illuminant used. This can be a real problem since artificial illuminants of specified spectral power distribution are difficult to manufacture and lamp aging can significantly alter its spectral output. Luminance contrast and colour differences between pairs of isochromatic colours rely on the use of appropriate illuminants.

The level of difficulty involved in the discrimination task is shown by the colour differences. Either false positives or false negative results are obtained if this is not appropriate. In screening plates, small colour differences are used to be able to detect subjects with only slight colour deficiency. However, if the colour differences are too small then some normals cannot see the figures in vanishing designs and are incorrectly diagnosed as colour deficient and conversely, if the colour difference is too large some mild colour deficient subjects identify the figure and are incorrectly classified as normal.

In plates intended for grading the severity of colour deficiency, isochromatic colour confusions with ranked colour difference steps are used. These can be considered as representing isochromatic lines, or the long axes of ellipses (see Figure 14, section 3.4), which increase in length (Figure 23).

However, the isochromatic lines shown in Figure 14 are indicative of an average group of dichromats so individual results will vary due to variations in lens and macular pigment absorptions (see section 2.1.3) from person to person. The straight lines indicated on the CIE 1931 x,y diagram may therefore be slightly curved for an individual and this may lead to a protan subject misreading a plate meant to identify a deutan, or vice versa (Birch, 1973).

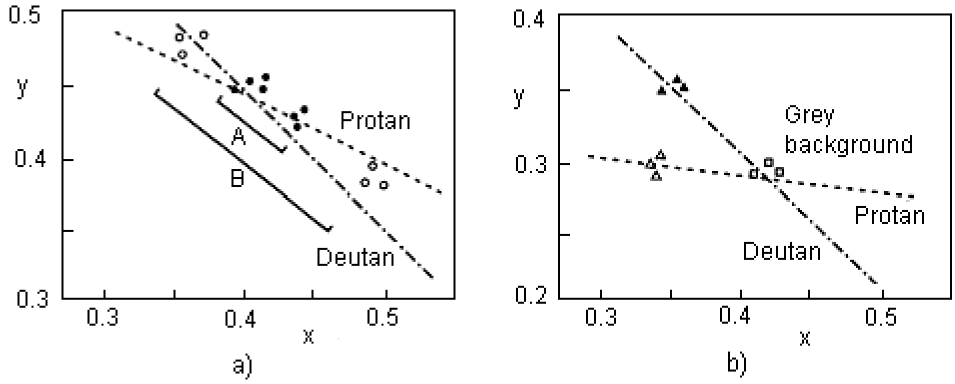



**Figure 23** Colours selected for pseudoisochromatic tests compared with isochromatic zones (section3.4.5) for protan and deutan defects. Colours selected for the background matrix of dots and for 'vanishing' figures have coordinates within isochromatic zones for the particular type of colour deficiency for which the design is intended. (a) Small colour differences are employed in vanishing designs for the detection of red/green colour deficiency (A) and large colour differences are used to distinguish severe defects (B). (b) Dichromatic neutral colours (colours confused with grey, see section 3.4.3) are used to differentiate protan and deutan defects. The background consists of grey dots (☐) and the diagnostic colours are blue-green for protans (Δ) and green for deutans (▲) (from Birch, 2001).

In protan, deutan and tritan classification plates, neutral colours (see section 3.4.3), which are colours confused with grey by colour deficients, are used. The background consists of grey dots that vary in lightness and the figure is made up of dots that are average neutral colours for protan, deutan and tritan colour deficiency. A series of grading plates, such as in the American Optical Company (HRR) plates (section 6.3.2), can make use of desaturated neutral colours with ranked colour difference steps.

Pairs of colours within isochromatic zones only appear identical when no luminance contrast exists. Relative luminous efficiency (section 3.3) is different in protan and deutan defects so designs intended to identify both these deficiencies contain chroma and lightness (section 2.2) differences which give a range of luminance contrast values.

**Advantages:**

- Pseudoisochromatic plate tests provide a simple, readily available, inexpensive and easy to administer screener for (mostly) red/green deficiencies.
- No calibration is required by the user.
- The Ishihara (see section 6.3.1, Table 8) has excellent sensitivity and specificity (CIE 143, 2001). It is rare for a person with defective red/green colour vision not to be identified by it or (if the CIE recommended fail criteria are followed: 'three or more errors on the transformation and vanishing plates' (CIE 143, 2001)) for a person with normal colour vision to be wrongly diagnosed (Vingrys, 1984; Birch, 1997a; Dain et al., 1998).

**Disadvantages:**

- The accuracy of the results depends on the interpretation made by the examiner; for example, with some tests, eg Ishihara, it is possible for normal colour vision subjects to make 'misreadings' as opposed to mistakes (see section 6.3.1); the efficiency (ability to correctly differentiate between colour normals and colour deficients) of each plate is also different so they are not all equally good for screening.
- There is not an internationally agreed fail criteria for many of the tests.
- Plate tests tend to be relatively easy to learn, so encouraging cheating.
- The spectral quality of the light source illuminating the plates is critical; CIE Standard Illuminant D65, representing average daylight, (or CIE Standard Illuminant C which D65 supersedes) must be used when giving the test.
- The success of the plates depends on the selection of confusion colours, which may be difficult to print.
- Plates may be degraded by fingerprints, dust and excessive light exposure if not kept properly.

### 6.3.1 Ishihara pseudoisochromatic plates

The Ishihara plates are used as a screening test for red/green colour deficiency throughout the world and have been shown to be the most efficient for that purpose (Sloan and Habel, 1956; Belcher et al., 1958; Frey, 1958; Birch, 1997a). The test is not designed to identify tritan deficiency and so will not identify the blue/yellow deficiency which is usually predominant in acquired deficiency (see section 7); any red/green deficiency identified will not necessarily be able to be defined as congenital or acquired without further examination on other colour vision tests, from knowing the history of the examinee or identifying other symptoms accompanying acquired deficiency. The Ishihara test consists of single or double-digit numbers and pathways for tracing for those who cannot read numbers. There are three versions of the test:

38-plate test: plate 1 for demonstration, plates 2-21 for screening, plates 22-25 for protan/deutan classification and plates 26-38, pathways for testing illiterates;

24-plate test: plate 1 for demonstration, plates 2-15 for screening (used for screening by JAA Member States (see section 5.3.1)), plates 16-17 for protan/deutan classification and plates 18-24, pathways for testing illiterates;

16-plate test: plate 1 for demonstration, plates 2-9 for screening, plate 10 for protan/deutan classification and plates 11-16, pathways for testing illiterates;

Many of the most efficient plates are excluded from the two shorter tests (Birch and McKeever, 1993).

#### 6.3.1.1 Administration at City University

The first 25 plates are used of the 38-plate test (see Table 7). The instructions issued with the test are basically followed. The test is viewed at about two-thirds metre (arm's length) distance using a MacBeth easel lamp for illumination. The book is placed in the tray beneath the lamp and the illumination, equivalent to CIE Standard Illuminant C (representing average daylight), is incident at an angle of 45° to the plate surface. The examiner asks the person being tested to tell them what number they can see as the pages are turned, and warns that they may not see a number. The first introductory plate is used to demonstrate the visual task, as everyone should see this number. With a viewing time of about 4 seconds allowed for each plate, undue hesitation is a sign of slight colour deficiency.

| Plate number | | Plate type | Function | Intended design |
|---|---|---|---|---|
| 38-plate test | 24-plate test | | | |
| 1 | 1 | | Introduction | Seen correctly by all observers. Demonstrates the visual task. Identifies malingering. |
| 2-9 | 2-7 | Transformation | Screening | A number is seen by colour normals and a different number is seen by red/green colour deficient people. Sometimes colour- deficient people see no number. |
| 10-17 | 8-13 | Vanishing | Screening | A number is seen by colour normal people but cannot be seen by red/green colour deficient people. |
| 18-21 | 14-15 | Hidden digits | | A number cannot be seen by normals but can be seen by red/ green colour deficient people (N.B. These plates have poor sensitivity and specificity and should be omitted). |
| 22-25 | 16-17 | Classification<br><br>Only used when screening plates identify colour deficiency | Classification of protan and deutan deficiency | Protans only see the number on the right side of each plate and deutans only see the number on the left.<br>If colour deficiency is identified by screening plates and both numbers are seen, classification can be obtained from comparing the relative contrast of the paired numbers; interpretation is as if the less clear number cannot be seen.<br>People with severe red/green colour deficiency, especially protanopes, cannot see either classification number. |

**Table 7** Design and function of the 25 numerical designs of the 38-plate Ishihara test and the 17 numerical designs of the 24-plate Ishihara test (adapted from Birch, 2001).

As Hidden Digit designs tend to be seen by fewer than 50% of colour deficient people (Birch 1997a), only the 16 transformation and vanishing number plates tend to be used for screening. The sensitivity and specificity of these 16 plates is summarised in Table 8. The design of the numerals in these plates is such that normals sometimes 'fill in' the partial loops so giving a 'misreading' (Cole, 1963). For example, a '5' may be interpreted as '6', or '3' as '8'. These 'misreadings' are not included as errors or as failure of the plate. Only about 55% of normals obtain a perfect result (Birch and McKeever, 1993). The number of errors made is not a useful guide to the severity of a colour vision defect (CIE 143, 2001) except that it has been found that only colour normals and a few mild anomalous trichromats make less than about 10 mistakes or misreadings on the Ishihara plates (Birch, 1997a; Birch and McKeever, 1993; Cole, 1963; Hovis and Oliphant, 1998) (see Table 9).

The instructions issued with the 38-plate test (Ishihara, 1978) state that *'if 17 or more [of plates 1-21] plates are read normally, the colour vision is regarded as normal. If only 13 or less than 13 plates are read normally, the colour vision is regarded as deficient.'* The fail criterion suggested by the CIE is 'three or more errors on the transformation and vanishing plates' (CIE 143, 2001; Birch, 1997a).

The instructions issued with the 24-plate test (Ishihara, 1989) state that *'if 13 or more [of plates 1-15] plates are read normally, the colour vision is regarded as normal. If only 9 or less than 9 plates are read normally, the colour vision is regarded as deficient.'* The pass criterion of this 24-plate test for JAA (section 5.3) is to correctly read every plate. However, there is a further test, if the Ishihara plates are failed, of either a lantern test (section 6.5) or the Nagel anomaloscope (section 6.6.1). The JAA colour vision test is only failed if one of these two tests is failed in addition to the Ishihara plates.

| Number of misreadings by normals | Specificity (%) | Screening efficiency (overall predictive value) | Sensitivity (%) | Number of errors by red/green colour-deficient people |
|---|---|---|---|---|
| 8 | 100 | 90.2 | 80.5 | 8 |
| 6 | 95.4 | 94.7 | 94.0 | 6 |
| 3 | 94.1 | 96.4 | 98.7 | 3 |

**Table 8** Specificity (the percentage of normal subjects correctly identified as such), screening efficiency, and sensitivity (the percentage of colour deficient subjects correctly identified as such) of the 16 Transformation and Vanishing plates of the 38 Plate Ishihara test for 471 normal subjects and 401 colour deficient subjects identified with the Nagel anomaloscope. (Birch, 1997a).

| Number of misreadings or number of errors | Number of normal subjects making certain no. of misreadings | Number of all colour-deficient subjects making certain no. of errors | Number of people with different types of red/green colour deficiency making certain no. of errors | | | |
|---|---|---|---|---|---|---|
| | | | P | PA | D | DA |
| 16 | | 187 | 67 | 14 | 56 | 5 |
| 15 | | 89 | 15 | 7 | 23 | 44 |
| 14 | | 42 | 1 | 2 | 14 | 25 |
| 13 | | 19 | | | 12 | 17 |
| 12 | | 17 | | 3 | 1 | 13 |
| 11 | | 6 | | | | 6 |
| 10 | | 9 | | 1 | | 8 |
| 9 | | 5 | | 1 | | 4 |
| 8 | | 9 | | 1 | | 8 |
| 7 | | 5 | | 1 | | 4 |
| 6 | 1 | 3 | | | | 3 |
| 5 | 2 | 2 | | | | 2 |
| 4 | 6 | 3 | | | | 3 |
| 3 | 21 | 1 | | | | 1 |
| 2 | 41 | 2 | | | | 2 |
| 1 | 141 | 2 | | | | 2 |
| 0 | 259 | | | | | |
| **Total number of subjects** | 471 | 401 | 83 | 30 | 96 | 192 |

Key: P= protanopia; PA= protanomalous trichromatism; D= deuteranopia; DA= deuteranomalous trichromatism

**Table 9** Number of misreadings made by 471 normal subjects and number of errors made by 401 red/green colour-deficient subjects on 16 Transformation and Vanishing plates of the 38-plate Ishihara test. Subjects identified and diagnosed with the Nagel anomaloscope (Birch, 1997a; from Birch, 2001).

### 6.3.2 The American Optical (HRR) plates (second edition)

The American Optical Company (Hardy, Rand and Rittler) (AO HRR) (second edition) plates are not particularly good for screening but are intended to identify protan, deutan and tritan defects and to grade their severity. Twenty-four plates are used. These have vanishing designs containing geometric shapes (circle, cross and triangle) that are printed in neutral colours (section 3.4.3) on a background matrix of grey dots. The saturation of the neutral colours increases in successive plates to produce designs with progressively larger colour difference steps (Hardy et al., 1954) so identifying different levels of deficiency. This test can be used complementary to the Ishihara plates.

This second edition of the AO HRR test is no longer available and the third edition, the Richmond HRR test, is not recommended for clinical use as the colour design is unsatisfactory (Birch, 2001).

### 6.3.3 JAR Manual comments

*'The most readily available tests for screening are the pseudo-isochromatic plates. Most of them are made only for detection of red-green deficiencies; some series have plates which enable a classification and graduation of severity. The different series perform the screening task more or less well; among well-known series are those of*

*Ishihara, Dvorine, Stilling-Velhagen, and Bostrom-Kugelberg. These tests effectively separate normal from colour defectives. There are, however, subjects who fail only a few plates and in these cases a definite diagnosis is only possible with the aid of an anomaloscope.*

*There is a weak correlation between the number of failed charts and the severity of the defect; dichromats usually fail more plates than do anomalous trichromats. The classification of protans and deutans is not always possible with the charts. The American Optical Hardy-Rand-Rittler plates are especially designed for qualitative and quantitative diagnosis. These tasks are better fulfilled with this series than with any other plates. Unfortunately, this test, which is also excellent for testing acquired defects, is no longer available.*

*Testing with pseudo-isochromatic plates should be performed according to the instructions given by each test. It is important that the quality of the illumination is correct: either northern daylight or an artificial daylight source should be used. Ordinary incandescent lamps or fluorescent tubes make these tests easier to pass, especially to deuteranomals. The daylight source should give an illumination equivalent to the standard illuminants 'C' or 'D' of CIE (Commission Internationale de l'Eclairage). The plates should be shown at right angles to the visual axis of the applicant, at the correct distance and for the time specified in the test. The applicant should not wear tinted glasses. The number of failed plates serves to classify the subject as normal, defective or 'doubtful' according to the specifications of the test.' (JAR-FCL 3 Section 2, 2000)*

## 6.4 Hue discrimination tests

Hue discrimination tests (Birch, 2001) were originally designed to identify people, with significant colour deficiency who are likely to experience practical difficulties in specific occupations (Farnsworth, 1947). They consist of colour samples, usually placed in the top of small cylindrical caps, which the subject arranges in a natural order according to hue, lightness and saturation. Caps can be moved freely during the test and are numbered on the back to record the resultant order. CIE Illuminant $D_{65}$, representing average daylight, (or CIE Standard Illuminant C which $D_{65}$ supersedes) must be used for these tests.

**Advantages:**

- Tests are easy and quick to administer.
- They are readily available and relatively inexpensive.

**Disadvantages:**

- Fingerprints may damage pigments so the colours must not be touched.
- The spectral quality of the light source illuminating the plates is critical.
- On retesting for the Farnsworth Munsell 100 hue test scores can be improved after training or from familiarity.

### 6.4.1 The Farnsworth D15 test

The Farnsworth D15 test (Farnsworth, 1943, 1947) is one of the most widely used hue discrimination tests. It will identify moderate and severe protans, deutans and tritans. The test is based on colour confusion: protans confuse certain reds and greens; deutans confuse other reds and greens. It consists of 15 moveable matt colour samples, selected from an incomplete hue circle (Figure 24), placed in a box with one fixed colour sample. The colour samples are held in circular caps that subtend 1.5° at a test distance of 0.5 m. The colours range from blue through blue-green, yellow-green, yellow, orange and red to red-purple. The moveable caps are numbered on the backs according to the ideal colour circle. The level of difficulty of the test is such that a person who fails the test will have difficulty distinguishing surface colour codes (CIE 143, 2001). Protans are more likely to do better in this test than deutans as they can use luminance cues more effectively due to their reduced luminance sensitivity for reds.

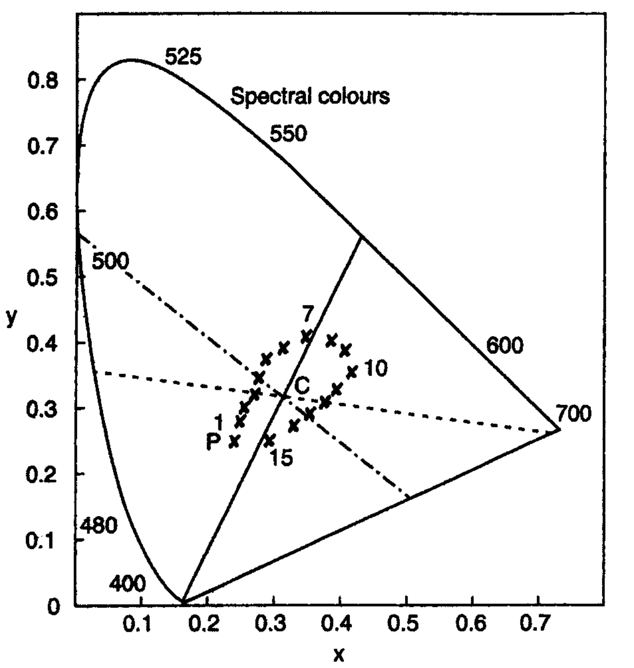



**Figure 24** Chromaticity coordinates of the samples used in the Farnsworth D15 test. The 16 Munsell (a colour reference system) samples of the test represent a circle of equal value and chroma. Colours from opposite sides of the circle, which have coordinates within isochromatic zones, have similar colour appearance to colour deficient observers and may be mingled in the arrangement of colours (from Birch, 2001).

#### 6.4.1.1 **Administration at City University**

For the test, all the colour caps, except the reference colour, are removed from the box and mingled on the table in front of the subject. The caps are illuminated using a MacBeth easel lamp, the equivalent of CIE Standard Illuminant C (representing average daylight). The subject is then asked to put the caps back in the box in what they perceive to be a natural colour order, starting from the one fixed reference cap, so having to find the coloured cap that looks most like the colour of the cap already in the box and put it next to it. They then carry on from there finding the colour nearest to the last one placed in the box until the last cap is used. They are asked to look again at the finished order, when all the caps are in the box, to see if they want to make any changes. It is informative for the examiner to note the mistakes corrected and also the speed and care taken by the subject during the test.

After the final review of the order by the subject, the examiner records the number order on the back of the caps. The results are then transferred to the results diagram (Figure 25). A line is drawn joining the cap numbers as arranged by the subject. As all the colours are presented at the same time, isochromatic colour confusions are demonstrated when colours from opposite sides of the hue circle are mingled in the subject's arrangement. The record sheet provides an aid to interpretation by illustrating the direction of lines representing typical isochromatic confusions in protan, deutan and tritan colour deficiency (Figure 25).

One transportation of adjacent colours indicates a minor error or 'normal' confusion. Caps that are placed on the wrong side of the hue circle are considered a major error. People with normal colour vision and slight colour deficiency pass, and typical results are obtained in moderate/severe protan, deutan and tritan deficiency. The number of isochromatic confusions made is used to identify the two grades of deficiency, moderate and severe (Figure 25).

This test is sometimes used in aviation instead of a lantern test, for example by Canada, after a screening test is failed. The fail criterion in Canada (and recommended by the CIE, (CIE 143, 2001)) is two or more major (diametrical) crossings across the colour circle (see Figure 25).

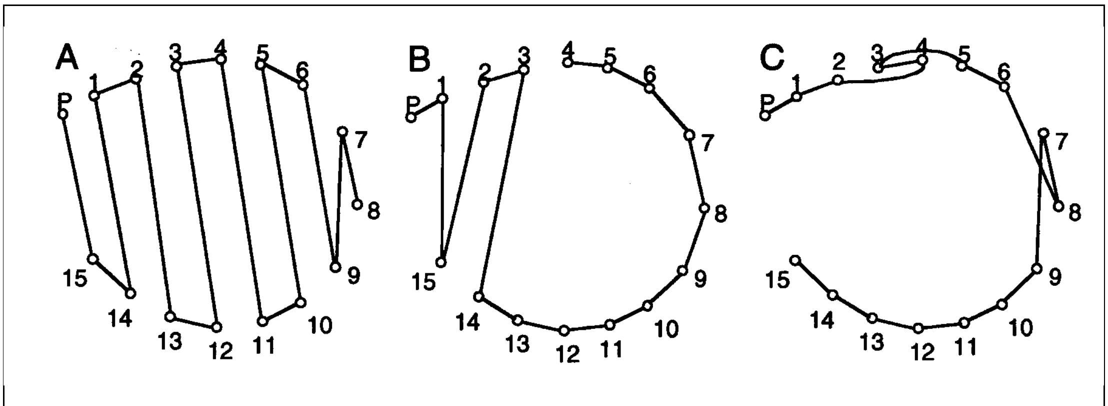



**Figure 25** Plots of Farnsworth D15 test results. The order of the 15 moveable colours made by the subject is drawn on a circular plot. A The typical arrangement of colours made by a protanope. This is a clear fail result because there are many more than two diametrical crossings. B An arrangement made by a deuteranomalous subject. There are three diametrical crossings, which is also a fail. C Minor transportation errors made by a mild deuteranomal. There are no diametrical crossings so this is a pass result (from CIE 143, 2001).

### 6.4.2 The City University (CU) test (second edition)

This test is designed to identify moderate to severe defects and is derived from the Farnsworth D15. It displays a small selection of colours of the same hues as the D15 (along with grey) on ten pages in a book. Each plate contains five coloured circles - a central circular colour surrounded by four comparison colours, in the shape of a cross. Three of the four comparison colours are typical isochromatic confusions for protan, deutan and tritan. The fourth colour is an adjacent colour in the D15 sequence and is the intended normal preference. The task is to identify which of the four comparison circles is most similar in colour to the central one. The CU test is not intended for screening.

The second edition of the CU test is no longer available and the third edition is unsatisfactory as it has completely new designs and different aims (Birch, 2001). This uses untried designs intended for screening.

A similar percentage of colour deficient people fail the CU test second edition as fail the Farnsworth D15, but there is not 100 percent agreement; the number that fail both tests varies from only 60 percent (Birch, 1997c) to 93 percent (Oliphant and Hovis, 1998) depending on the fail criteria used for both tests. More deutans fail the CU test and more protans fail the D15. Table 10 shows the combined use of the Ishihara plates, the Farnsworth D15 test and the City University test (second edition).

| Ishihara plates | Farnsworth D15 test (fail >1 minor transportation) | City University test (2nd edition) | Severity of red/green colour deficiency |
|---|---|---|---|
| Fail† | Pass | Pass | Slight |
| Fail† | Fail with two errors or incomplete errors | Fail with four* errors or less | Moderate |
| Fail† | Fail with complete errors | Fail with five* errors or more | Severe |

† A fail is a minimum of 3 errors on the 16 transformation and vanishing plates of the 38-plate test and 2 errors on the 12 transformation and vanishing plates of the 24-plate test.

* Effective for deutans but not protans

**Table 10** Combined use of the Ishihara plates, the Farnsworth D15 test and the City University test (second edition). (from Birch, 2001).

### 6.4.3 Farnsworth-Munsell 100 hue test

The Farnsworth-Munsell 100 hue test (F-M 100 hue test) (Farnsworth, 1943, 1947) is one of the most widely used hue discrimination tests. It is not reliable for screening and only people with moderate or severe colour deficiency are identified (Birch, 1989). It consists of four boxes of caps that are used one box at a time. The colours form a complete hue circle from a special series of colour samples.

The task is to put the colours back in each box in what is perceived to be a natural colour order, starting either from a single reference point or arranging the colours between two reference caps. There are no confusion colours from opposite sides of the hue circle in a box and therefore the purpose of the test is to measure hue discrimination ability at constant value and chroma. An error score can be calculated and this demonstrates the subject's ability to make careful observations. There are less than three colour difference steps between adjacent hues, making the test difficult for normal trichromats to complete without error.

### 6.4.4 JAR Manual comments

*'In the assortment tests [e.g. Farnsworth D15 and Farnsworth-Munsell 100 hue test and other similarly designed tests], the subject is asked to arrange a number of coloured chips or to separate them into coloured or neutrally tinted. Of these tests, the Farnsworth Panel D-15 effectively parts subjects with minor defects from those with more severe defects. The test is easily performed and evaluated and, when failed, gives a qualitative diagnosis. It may be used as a valuable adjunct to other tests.'* (JAR-FCL 3 Section 2, 2000)

## 6.5 Lantern tests and the aviation signal light test

Colour vision lanterns (Birch, 2001) are vocational tests that employ colour naming, which is not an ideal method for identifying colour deficiency. There is a 50 per cent chance, if someone has a difficulty distinguishing red and green, that the first colour name is correct and even people with normal colour vision can incorrectly name a colour. To demonstrate reliable identification, therefore, the two colours need to be shown several times and with different intensities. Some lanterns display single colours and others show colours in pairs. The aim is to determine if signal lights (as defined by CIE, 1975) can be identified correctly. The Holmes-Wright A and B lanterns, the Beyne lantern, the Farnsworth lantern, and the Optec 900 lantern (update of the Farnsworth) are currently approved by the CIE (CIE 143, 2001) (see Table 11). The Holmes-Wright A, the Beyne and the Spectrolux lanterns are currently recommended by JAR.

| Lantern | Test distance (m) | Colours of lights | Number of apertures | Aperture sizes (minutes of arc) | Stimulus duration (seconds) | Room lighting condition |
|---|---|---|---|---|---|---|
| Farnsworth (FALANT) | 2.4 | R,G,W* | 2, vertically separated | 2.9 | 2 | Light |
| Holmes-Wright Type A | 6 | R,G,W* | 2, vertically separated | 0.9 | Max. 4 (manual) | normal / dark |
| Beyne | 5 | R,G,W, Y/O,B* | 1 or | 6 sizes from 1.0 to 6.0 | Several settings: 1/500 to 1 | dim |
| | | R,G,W* | 2, vertically separated | | | |
| Spectrolux | 2.5 | R,G,W* | 2, vertically separated | 4.8 | 3 | light |

R=red, G=green, W=white, Y/O=yellow-orange, B=blue

**Table 11** Details of lantern tests (adapted from CIE 143, 2001).

The lighting conditions for each individual lantern varies, with some being used in the equivalent to normal daylight (photopic viewing), some in dim room light and, for the Holmes-Wright, testing is carried out in the light and then, if necessary, in the dark after a period of dark adaptation (scotopic viewing). Lanterns may have several intensity levels and aperture sizes to represent signal lights (CIE, 1975 and 2001; ICAO ISRP Annex 14, 1999; ICAO Airworthiness Manual Vol II, 2001) at different distances. Some lanterns (e.g. Farnsworth, Spectrolux and Beyne) have introduced speed of exposure as part of the examination by having a programmed exposure time.

A lantern test is used to determine if a person has adequate colour discrimination for a visual task that is of fundamental importance for safety and efficient operation. It is implicitly assumed that some colour deficient people are 'safe' and will pass. However, it has not been scientifically shown which colour deficient people are safe, or not, to carry out the necessary tasks, and also people with the same type and severity of deficiency do not always pass or always fail. Pass/fail criteria based on the number of errors, or on the type of colour naming error, have been found in trials to allow some people with slight/moderate colour deficiency to pass (Birch, 1999; Birch and Dain, 1999). It is not possible to predict who will pass lantern tests from the results of other tests (Mertens and Milburn, 1993; Cole and Maddocks, 1998), although most dichromats do fail. It is thought that some people must guess more effectively than others in lantern tests (Birch, 2001). Protans tend to make fewer errors with reds than deutans because brightness differences can still be perceived.

**Advantages:**

- Lantern tests are specifically designed to test if signal lights (CIE, 1975 and 2001; ICAO ISRP Annex 14, 1999; ICAO Airworthiness Manual Vol II, 2001) used in specific occupations, e.g. aviation, will be seen properly.
- Tests are usually easy and quick to administer.

**Disadvantages:**

- Lantern tests are not so relevant for professional aviation now as signal lights have become less important, mainly due to the increased use of radio contact with air traffic controllers and improved methods of separating aircraft in flight, which do not rely on visual cues.
- Other cues apart from colour vision may be involved for these tests, such as luminance level, and contrast to surround (particularly for the aviation signal light test (section 6.5.5) as this is external so not in a controlled condition). This helps some subjects pass whilst others with the same type and severity of deficiency may fail.
- Although the lanterns are designed to test if signal lights (CIE, 1975 and 2001; ICAO ISRP Annex 14, 1999; ICAO Airworthiness Manual Vol II, 2001) will be seen by the subject, there are several different designs of lantern which all use slightly different colours and other criteria such as effective size of light and luminance.
- Different lanterns also specify different testing conditions, such as ambient lighting, time lights viewed for, time to respond and how many lights viewed at the same time.
- Some of the lanterns have strict testing protocol, such as how many times the different coloured lights, or combinations of lights are shown and the fail criteria. However, others do not have a strict protocol so could be used in a different way by different examiners, if not within the same organisation or country, then internationally.
- The variations between lanterns demonstrate that different criteria are being assessed with different lanterns and even with the same lantern.
- The bulbs and filters can deteriorate with age and so change the results.
- Some subjects are better at guessing than others in lantern tests, especially those with a protan defect who see reds as darker than other colours so will tend to call what they perceive as dark colours red.

### 6.5.1 The Holmes-Wright Type A lantern (UK)

The Holmes-Wright Type A lantern (Holmes and Wright, 1982) shows vertically separated pairs of colours (Figure 26). Two reds, two greens and a white are used (Figure 27), and these have x,y chromaticity co-ordinates within the internationally agreed specifications for signal lights (ICAO ISRP Annex 14, 1999; CIE 02.2, 1975). Nine pairs of the colours are shown representing all the possible colour combinations. The lanterns are viewed at 6 m (20 ft).

Several surveys have been carried out to estimate the percentage of colour deficients that would fail this test. The results vary from 77% (Vingrys and Cole, 1983; Vingrys, 1984) to 94% (Hovis and Oliphant, 1998) and 97% (Birch, 1999). However, all of these percentages vary as different test conditions were implemented, different pass/fail criteria used and also a different distribution of colour defective (especially anomalous) subjects were tested, so weighting each set of results differently.

The most frequent qualitative errors in all types of colour deficiency are misnaming green as 'white' and white as 'green'. Only 40 per cent of dichromats and 25 percent of anomalous trichromats make red/green naming errors (Birch, 1999).

**Figure 26** Holmes-Wright A lantern.

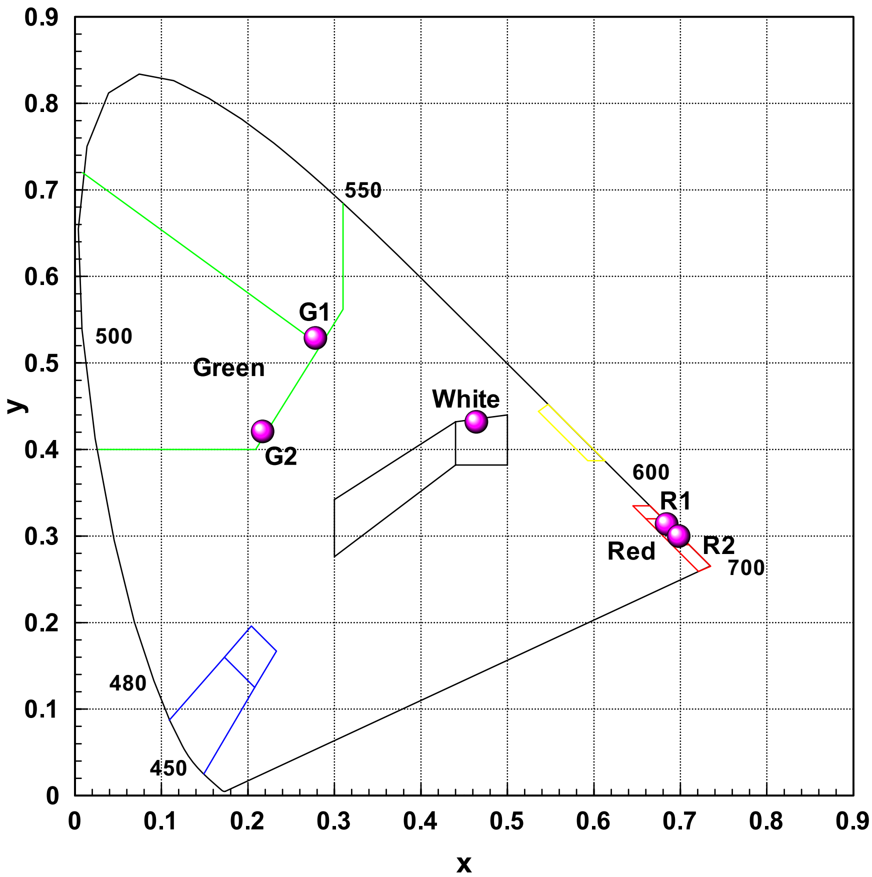



**Figure 27** Chromaticities of the Holmes-Wright lantern lights plotted on a CIE 1931 x,y chromaticity diagram showing the boundaries for the allowed chromaticity areas for the colours of light signals (CIE Standard, 2001).

#### 6.5.1.1 **Administration at City University**

Before beginning the test, the examiner demonstrates the colours by showing one red, one green and one white light in the top positions of the first three pairs and naming them correctly; the luminance is set to 'DEM' (demonstration mode with higher luminance) for this. The subject is not told that there are different reds and greens and does not need to distinguish between them. This is so that the colour naming is not too complicated, but the ability to name different types of these colours is still tested. The examination is then carried out, starting in fairly dim room illumination, with colours at high luminance ('HIGH' setting). The nine pairs of colours are shown three times, for about four seconds each presentation; the time of exposure is completely controlled by the examiner. The subject is told to name the top and then the lower colour shown each time. The room is then darkened and the subject is dark adapted for about fifteen minutes; the test is repeated with the three sequences of nine colour pairs again, at the same luminance level. The examiner notes each misnaming of a colour.

The results are sorted into number of types of misnaming in each light level, e.g. 3 greens called 'white', 2 whites called 'green', etc. The two different greens and two different reds do not need to be distinguished between for simple pass/fail testing, but can be to analyse the data further if needed.

The UK CAA administration practice is set out in section 5.3.2. This consists of one run of the nine pairs in the light and with the luminance set at 'HIGH'. If no mistakes are made then the test is passed, otherwise two more runs are carried out. If any mistakes are made in these two runs then the subject is dark adapted for 15 minutes and a final one run carried out in the dark. If any mistakes are made in this run then the subject fails. If, at any point, the subject calls red 'green', or green 'red', then this is an automatic failure and the test is over.

### 6.5.2 **The Farnsworth lantern (Falant)**

The Farnsworth lantern differs from the Holmes-Wright in that the colours it displays (desaturated red, yellow-green, and yellowish-white) are selected to be within common isochromatic zones for both protan and deutan colour deficiency. These colours do not conform with the agreed specifications for transport signals. The effective aperture size of the lights is also much larger. The test is carried out at a test distance of 8 feet (2.4 metres) in a normally lit room. The examination procedure, however, is similar to that of the Holmes-Wright. An error score determines the pass/fail level. For initial assessment, a single showing of the nine colour pairs is recommended, with a second and third repeat of the sequence only if mistakes are made. The error score is the average number of mistakes on the second and third runs. A fail is the score of 1.5 (3 errors on 2 runs) or more. An error naming one or both colours in the pair is counted as a single error. In a study by Birch and Dain (1999) all dichromats and 75 per cent of anomalous trichromats failed the Farnsworth lantern. Error scores were continuous and there was no clear demarcation between pass and fail. The type and severity of red/green colour deficiency were not distinguished by either the error score or the number of qualitative error categories. It is not possible to identify anomalous trichromats likely to pass the Farnsworth lantern from anomaloscope or Farnsworth D15 results (Mertens and Milburn, 1993; Cole and Maddocks, 1998).

### 6.5.3 **The Beyne lantern**

The Tritest L3 (previously called Beyne lantern Type 2) was developed for aviation. It shows single (Figure 28) and paired colours derived from narrow wavelength bands in the blue, green, yellow-orange and red parts of the spectrum with a white light as well (Figure 29). The test distance is 5 metres. There are six apertures for single lights, one for paired, and nine shutter speeds to vary the exposure time. The CIE report on colour vision requirements for transport (CIE 143, 2001) points out that ' this diversity of testing conditions means that there is no standard test condition and no clearly defined fail criterion'.

The report carries on to state that: *'Rui (Rui, 1956) found that subjects with normal colour vision made no errors recognising the red, green and white colours, provided the duration of the stimulus was greater than 66 ms. He found that 60% of colour vision defectives fail when one error is allowed and no person with normal colour vision fails with this fail criterion. He recommends use of the red, green and white colours, the 1' aperture and a duration of 1 s [report produced for marine purposes]. Perdriel and Chevaleraud (Perdriel and Chevaleraud, 1972) also provide validation data for this lantern test.'*


**Figure 28** Beyne lantern.

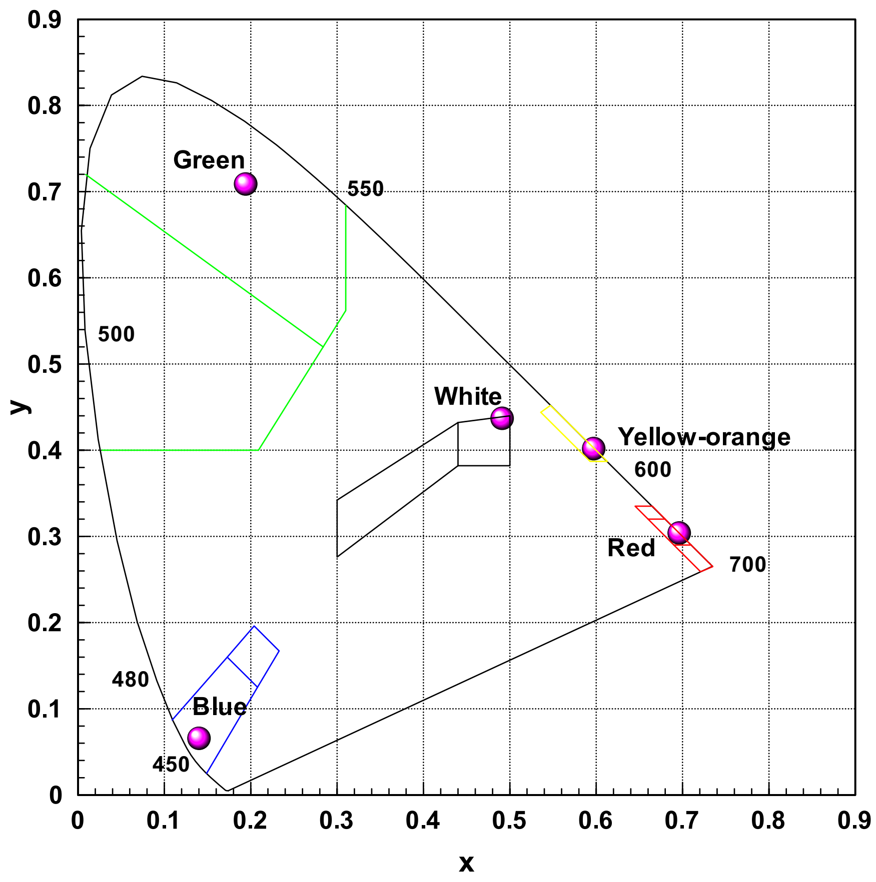



**Figure 29** Chromaticities of the Beyne lantern lights plotted on a CIE 1931 x,y chromaticity diagram showing the boundaries for the allowed chromaticity areas for the colours of light signals (CIE Standard, 2001).

### 6.5.3.1 Administration at City University

Three different testing conditions are used at City University, which are the conditions used in France for civil pilots, ATCOs (Air Traffic Control Officers) and military (see Table 12). Three runs for each condition are carried out, though only one run is carried out in France. Before beginning the test, the examiner lists what the colours are but does not demonstrate them to the subject. The subject has to name what colour they see when each light is shown. For the paired lights the subject states the top colour first and then the lower one. At City University it has been found that, as the colours are not demonstrated before the test, some subjects with normal colour vision call the white light 'yellow-orange', as this is shown first in the sequence. They sometimes correct this in the second run once the white has been seen, but to pass this test all colours have to be named correctly in the first (and only run in France) run, so this would be counted as a fail. For the civil pilot condition (see Table 12) about 30% of the 26 normal subjects in this study called the white light 'yellow-orange' in the first run, and about 46% of the 26 normals made one or more mistakes in the first run, so would have failed if not diagnosed as having normal colour vision with other tests. The UK CAA use this lantern, with the civil pilot conditions and just one run, in addition to the Holmes-Wright lantern. No normals failed on the Holmes-Wright lantern in the City University study.

| Test | Colours | Single/Paired lights | Aperture size | Exposure time |
|---|---|---|---|---|
| Civil pilot | W, G, R, B, Y/O | Single | 3' arc | 1 sec. |
| ATCO | W, G, R | Vertical pair | Double aperture | 1 sec. |
| Military | W, G, R, B, Y/O | Single | 2' arc | 1/25 sec. |

**Table 12** Tests carried out on the Tritest L3 (Beyne) lantern at City University. Three runs are carried out for each test. The aviation pass standard is no mistakes in the first run. (W=white, G=green, R=red, B=blue, Y/O=yellow-orange).

### 6.5.4 The Spectrolux lantern

The Spectrolux lantern was developed for aviation in 1985 as an improvement on the Farnsworth lantern. It shows pairs of colours separated vertically (Figure 30). Two reds, two greens and two whites (Figure 31), which have x,y chromaticity co-ordinates within the limits agreed for aeronautical ground lights (ICAO ISRP Annex 14, 1999; CIE 02.2, 1975), are used. Twelve pairs of the colours are shown in different colour combinations. The lantern is viewed at 2.5 m.

**Figure 30** Spectrolux lantern.

#### 6.5.4.1 Administration at City University

The 3.5 mm aperture is used with a 3 second shutter opening time. The test is carried out in a light room. The subject is not demonstrated the colours before the test but is told that there are three different colours, red, green and white, of different intensities, which will be shown in vertically aligned pairs. As for the Holmes-Wright lantern, the subject is not told that there are different reds, greens and whites and does not need to distinguish between them. This is so that the colour naming is not too complicated, but the ability to name different types of these colours is still tested. They are told they will see each pair for three seconds and must say what colours they see, naming the top colour first. The pass standard is no mistakes.

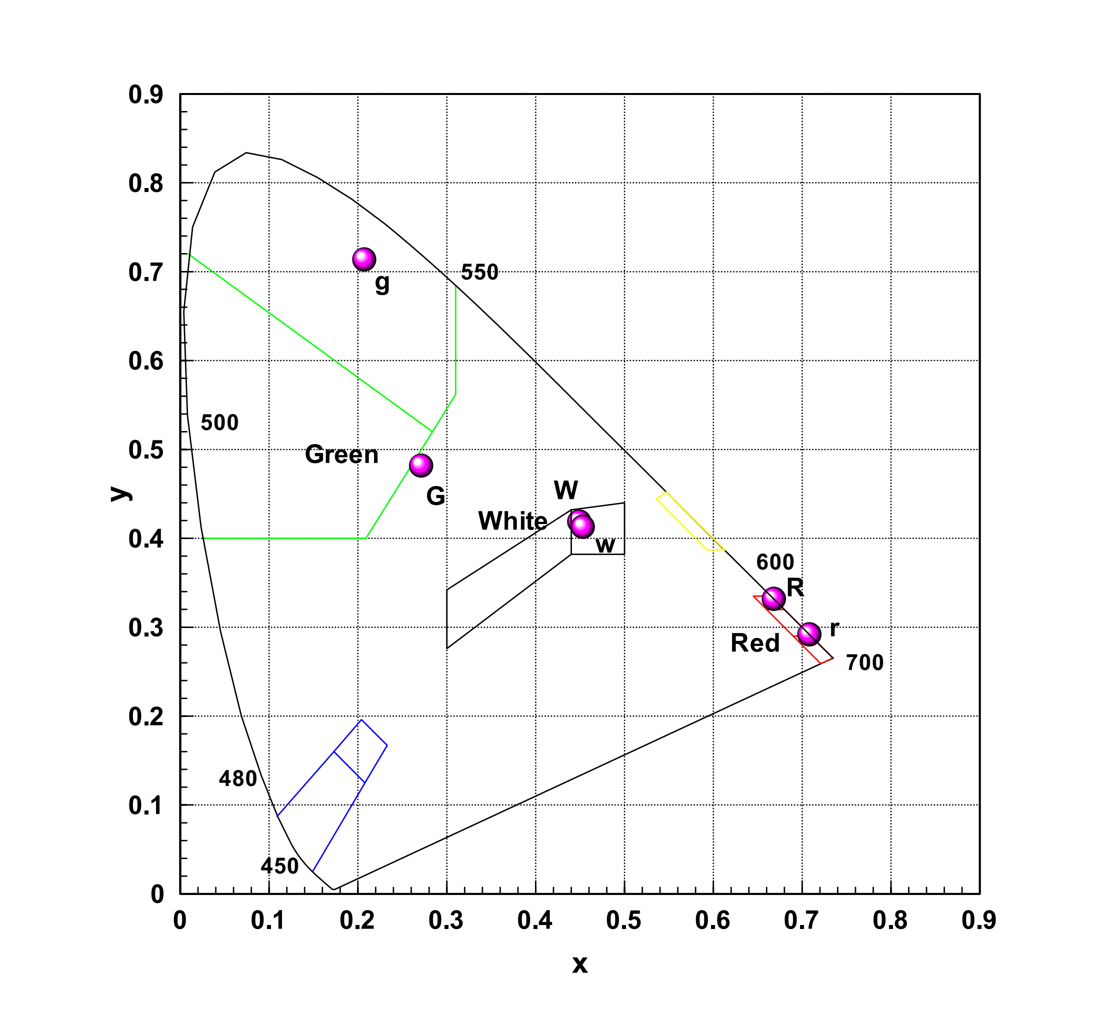



**Figure 31** Chromaticities of the Spectrolux lantern lights plotted on a CIE 1931 x,y chromaticity diagram showing the boundaries for the allowed chromaticity areas for the colours of light signals (CIE Standard, 2001).

### 6.5.5 Aviation Signal Light (ASL) Test

The Aviation Signal Light test (Mertens and Milburn, 1993) is a practical test to demonstrate ability to correctly identify the aviation signal colours. It differs from lantern tests as it tends to be performed at an airport and involves the identification of actual ASL signals shown from the air traffic control tower, rather than being carried out in the controlled environment of an examination room that lantern tests are carried out in. The test is used in the USA and is given first during daylight as reduced signal/background contrast makes it a more difficult observing condition than night time (Steen and Lewis, 1972; Steen et al., 1974). The test is carried out (Federal Aviation Administration (FAA), 2000) at 1000 and 1500 feet and the observer has to identify the colour of light that he sees, red, green or white. This is used by the FAA as a final test to see if any restrictions that have been put on a pilot's licence due to failing other colour vision tests may be waived. If the observer passes the day ASL test, calling all the colours correctly, then all restrictions related to colour vision are removed. The observer may request an ASL test at night if the day test is failed. The restriction from flight at night is removed if the night test is passed, but the pilot is still restricted from flight under colour signal control (i.e. flight without a working radio into a controlled airport where the tower would use colour-coded signals from the ASL to direct the aircraft) in daytime.

| | | Normal | Anomalous trichromats | | | | Dichromats | |
|---|---|---|---|---|---|---|---|---|
| | | | Simple | | Extreme | | | |
| | | | Protan | Deutan | Protan | Deutan | Protan | Deutan |
| Daytime | Pass | 119 | 3 | 15 | 2 | 6 | 0 | 7 |
| | Fail | 1 | 5 | 8 | 16 | 19 | 18 | 23 |
| Night time | Pass | 117 | 4 | 17 | 6 | 18 | 7 | 15 |
| | Fail | 0 | 3 | 5 | 12 | 7 | 10 | 15 |

**Table 13** Number of subjects passing or failing the ASL test in daytime and night time as a function of anomaloscope classification under chromatic adaptation (see section 6.6.1). Classification followed that given in the National Research Council-National Academy of Science (NRC-NAS) Committee on Vision (1981), where extreme anomalous trichromats accept a wide range of red-green ratios, usually including the ratio accepted by normal trichromats and perhaps either pure red or pure green, and all other anomalous trichromats (as explained in section 6.6.1.1) are described as simple (Mertens and Milburn, 1993).

### 6.5.6 JAR Manual comments

*'The lantern tests are produced to test the ability to identify the hue of signal colours; they are meant to simulate the practical situation. There are a number of different lantern tests. In some of them, fixed red, white and green stimuli are presented. In others, there are extensive possibilities to vary the hue and saturation of the stimuli as well as the aperture size and presentation time. The possible advantage of being able to vary the stimuli is counteracted by the lack of knowledge of what these differences signify. Well known lantern tests are those of Edridge-Green. Giles-Archer, Beyne, Farnsworth, and Holmes-Wright. At present, however, only the lanterns of Holmes- Wright and of Beyne have been approved for assessing colour deficient pilots as to whether they can be considered colour safe or not.*

*The correlation between lanterns and practical colour recognition is weak and has never been properly examined. It is not established how the performance on these lantern tests is related to the 'ready perception of colours necessary for safe duty performance'. Without this knowledge, it is safest to follow the norms given for each test.*

*The Holmes-Wright lantern has an aperture size of 1.6 mm, corresponding to a visual angle of 0.9 minutes of arc. The light intensity is 2 000 m-candelas for demonstration, 200 m-candelas for daylight testing and 20 m_-candelas for testing in complete darkness. [The latter not used by City University or by the UK CAA.] The lantern is easy to use. The examinee is placed in front of the lantern at a distance of 6 metres. Five different colours are presented: two red, two green, and one white light stimulus in nine different combinations, each presenting two colours (which may be identical in some of the presentations). The 2 x 9 fixed stimuli are presented for two to three seconds each and the examinee must identify the colour of each without delay. If all colours are correctly identified, the lantern test has been passed. If the examinee makes two or more errors, the lantern test has not been passed and the examinee is classified as colour unsafe. If the examinee makes one mistake or shows uncertainty during the test run, the lantern test is re-performed by executing two consecutive* *runs of the nine presentations. No errors or mistakes are allowed during this second run.*

*The Beyne's lantern (lanterne chromoptometrique de Beyne) presents the colours green, red, blue, white, and yellow-orange with an aperture size corresponding to a visual angle of 3 minutes of arc. Each colour is shown for one second. The examinee is placed in front of the lantern at a distance of 5 metres. No errors are accepted.'* (JAR-FCL 3 Section 2, 2000)

## 6.6 Anomaloscopes

A spectral anomaloscope (Birch, 2001) is a psychophysical test that presents a diagnostic colour match and is the standard reference test for identifying and diagnosing red/green colour deficiency. The efficiency of other red/green colour vision tests is often compared with the results obtained on the anomaloscope.

Most anomaloscopes provide a Rayleigh match: red added to green to match yellow (See sections 2.4.4 and 3.4.4). A circular split field is viewed, with the red/green field in the top half and the yellow field below. Accurate calibration is required and the observation parameters must be carefully controlled. The subject is able to alter the percentage mixture of red to green in the top field, and the luminance of the lower yellow field until the top and bottom of the field look like the same colour to them. This 'match' determines whether a person has normal or defective red/green colour vision; whether colour deficiency is deutan or protan, and whether the subject is a dichromat or anomalous trichromat, and the severity of the latter (see section 3.4.4). Though several different wavelengths can be used successfully for the fields in a Rayleigh match, the most reliable results are obtained if the matching wavelengths are widely separated on the straight line of the CIE spectral locus (section 2.3.2, Figure 8). To provide ease of calibration, emission lines are chosen for the test wavelengths.

Before it can be used, the normal matching range has to be established for each instrument by examining a large number of normal subjects. Normal trichromats make a precise colour match within a small range of red/green mixture ratios. This means that mixture ratios obtained on different instruments cannot always be compared objectively.

### 6.6.1 Nagel anomaloscope

The Nagel Anomaloscope is a Maxwellian view instrument which projects an image of a circular split field onto the retina by first focusing the light into a small portion of the eye's pupil (Figure 32). The top half of this circle is illuminated by a mixture of monochromatic red and green wavelengths (670 and 546 nm) and the lower half illuminated by monochromatic yellow (589 nm). The luminance of the mixture field is kept constant for any red/green mixture ratio. Two control wheels are used, one to alter the red/green colour mixture ratio of the top field, and the other to alter the luminance of the yellow lower field. This instrument is widely used but is currently out of production. However, other similar instruments are available such as the Neitz anomaloscope.

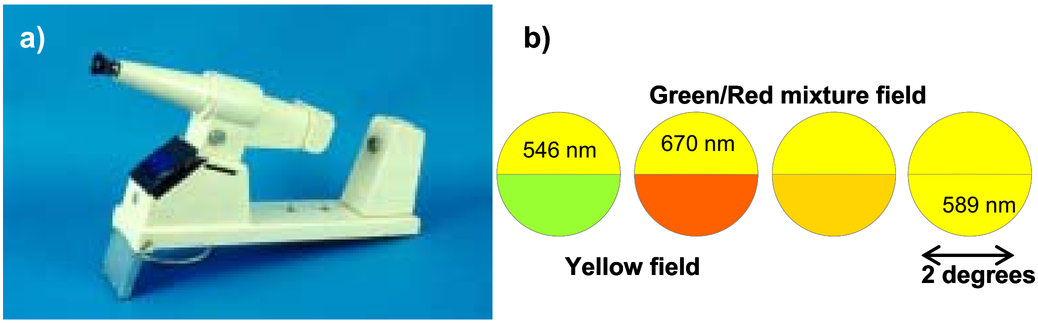



**Figure 32** a) Photograph of the Nagel anomaloscope; and
b) illustration of the Nagel anomaloscope split field.
The percentage mixture of red to green in the top half and the luminance of the yellow bottom field can be changed until a match of the two fields can be perceived.

**Advantages:**

- Generally recognised as the best instrument for differentiation of normal trichromats from individuals with red/green colour deficiencies, for differentiation of protan and deutan types amongst the red/green deficients and also recommended for diagnosis and differentiation of the level of deficiency by the National Research Council-National Academy of Sciences (NRC-NAS) Committee on Vision (1981).

**Disadvantages:**

- Accurate calibration is required and the observation parameters must be carefully controlled.
- Administration of an anomaloscope test requires knowledge and skill.
- There is no standard method for the interpretation of results.
- There are also different ways of reporting the results and these are not standardised. Some examiners quote their results as anomaloquotients (the numerical mean match divided by the mean value obtained for a large group of normal subjects). Anomaloquotients are useful for redefining the normal matching range in an individual instrument after the light source has been replaced. However, they are completely inadequate for classifying colour deficiency, whether they are calculated from a single match or from the midpoint of the matching range (Birch, 2001); the range of the match is not given, and dichromats could have a similar anomaloquotient value as a normal (see Figure 33 and section 6.6.1.1) as they have a similar mean match (though a range of 74 as opposed to about 3-6 for normals).
- Results can vary with the method of administration: there are three methods of pre-adaptation for each match (Steen et al., 1974):

  1) using the provided built-in light (neutral adaptation);

2) continue to stare in to the anomaloscope at the circle between matches (chromatic adaptation) (recommended by the NRC-NAS Committee on Vision (1981));
3) look away from the anomaloscope into the dim room to avoid after images (see section 6.6.1.1).

- The subject needs to have patience and concentration to find a correct match each time.
- There is a certain amount of decision-making needed for subjects to state if an exact match is made or if it is just close.

#### 6.6.1.1 **Administration at City University**

Just one eye (the dominant eye) is fully tested and the other just checked that it is the same, if the deficiency is congenital. The test is done in two stages. The subject is first familiarised with the instrument controls. They are then asked to alter both the control wheels until the two halves of the circle look exactly the same colour and brightness. The subject is not asked to name the colours. A few matches are made, with the examiner "spoiling" the match in between each time. About ten seconds are allowed for each match and then, to minimise the effect of chromatic after images, the subject looks away from the instrument into the dimly lit room.

The second stage of the test is to determine the limits of the matching range. The initial matches made by the subject in the first stage are used as a guide for the examiner to set the red/green mixture ratio near to the estimated limits of the range. The subject has to just alter the luminance of the lower yellow half of the field and see if an exact 'match' in both colour and brightness can be made with the set red/green mixture in the upper half. The ratio of the red/green mixture half is slightly altered by the examiner until the limits of the matching range are found. These limits are then compared with the normal limits and a diagnosis made.

Dichromats will accept the full range of red/green mixtures as a match with the yellow field, as they have only one photopigment in the spectral range provided by the instrument (section 3.4.1). Deuteranopes are distinguished from protanopes as the luminance of the yellow they set for both ends of the red/green scale is fairly similar whereas protanopes set the luminance of the yellow very low to make a match at the red end of the scale and much higher at the green end (Figs. 33 and 34). This is because protans tend to see red as fairly dark as they have reduced long wavelength sensitivity (section 3.3).

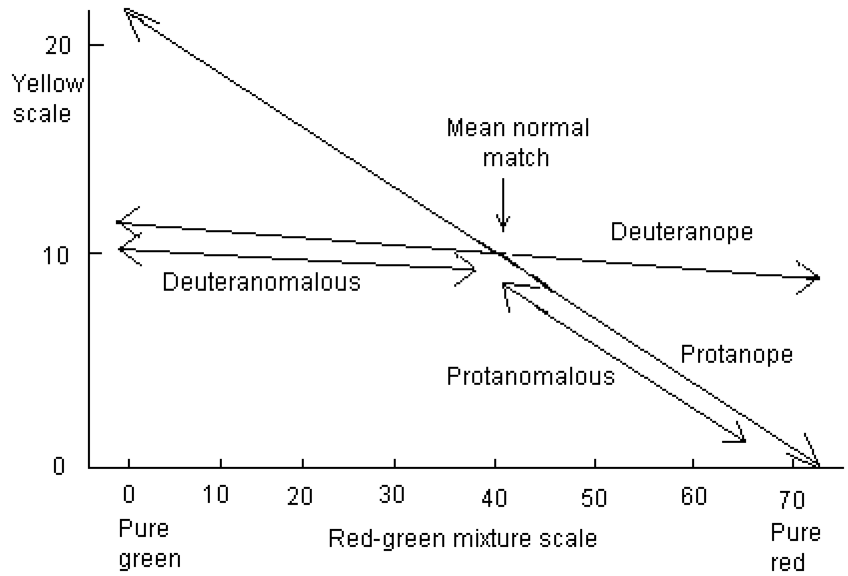



**Figure 33** Colour matches obtained with the Nagel anomaloscope in protan and deutan deficiency. Protanopes and deuteranopes are able to match the yellow with all red/green mixture ratios by adjusting the luminance of the yellow comparison field. Protanomalous trichromats obtain matching ranges with an excess of red and deuteranomalous trichromats obtain matches with an excess of green in the matching field. The normal match is not accepted in anomalous trichromatism.

If a colour match within the normal range is not accepted then the subject is an anomalous trichromat (see Figure 33). Two separate distributions are formed either side of the normal range as protanomalous trichromats require significantly more red light in their colour mixture and deuteranomalous trichromats require more green. The severity of the discrimination deficit and, by inference, the alteration in sensitivity of the abnormal photopigment, is shown by the extent of the matching range. As for protanopes, protanomalous trichromats set the yellow luminance lower than normal when making a match.

Only extreme anomalous trichromats (Birch, 2003; NRC-NAS Committee on Vision, 1981), who have abnormal L- and M-cones, obtain matches that include the normal match range but not all red/green mixture ratios (Figure 33).

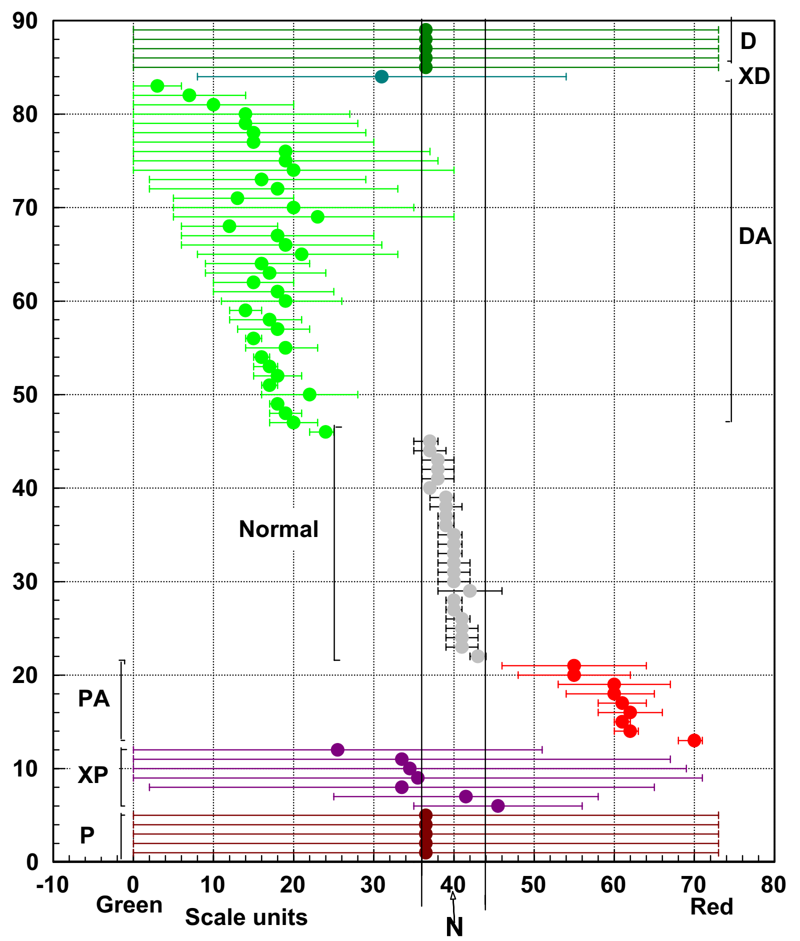



**Figure 34** Matching ranges for 89 observers obtained with the Nagel anomaloscope. The normal mean match (N) for the anomaloscope is at 40 on the red/green mixture scale (SD ± 2 scale units). 24 observers are normal trichromats (mean matches within N ± 2SD) with matching ranges between 35 and 44 on the mixture scale. 5 observers are deuteranopes (D) and 5 are protanopes (P) (matching ranges 0-74). 38 observers are deuteranomalous trichromats (DA) and have matching ranges between 0 and 40. 9 observers are protanomalous trichromats (PA) and have matching ranges between 46 and 71. 7 observers are extreme protanomalous trichromats (XP) and one extreme deuteranomalous (XD), and all have matching ranges that include the normal matching range and extend to both the red and green sides of the mixture scale. Protanopes, protanomalous trichromats and extreme protanomalous trichromats have reduced threshold sensitivity to long wavelengths compared with normal trichromats (From Squire et al, 2004 (submitted)).

### 6.6.2 JAR Manual comments

*'The exact qualitative and quantitative diagnosis is given by the anomaloscope. Looking into this instrument, the subject compares two juxtaposed fields and judges when they appear identical. Red-green deficiencies are studied with the 'Rayleigh match' where one field is yellow and the other an additive mixture of red and green. The examination demands a thorough knowledge of colour vision physiology and*

*large experience. Most widely known and used is the Nagel anomaloscope, but equally efficient other apparatuses have recently been put on the market (e.g. Heidelberg Anomaloscope from Oculus). All dichromats should be rejected as they are colour unsafe. When examining an anomalous trichromat with Nagel's anomaloscope, different scale readings are used to express the result. The colour matching range is defined as the difference between the maximum and the minimum scale reading accepted by the examinee as identical to the test colour. If the colour matching range exceeds four scale units, the applicants must be considered colour unsafe. The relation between the mean scale reading for colour identity and the standard scale reading is expressed by the anomaly quotient. This quotient has diagnostic value, but provides no guidance in assessing colour safety. The anomaly quotient per se is thus irrelevant in the assessment of an applicant's fitness for flying.'* (JAR-FCL 3 Section 2, 2000)

The limiting of the colour matching range to four scale units seems too restrictive as it will fail as 'colour unsafe' applicants who have acceptable colour vision and maybe pass some who would fail a lantern test. Some subjects with normal colour vision can exceed four scale units with a range of, for example 35 to 42 on the red/green scale, which is a range of 8 scale units, and some subjects with anomalous colour vision deficiency can have a range of only 2 or 3 units (e.g. 14 - 16 on the red/green scale).

# 7 Acquired colour deficiency and tests

## 7.1 Introduction

Defective colour vision can be acquired due to retinal or general diseases, brain injuries, responses to toxic substances and the prolonged use of some therapeutic drugs. Congenital (section 3) and acquired colour deficiencies differ in several ways (Table 14).

Unlike congenital colour vision deficiencies, in ophthalmic diseases colour vision deficiencies arise together with reduced acuity, increased glare effects, retarded adaptation, field deficits and abnormal electropotentials occurring in combination with other functional or morphological signs and symptoms.

| CONGENITAL | ACQUIRED |
|---|---|
| Present at birth (identified at 3 months) | Onset after birth (after 3 months)Colour vision previously normal |
| Colour loss in specific spectral region | Often no clear cut area of discrimination loss |
| Less marked dependence of CV on target | Marked dependence of CV on size and illuminance |
| Characteristic results obtained on various clinical CV tests | Conflicting or variable results on clinical CV tests |
| Type of deficiency can be classified and diagnosed precisely | Not easy to classifyCharacteristics may combine those of more than one type of congenital deficiency. |
| Many object colours are named correctly or predictable errors are made | Some object colours are named incorrectly |
| Both eyes are equally affected | Eyes are affected asymmetrically |
| Usually no other visual complaint | May have decreased acuity and field loss |
| Type and severity the same throughout life | Type and severity changes with time |
| Predominantly red/greenIn order of prevalence: deutan/protan/tritan | Predominantly tritan loss, but often accompanied by red/green loss |
| Higher prevalence in males | Equal prevalence in males and females |

**Table 14** Characteristics of congenital and acquired colour vision defects (Birch, 2001; Yates et al., 2001).

## 7.2 Classification

There are three broad categories of acquired deficiency, two of which are red/green and are similar to congenital protan and deutan deficiency (Table 15). However, features may be less clear-cut and the deficiency often changes with time. Studies that involved measurements of chromatic sensitivity loss show that diseases such as optic neuritis, diabetes and glaucoma cause both blue/yellow and red/green loss of chromatic sensitivity (Barbur et al., 1997; Pacheco-Cutillas et al., 1998; Pacheco-Cutillas et al., 1999; Pacheco-Cutillas et al., 2001).

| Classification | Characteristics | Association |
|---|---|---|
| **Type 1red/green** | Similar to a protan defectWavelength of maximum luminous efficiency displaced to shorter wavelengths | Progressive cone dystrophies (e.g. Stargardt`s disease)Chloroquine toxicity |
| **Type 2red/green** | Similar to a deutan defect but with reduction of relative luminous efficiency for short wavelengths | Optic neuropathy (e.g. retrobulbar neuritis associated with multiple sclerosis)Ethambutol toxicity |
| **Type 3 (tritan)Blue** | a) Similar to tritan defect but with reduction of relative luminous efficiency at both spectral limits | Progressive rod dystrophiesRetinal vascular lesionsPeripheral retinal lesions(e.g. retinitis pigmentosa, diabetic retinopathy, glaucoma) |
| | b) Similar to a tritan defect but with displaced relative luminous efficiency to shorter wavelengths (pseudo-protanomaly) | Macula oedema (e.g. central serous chorioretinopathy, diabetic maculopathy, age-related macular degeneration) |

**Table 15** Clinical classification patterns for acquired colour deficiency. (from Birch, 2001).

Type 3 (tritan) is the most common acquired deficiency that can be associated with fairly common diseases such as diabetes and glaucoma. The prolonged use of drugs to treat disorders such as rheumatoid arthritis, can also affect the colour vision of a person. Optic nerve diseases, such as optic atrophy, can produce red/green changes. A problem is that some people may recover good visual acuity but may retain their acquired colour deficits.

Krastel and Moreland (1991) make it clear that:

*'Establishing rules and types from the variegated phenomenology of acquired colour vision deficiencies in ophthalmic conditions necessarily leads to some over-simplification in the description of disease entities. Moreover, it is not only the site but also the mode of impairment that determines the resulting colour deficit: specific disorders of particular cells may not necessarily obey the rules which grossly establish a correlation between an affected layer and the pattern of functional deficit. Consequently, colour vision testing may not be used independently as a diagnostic tool. However, a useful contribution to clinical diagnosis and follow-up is provided by assessing the results of colour vision examinations in conjunction with family and individual history and with a thorough evaluation of other functional criteria and biomicroscopic findings.'*

### 7.3 **Testing procedure**

For the evaluation of acquired colour deficiency each eye must be examined separately and a battery of tests is often required. The same tests as used for congenital colour deficiency (section 6) are recommended, except that the F-M 100 Hue test (section 6.4.3), or a graded series of D15 tests (different saturation levels), is usually obligatory and a lantern test (section 6.5) is not needed. Many of the congenital tests, however, do not test for blue/yellow deficiency so tests capable of identifying tritan defects must be included, and additional tests for examining short-wavelength sensitivity are desirable. For older patients, over fifty years of age, the detection of Type 3 defects can be quite challenging due to increased lens density (section2.1.3), cataract or vitreous haze that cause physiological changes in threshold short-wavelength sensitivity. Reduced visual acuity and central field defects restrict the use of some clinical tests.

If congenital colour deficiency is present the identification of acquired colour deficiency is more difficult. In such cases the use of larger stimuli and dynamic luminance contrast noise that achieves a high level of luminance contrast masking with saturated colours can reveal both the type of congenital deficiency and the acquired loss of chromatic sensitivity (Barbur et al., 1997).

A congenital red/green dichromat who acquires a severe Type 3 tritan defect may exhibit severe complete absence of hue discrimination (acquired achromatopsia).

### 7.4 Acquired colour deficiency and aviation

The most common acquired colour deficiency, blue/yellow, is not currently assessed in civil aviation as only conventional tests for congenital red/green deficiencies are used. However, acquired colour deficiency is not that common and is usually accompanied by other medical symptoms that should be detected.

# 8 The CAD test - a new approach for Colour Assessment and Diagnosis of colour deficiency

## 8.1 The need for a new test for aviation

At present different colour vision tests for aviation are used by different countries. As mentioned in Chapter 5, a screening test is first carried out, usually Ishihara plates, and then, if the subject fails, a second test is used to decide on the type of licence a pilot can be granted, if any, or if any restrictions should be imposed. The pass criterion for Ishihara plates (section 6.3.1) in JAA countries (section 5.3) is standardised to no mistakes, but outside JAA this can vary. The result of this test is very much up to the examiner as hesitation in reading the numbers, or misreadings as opposed to mistakes, may or may not be taken into account. The second test in JAA member countries is either a lantern test or an anomaloscope test. As illustrated in section 6.5 there are several types of lantern tests that are used by different countries (e.g. Holmes-Wright, Beyne and Spectrolux), each with slightly different test criteria and outcome. The anomaloscope (see section 6.6) is used primarily in Germany, but is not so widely available and some models are not made any more. It also needs to be used by an experienced examiner who knows how to interpret the results. The FAA (USA), which is not part of the JAA, has a wide option of tests that can be used by an examiner, but often uses the Farnsworth lantern and the Aviation Signal Light (section 6.5); Canadian examiners usually use the Farnsworth D15 (section 6.4.1). Potential pilots can, and often do, try other countries' tests when they fail the first examination.

This international (and sometimes national) diversity in colour vision testing methods and standards illustrates the necessity to have an objective and accurate test, relevant to aviation and free from artefacts. The availability and wide use of such a test would ensure that the same standards are applied and that the results are reproducible and directly comparable. The aim is to identify accurately those subjects that have chromatic sensitivity outside the normal range. In addition, the test should provide a direct measure of chromatic sensitivity loss and direct classification of the type of colour deficiency involved. This information should then make it possible to identify objectively the kind of visual tasks for which the applicant's colour vision may not be adequate. This approach can be generalised to any occupational task for which a detailed visual task analysis, in relation to the use of colour signals, has been carried out.

## 8.2 Design and aims of new test

The new CAD test is based on earlier studies of camouflage (see sections 2.5, 4.1 and 6.1) that show how spatial luminance contrast (LC), or chromatic contrast noise affect the detection of colour or luminance contrast defined test patterns. It has been shown that the presence of dynamic luminance contrast noise in the background reduces drastically the sensitivity of the visual system for detection of luminance contrast defined stimuli, without affecting the thresholds for detection of colour-defined patterns (Barbur et al., 1994). Examples of such results are shown in Figure 35 (a and b).

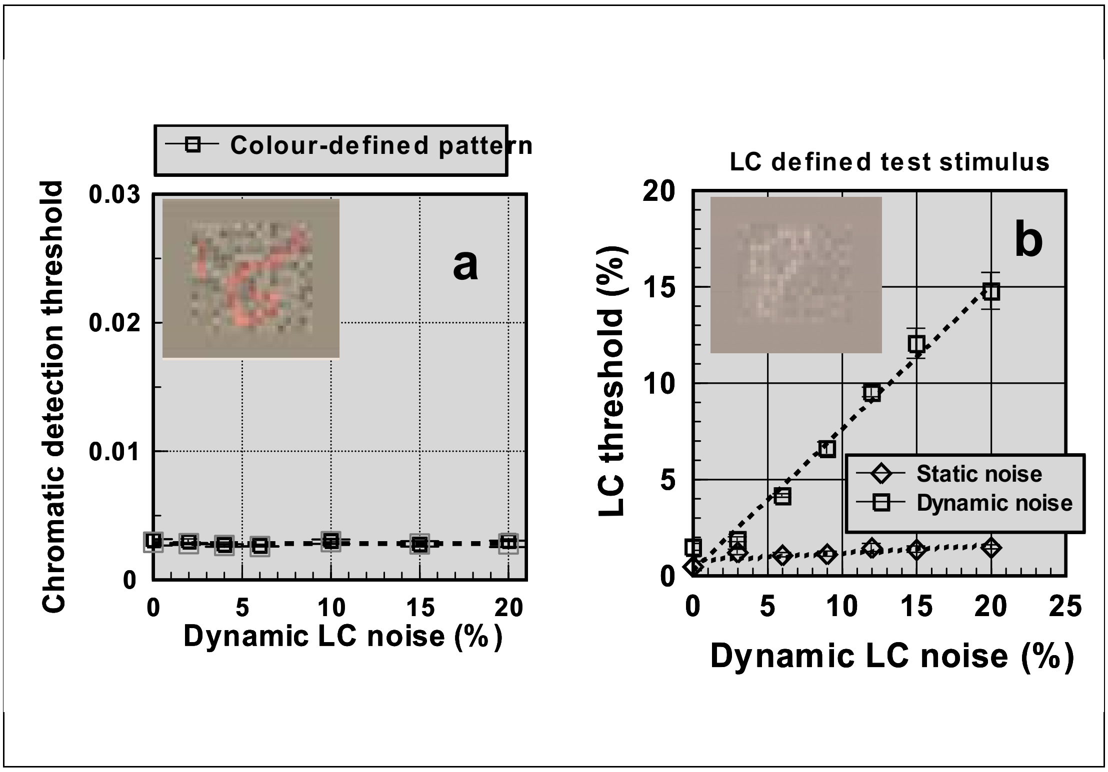



**Figure 35** Section a shows thresholds for detection of colour-defined stimuli (as shown in the inset) buried in various amounts of dynamic luminance contrast (LC) noise. The mean luminance of the stimulus array remains constant and equal to that of the larger uniform background field (24 cd m-2, CIE -(x, y): 0.305, 0.323). The results show that the processing of chromatic signals is independent of the ongoing LC noise. Section b shows thresholds for detection of luminance contrast defined motion buried in either static or dynamic LC noise (see stimulus appearance above the graph). The results reveal the effectiveness of dynamic LC noise in masking the detection of luminance contrast signals. Static LC noise, on the other hand, has little or no effect on the detection of LC defined motion (Barbur, 2003).

These findings were used to design a new test that isolates the use of chromatic signals. Figure 36 shows the effectiveness of the new test on dichromats (see section 3.1.2). A large number of normal trichromats (see section 2) have also been investigated in order to establish the limits of visual performance expected of the normal trichromatic observer. The 2.5 and 97.5% limits that describe the expected range of performance in normal trichromats (see Figure 37a) define a useful template against which the result of any observer can be compared. Figure 37b shows the outcome of the test for a protanomalous observer (see section 3.1.3).

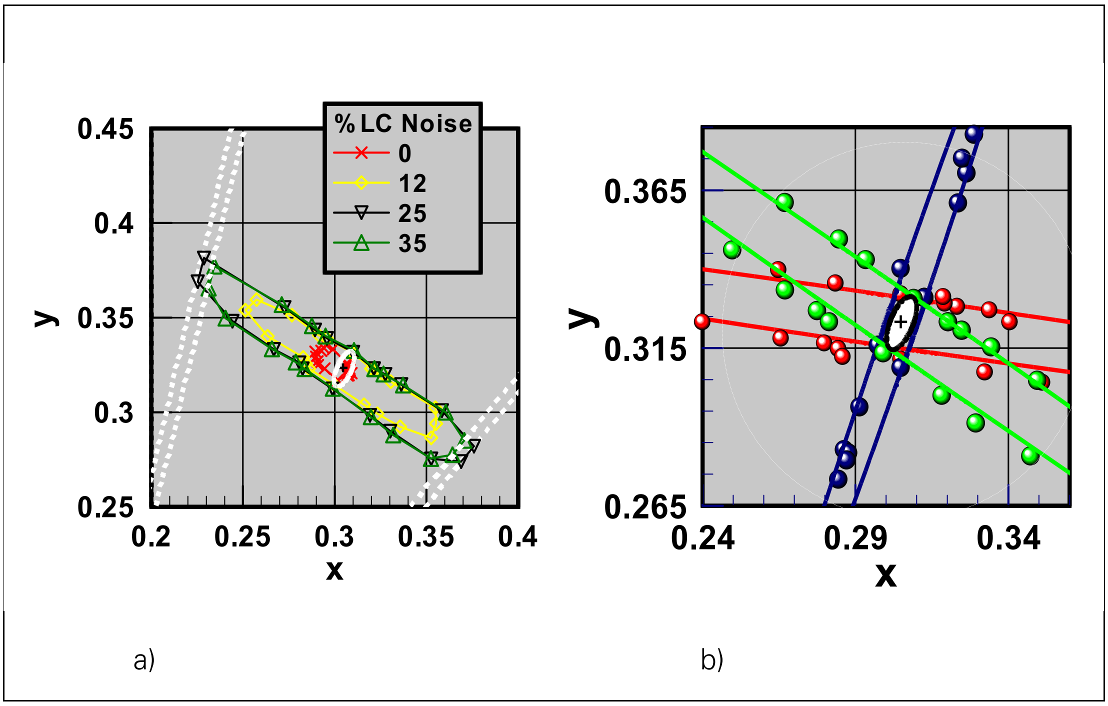



**Figure 36** Section a shows how the use of dynamic LC noise isolates the colour confusion line (see section 3.4.1) in a deuteranope. The white, dotted lines show the limits set by the phosphors of the display. Although the chromatic saturation of the coloured stimulus hits the phosphor limits along the colour confusion line, the subject is unaware of the presence of the coloured stimulus. Section b shows data measured for each class of dichromat.

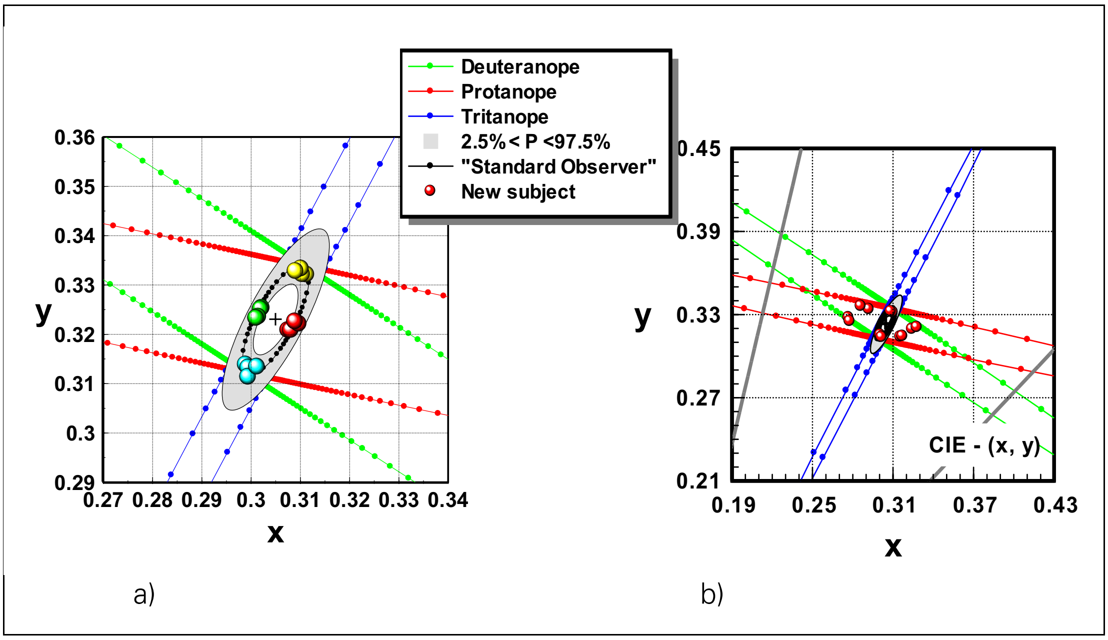



**Figure 37** Section a shows the template that defines the limits of visual performance for the normal trichromat. The coloured discs show the results of the test for a normal trichromat. Section b shows the results of the test for a protanomalous observer. Note the different scales employed for section a and b in order to represent the data for the protanomalous observer.

**Advantages of the new CAD test**

- Quick and easy to use, device-independent, easy to interpret.
- A full assessment of chromatic sensitivity is made which is quantified with reference to the internationally agreed colour reference system (CIE proceedings, 1931, see section 2.3.2).
- The test screens for normal colour vision, quantifies loss of chromatic sensitivity and classifies and grades colour deficiency. These functions can be achieved in less than 15 minutes; a whole battery of clinical tests (see section 6) can take 40 to 60 minutes and produce data that are often difficult to interpret. Unlike the Nagel anomaloscope (section 6.6), an expert examiner is not needed to carry out the test; the results are interpreted by the computer from a standard formula so this also does not rely on examiner decision as for the Nagel and Ishihara plates (section 6.3.1).The test employs a four-alternative, forced-choice procedure and therefore the subject cannot cheat or learn responses. The results give a direct measure of chromatic discrimination sensitivity.
- No colour naming is involved.
- The procedures employed to measure chromatic detection thresholds allow for a certain amount of indecision and lapses in subject's concentration.
- The detection of luminance contrast signals that may be present in the "isoluminant" coloured stimulus (particularly for protans who have reduced luminance sensitivity for longer wavelengths so see reds as dark) is completely masked. The subject can only make use of colour signals and when these are not available, the subject fails to see the coloured pattern.
- The test reveals both red/green and blue/yellow deficiency and can be used to characterise the loss of chromatic sensitivity in acquired colour deficiencies.

**Disadvantages of the new CAD test**

- Extremely mild deficiency can occasionally show as a circle, particularly for deuteranomalous observers. Fortunately this is not the case for mild protanomalous observers and this makes it possible to separate minimal deuteranomalous from protanomalous observers. More data are however needed to validate the accuracy of classification when extremely mild deficiencies are involved.
- Anomalous trichromats can vary widely in the severity of their colour vision loss. A few subjects can exhibit a massive loss of chromatic sensitivity and are unable to detect the most saturated colours on the display. In order to distinguish the very severe anomalous trichromats from dichromats, a display that exhibits the largest gamut and high phosphor luminances needs to be used. However, this would probably not be relevant for aviation as both severe anomalous trichromats and dichromats should certainly be found to be colour unsafe for flying using current standards and tests, and are most likely to remain classified as such if any changes occur.
- The test requires the subject to press one of four buttons to indicate the correct response and this requires some manual dexterity. Older people and those not familiar with computers may therefore find this manual task difficult to carry out.
- The cost of the apparatus (i.e., mainly the calibrated monitor, 10 bit display driver and computer), remains relatively high by comparison with occupational colour vision tests. The cost may be acceptable may not be too high for aeromedical centres, for which secondary tests such as lanterns are already quite expensive, but may not, at present, be feasible for Authorised Medical Examiners just for screening.

- Automatic calibration of the luminance of each phosphor of the display has to be carried out at regular intervals and this requires the use of a good photometer.

# 9 Discussion

## 9.1 Colour vision concerns in aviation

Visual acuity, visual detail discrimination, is relatively easy to assess with impairment and decrement being apparent to the subject, pilot, operator and test conductor alike. This can usually be corrected.

However, though an individual's colour visual competence is also a physical ability, variation in that ability is less obvious. Colour vision varies from 'normal' to colour-blind, with degrees of colour impairment between those extremes. Even the congenital colour deficient individual may not know they have a deficiency until they are tested, as they have always seen the world that way.

There are three types of colour receptors, or cones, in the retina (section 2.1.1) that contribute to colour vision. These are primarily 'red' (L-cones), 'green' (M-cones) and 'blue' (S-cones) sensitive and they absorb light in different parts of the visible spectrum. A person is colour-deficient (section 3) when one or more of these cones are either missing or abnormal. The most common deficiency is congenital and red/green (the L-cone or M-cone either missing or abnormal). Fewer colours are distinguished by a person with a colour vision deficiency, so two colours that look different to someone with normal colour vision could look the same to someone with a colour vision deficiency. If a cone is missing then the deficiency can be debilitating in everyday life; if a cone is abnormal then the severity of the deficiency can vary from being almost as severe as if the cone were missing, or is almost as unnoticeable as if the colour vision were normal, or any severity in between.

For historical reasons, colour vision ability has traditionally been judged in terms of simple red/green discrimination. Where control of aircraft from the ground relies on red/green/white signals to ensure flight safety and operational effectiveness this is sensible.

In commercial aviation multi-coloured EFIS displays are used (section 4.2). In busy displays or complex visual scenarios, colour adds a valuable further dimension. It allows slower, deliberate assimilation of much more visual information than is possible with monochromatic or grey-scale instruments. With training, automatic performance and pattern recognition appear to be enhanced. Firth (2001) points out that: "once colour displays are experienced, few wish to return to "black and white" formats".

It is accepted that the addition of colour to display systems is aesthetically pleasing, that colour sells displays and that the colour dimension allows more information to be presented. However, the design of displays for aviation has not been standardised, so the colour may not be used to the greatest advantage for its intended purpose in every display.

*'In the selection of aircrew, airborne or remote, the potential future aces, upon whose cunning and intelligence the defence of realms will depend, may be colour defective. There is no established relationship between colour and military, let alone commercial or civil competence. The future's essential heroes may not be 'colour normal'. Do we, dare we, exclude the otherwise-best candidates on colour competence alone?'* (Firth, 2001)

There are good physiological reasons to expect that the addition of chromatic signals should cause some improvement in visual performance, even when colour is not used for coding or identifying groups of objects. The visual system extracts edges and boundaries in the retinal image that are formed by spatial modulation of either intensity or spectral content. In real working environments, or natural images, edges and contours are often defined by both intensity and spectral modulation. Some neurones in the primary visual cortex in the brain respond to either luminance contrast, chromatic contrast or to both (Zeki, 1983a; Zeki, 1983b). A large percentage of neurones combine luminance and colour signals when processing edge boundaries, but are not interested in the colour of the stimulus. This could imply that normal trichromats have some advantages over subjects with reduced chromatic discrimination. However, this has not yet been proved to be true, or if so, how much of an advantage.

## 9.2 **Colour vision testing**

Any of the tests outlined in section 6, and others, may be employed by licensing authorities to determine those applicants who meet their colour perception standards. As it is generally left to each member country to decide which tests to use, and each test, even those of the same general type (e.g. lantern tests), has slightly different testing criteria and outcome, the colour vision standards are not uniform throughout the world. There is also repeat testing at regular intervals, at least in JAA countries. However, the colour vision of congenital colour deficients does not change any more than that of colour normals. Additionally, only Ishihara plates are used for repeat testing and these do not test for blue/yellow deficiency, which is what is affected by ageing and is the most common acquired deficiency. It is also not known which aviation requirements these standards should reflect, or if all types and grades of defective colour vision are a significant risk to aviation safety.

Generally, colour vision aeronautical aptitude tests were created for reasons of safety with particular reference to perception of the world outside the aircraft, whereas today, some exterior indicators, such as flares, are almost obsolete and colour has entered the cockpit (colour liquid crystal displays or cathode ray tubes). What is more, these colours may change over time or depend on the light environment (de-saturation of colours or bleaching of primary colours with the increased illumination at high altitude).

The conditions governing the use of colour have therefore changed:

*'- a pilot needs to observe colour screens for long periods (for several minutes or even hours).*

*- specific colours may no longer have distinct safety connotations; a given colour tends to acquire connotation as part of the task itself. Colour coding enables time saving in the uptake of information; for example, the colour yellow tends to be reserved for power information, the colour magenta for track or trajectory processing.*

*- complex images have several juxtaposed or superimposed colours. The luminance contrast between a coloured target and its background is no longer appropriate. Colour contrast is commonly used. '* (Menu, 2001)

Menu goes on to state that the tests used for testing pilots' colour vision should also change to suit the new environment.

This is just one of many papers, which include the ICAO Manual of Civil Aviation Medicine (1985), published within the last twenty years, that mention the need for new colour vision tests that are more appropriate to the tasks that pilots carry out. Many publications emphasise the importance of objective tests. It is clear that colour naming and decision making draws in further elements of guessing and assessed judgements rather than certainty of seeing and recognising a colour. There could also be a variability and scatter of opinions on what a certain colour should be called and an argument that it does not matter if a colour deficient person sees the colour as the same as a 'normal' person, as long as they can see and distinguish the colour.

Recently, the ICAO Vision and Colour Perception Study Group, in its final report, expressed considerable concern about several aspects of colour perception (ICAO ANC Task No. MED-9601, 1999). The study group strongly recommended that further work be undertaken in the following areas: determination of colour-critical tasks in aviation, a study of colour-coded information inside and outside the cockpit, and the relevance of practical colour vision testing.

After a short questionnaire was sent to pilots about colour and colour vision, Dr. Claus Curdt-Christiansen, the Chief of the Aviation Medicine Section of ICAO, reported that: *'The use of colours in aviation is likely to remain or increase because, from an operational standpoint, coloured displays are superior to black and white displays. A return to black and white displays (to accommodate colour defective pilots) is not to be expected and would in any case not change the problem with colours outside the cockpit including coloured light signals.*

*Obviously, no investigation of pilots' attitudes and operational concerns can replace a scientific study aimed at determining the colour-critical tasks in aviation and the validity of the colour perception tests in use world-wide. In 1974, Drs. Viggo Dreyer (Denmark) and Jean-Paul Boissoin (France) wrote in the first edition of ICAO's Manual of Civil Aviation Medicine:*

*'An extensive study of aviation coloured lights based upon a teamwork between air crew and air traffic controllers, illumination engineers, physicists and visual physiologists may perhaps in the future solve the problem of what are the most critical colour perception tasks in aviation.'*

*Twenty-five years later, the situation is virtually unchanged except that colours are used more widely now than ever before. If anything, it is even more necessary today to define the colour-coded information inside and outside the cockpit, determine the critical colour perception tasks in aviation, and validate one or more suitable methods for testing colour perception of those who apply for aviation licensing.'* (Curdt-Christiansen, 2000)

# 10 Conclusion

The CAA UK is currently reviewing the colour vision requirements for professional flight crew. Many documents and papers over the last twenty years, including ICAO publications, have stated the need for new colour vision tests that are more appropriate to the tasks that pilots carry out. The diversity in colour vision testing methods and outcomes emphasise the importance of objective tests, which can be widely used to provide some standardisation in aviation.

This report addresses the appropriateness of these tests and the current standards within the ICAO and JAA by first understanding the physiological mechanisms for the generation of colour signals and the properties of both normal and colour vision deficiencies. The current methods for assessing colour vision deficiencies in aviation such as the Ishihara pseudoisochromatic plates, the lantern tests and the Nagel anomaloscope are described.

The main purpose of this project is to define and assess the colours used in aviation and their importance. This will result in a description of visual tasks and target configurations that involve colour and are considered critical. Typical illuminants, light levels, stimulus sizes, luminance contrasts and colour differences that describe best a number of visual tasks and environments during flying will be measured.

Experimental findings and current information on the use of colour in aviation will be used to establish minimum colour vision requirements in pilots that are specific to the visual tasks investigated. The displays based programs described in section 8 are being developed for testing colour sensitivity in pilots. There will be a quick screening test. For the few subjects that fail or are judged borderline from the results of the first test, then a second program will measure the subject's chromatic sensitivity for stimulus conditions that are considered important experimentally. The results from this will then make it possible to judge whether the subject's performance meets the minimum colour vision requirements that yield acceptable visual performance in the tasks investigated.

## 11 Definitions

(From CIE Publication No. 17.4, 1987; Hunt, 1998; SAE ARP4032, 1998; Wyszecki and Stiles, 2000, The Concise Oxford English Dictionary, 1990; JAR-FCL 3, 2002))

**Achromatic colour**: Colour devoid of hue. (The names white, grey, black, neutral and colourless are commonly used for these colours.)

**Achromatic stimulus**: Colour stimulus chosen because it usually yields a colour perception that is devoid of hue under the desired observing conditions.

**Adaptation**: Visual process whereby approximate compensation is made for changes in the luminances and colours of stimuli, especially in the case of changes in illuminants.

**Additive mixing**: Addition of colour stimuli on the retina in such a way that they cannot be perceived individually.

**Anomalous trichromat**: Person with anomalous trichromatism.

**Anomalous trichromatism**: Form of trichromatic vision in which colour discrimination is less than normal.

**Aeromedical Section (AMS)**: Each JAA Member State will include within its Authority one or more physicians experienced in aviation medicine. Such physicians shall either form part of the Authority, or be duly empowered to act on behalf of the Authority. In either case they shall be known as the Aeromedical Section (AMS).

**Authorised Medical Examiner (AME)**: Medical Examiners, qualified and licensed in the practise of medicine, who are authorised by the Authority in each JAA Member State to carry out aeromedical testing.

**Brightness**: This is the attribute of a visual sensation according to which an area appears to exhibit more or less light. It is the perceptual correlate of luminance and, hence, can only be measured via human observations and not via instrumentation. Variations in brightness range from 'bright' to 'dim'.

**Chroma**: The colourfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

**Chromatic adaptation**: Visual process whereby approximate compensation is made for changes in the colours of stimuli, especially in the case of changes in illuminants.

**Chromatic colour**: Colour exhibiting hue (as distinct from those commonly called white, grey, black, neutral and colourless).

**Chromatic discrimination**: The ability to observe differences between colours.

**Chromatic sensitivity**: The degree of responsiveness to slight changes in colour.

**Chromaticity**: Property of a colour stimulus defined by its chromaticity co-ordinates.

**Chromaticity co-ordinates**: The chromaticity co-ordinates, x,y,z, for a colour are the ratios of each tristimulus value of the colour to their sum in the CIE system. The tristimulus values (X, Y, and Z) are based on the amounts of each of three reference lights needed to make an additive colour mix that will match the colour in question. Since the sum of the chromaticity co-ordinates always equals 1, only two co-ordinates need be given to describe a colour. This serves to completely describe two psychophysical qualities of every colour: dominant wavelength and excitation purity. These correspond to the perceptual qualities of hue and saturation. A third term, the Y tristimulus value is the luminance of the colour.

**Chromaticity diagram**: This is a graphic representation of all possible colours on a two-dimensional diagram. Using two of the three chromaticity co-ordinates (for example, x and y in the CIE 1931 system) each colour will plot as a single point on this diagram. Colours of similar dominant wavelength and excitation purity (and correspondingly similar hue and saturation) will plot close to one another. The more widely spaced apart two colours are, the more different they will appear from one another in terms of hue and saturation. Chromaticity diagrams in the CIE system do not account for luminance and hence two colour stimuli having the same dominant wavelength and excitation purity but different luminances will plot at the same point. (See x,y diagram and CIE 1931 x,y chromaticity diagram.)

**Chromaticness**: 1.The attribute of a visual sensation according to which the (perceived) colour of an area appears to be more or less chromatic. 2.Chromaticness has also been used as an alternative term to colourfulness (obsolete). 3. Perceptual colour attribute consisting of the hue and saturation of a colour.

**CIE**: This is an international organisation responsible for colorimetry and photometry standards. The initials stand for: Commission International de l' Eclairage which translates as International Commission on Illumination.

**CIE standard illuminant C**: An illuminant having the relative spectral power distribution intended to represent average daylight.

**CIE standard illuminant $D_{65}$**: An illuminant having the relative spectral power distribution intended to represent average daylight. This supersedes CIE Illuminant C as it is intended to be more representative of daylight in the ultra-violet region (Figure 6). This is most significant for colours that fluoresce.

**CIE standard photometric observer**: Ideal observer whose relative spectral sensitivity function conforms to the photopic or scotopic spectral luminous efficiency function.

**CIE 1931 x,y chromaticity diagram**: (see x,y diagram and Chromaticity diagram)

**CIE 1931 standard colorimetric observer**: Ideal observer whose colour matching properties correspond to the CIE colour-matching functions for the 2° field size.

**Colorimetric purity, pc**: Quantity defined by the expression $p_c=L_d/(L_d+L_n)$ where $L_d$ and $L_n$ are the respective luminances of the monochromatic stimulus and of a specified achromatic stimulus that match the colour stimulus considered in an additive mixture. (In the case of purple stimuli, the monochromatic stimulus is replaced by a stimulus whose chromaticity is represented by a point on the purple boundary.)

**Colour**: This is that aspect of visual perception by which an observer may distinguish differences between two structure-free fields of view of the same size and shape, such as may be caused by differences in the spectral composition of the radiant energy concerned in the observation. In this sense, the term colour is sometimes referred to as perceived colour to distinguish it from colour used in the sense of psychophysical colour.

Psychophysical colour is specified by the tristimulus values of the radiant power (colour stimulus) entering the eye.

**Colour constancy**: Effect of visual adaptation whereby the appearance of colours remains approximately constant when the level and colour of the illuminant are changed.

**Colour-matching functions**: The tristimulus values, with respect to three given primary colour stimuli, of monochromatic stimuli of equal radiance, regarded as functions of the wavelength.

**Colour stimulus**: Radiant power of given magnitude and spectral composition, entering the eye and producing a sensation of colour.

**Colour temperature**: The temperature of a Planckian radiator whose radiation has the same chromaticity as that of a given stimulus. Tc, Unit Kelvin, K

**Colour vision deficiencies**: This is a decreased ability to discriminate and identify certain colours, relative to the normal observer. It varies in form according to the particular colours that are confused and in severity according to the magnitude of colour differences that cannot be discriminated. It is usually inherited, but may also result from the effects of disease, drugs, and ageing. Reduced sensitivity to light of certain colours is sometimes involved.

Colour vision deficiencies are categorised in terms of their impact on colour-matching and colour-discrimination performance. The population can be divided into three groups: trichromats, dichromats, and monochromats. Monochromats are extremely rare and can only discriminate brightness differences. The colour confusions which dichromats make are severe. There are two main types of dichromats: those that confuse colours along the red/green axis of the chromaticity diagram, and those that confuse colours along the blue/yellow axis. Trichromats can be divided into normal trichromats who have normal colour vision, and anomalous trichromats who have reduced colour discrimination ability falling between normal trichromats and the dichromats. Anomalous trichromats may also be categorised as red/green or blue/yellow types according to their patterns of colour confusion and may be further categorised according to the severity of their deficiency that may range from mild (near-normal colour discrimination ability) to severe (near-dichromatic levels of colour confusion). Twenty-five percent of red/green deficients, both dichromats and anomalous trichromats, have a marked loss of sensitivity to red light.

Inherited colour vision deficiency affects approximately 8% of the male and 0.4% of the female populations. Approximately 3% of private pilots, 2% of commercial pilots, and 1% of airline transport pilots are known to have some type of colour vision deficiency (SAE ARP4032, 1998). Over 99.9% of inherited colour vision deficiencies are of the red/green type. Almost all colour deficient pilots would, therefore, be expected to have deficiencies of the red/green type. Acquired colour vision deficiencies are of unknown frequency in the population. They are more often of a blue/yellow than the red/green type, may be temporary, and are those due to disease and drug effects. They are usually associated with a significant visual acuity loss. Age-related deficiencies are often associated with reduced sensitivity to blue light.

**Colour vision tests**: These are examinations that investigate the ability of a person to see colour and how they perceive it. There are several different types of tests, from laboratory-based tests, to clinical and occupational. They all have different test criteria and purposes. Some tests are used simply for screening, so just differentiating between normal and colour deficient people, others test how certain colours are perceived through colour naming or colour organisation, whilst a few actually grade, classify and define the type of colour vision a person has.

**Colourfulness**: Attribute of a visual sensation according to which an area appears to exhibit more or less of its hue.

**Complementary colour stimulus**: Two colour stimuli are complimentary when it is possible to reproduce the tristimulus values of a specified achromatic stimulus by an additive mixture of these two stimuli.

**Complementary wavelength**: The wavelength of the monochromatic stimulus that, when additively mixed in suitable proportions with the colour stimulus considered, matches the specified achromatic stimulus.

**NOTE:** Every colour stimulus has either a complementary wavelength or a dominant wavelength. Some, but not all, colour stimuli have both.

**Cones**: Photoreceptors in the retina that contain light-sensitive pigments (photopigments) capable of initiating the process of photopic vision. There are three types: L-cones ('red'), M-cones ('green') and S-cones ('blue').

**Congenital red/green colour defect**: Inherited form of colour vision deficiency causing confusion of colours along the red/green axis of the chromaticity diagram. The deficiency is connected to the X-chromosome so is passed down through the female line. The defect only becomes apparent when the full compliment of X-chromosomes is affected so it is predominant in males (who only have one X-chromosome) and females (who have two X-chromosomes) are usually only carriers. (See Red/green colour vision deficiencies - congenital.)

**Contrast**:

a) **Chromatic**: the chromaticity difference between two areas such as a symbol and its background. This includes the difference in dominant wavelength and excitation purity between two colours.

b) **Luminance**: the relative luminance difference between two areas. It can be defined in several different ways.

**Dark**: Adjective denoting low lightness.

**Daylight illuminant**: Illuminant having the same, or nearly the same, relative spectral power distribution as a phase of daylight.

**Defective colour vision**: Abnormal colour vision in which there is a reduced ability to discriminate some or all colours (see Colour vision deficiencies).

**Deutan**: Adjective denoting deuteranopia or deuteranomaly.

**Deuteranomalous trichromats**: Person with deuteranomaly.

**Deuteranomaly**: Congenital defective colour vision in which discrimination of the reddish and greenish contents of colours is reduced, without any colours appearing abnormally dim. The M-cone ('green') is abnormal.

**Deuteranope**: Person with deuteranopia.

**Deuteranopia**: Congenital defective colour vision in which discrimination of the reddish and greenish contents of colours is absent, without any colours appearing abnormally dim. The M-cone ('green') is missing.

**Dichromat**: Person with Dichromatism.

**Dichromatism**: Defective colour vision in which all colours can be matched using additive mixtures of only two matching stimuli. One of the three cone types is missing.

**Dim**: Adjective denoting low brightness.

**Dominant wavelength**: The wavelength of the monochromatic stimulus that, when additively mixed in suitable proportions with the specified achromatic stimulus, matches the colour stimulus considered. Dominant wavelength correlates with the hue of a colour. It is the spectrum colour one would mix with the reference white in order to make a colour match. Spectrum colours are those colours that are produced by passing white light through a prism and appear on the boundaries of the CIE chromaticity diagrams.

**Efficiency**: The efficiency of a colour vision test is its overall predictive value.

**Equal energy white**: Stimulus consisting of equal amounts of power per small constant-width wavelength interval throughout the spectrum.

**Excitation purity**: The excitation purity of a colour stimulus is the ratio of two lengths on a chromaticity diagram. The first length is the distance between the point representing the chromaticity of a specified achromatic stimulus and that representing the chromaticity of the colour stimulus considered; the second length is the distance along the same direction and in the sense from the first point to the edge of the chromaticity diagram.

**Fluorescence**: Process whereby materials absorb radiant power at one wavelength and immediately re-emit it at another (usually longer) wavelength.

**Fovea**: Central part of the retina that contains almost exclusively cones, and forming the site of most distinct vision. It subtends an angle of about 1.5° in the visual field.

**Foveola**: Central region of the fovea that contains only L- and M-cones and is limited to a diameter of about 0.3 mm; it subtends an angle of about 1° in the visual field

**High-ambient lighting conditions**: The maximum ambient illumination in a transport aircraft flight deck is at least 86,000 lux, while in a bubble-canopy aircraft the value is at least 107,500 lux. These figures, of course, are mediated by such factors as sun altitude, transmittance of the windshields or canopy and angle of incidence of light to the display.

**Hue**: Attribute of a visual sensation according to which an area appears to be similar to one, or to proportions of two, of the perceived colours red, yellow, green and blue. Hue is independent of both saturation and brightness.

**Illuminance**: A measure of the amount of light incident at a point of a surface. This can be measured by instrumentation. The SI units are lumens per square meter (lux), abbreviated as lx.

**Intensity**: 1. Luminous intensity - luminous flux per unit solid angle, the SI unit of light. Unit: candela, cd. 2. General term used to indicate the magnitude of a variable.

**Isomeric matching colour stimuli**: Colour stimuli that look exactly the same and have identical spectral composition and tristimulus values.

**L-cones**: Long wavelength cones. Commonly referred to as 'red' photoreceptors.

**Light**: 1. That aspect of radiant energy of which a human observer is aware through the visual sensations that arise from the stimulation of the retina of the eye by the radiant energy. 2. Adjective denoting high lightness.

**Lightness**: The attribute of a visual sensation according to which the area in which the visual stimulus is presented appears to emit more or less light in proportion to that emitted by a similarly illuminated area perceived as a "white" stimulus. In a sense, lightness may be referred to as relative brightness. Variations in lightness range from 'light' to 'dark'.

**Luminance**: The amount of light emitted, transmitted or reflected from a display, light source, or other object. It can be measured by instrumentation. The SI units are candelas per square metre (cdm-2).

**Luminous efficiency**: Ratio of radiant flux weighted according to the V(l) function, to the radiant flux.

**M-cones**: Medium wavelength cones. Commonly referred to as 'green' photoreceptors.

**Macula (macula pigment)**: Layer of photostable pigment covering parts of the retina in the foveal region. Wide variation of density from person to person.

**Maxwellian View**: A special kind of viewing that occurs when a visual instrument projects an image onto the retina by first focusing the light into a small portion of the eye's pupil. In order to examine visual function without the normal optical limitations imposed by diffraction and aberrations of the eye, clinical optometrists and vision scientists have adopted and modified the technique known as Maxwellian view. Diffraction effects are avoided by focusing all of the light into a small spot that fits well within the pupil of the eye.

**Mesopic vision**: Vision intermediate between photopic and scotopic vision. (Both the cones and rods are active to differing degrees depending on the level of mesopic light adaptation.)

**Metameric matching colour stimuli**: Spectrally different colour stimuli that have identical tristimulus values so look exactly the same.

**Monochromat**: Observer who is completely unable to discriminate stimuli by their colour. Two or all of the three cone types are missing.

**Monochromatic (radiation) stimulus**: Monochromatic radiant power of given magnitude and single wavelength (or frequency), entering the eye and producing a sensation of light or colour. (See Spectrum colours (spectrum)).

**Monochromatism**: Defective colour vision in which all colours can be matched using only a single matching stimulus.

**Munsell system**: A colour order system.

**Nanometre, nm**: Very small unit of length equal to 10-9 metre commonly used for identifying wavelengths of the spectrum.

**Neuron**: Nerve cell.

**Neutral colours**: Adjective for all colours with x,y, chromaticity co-ordinates along the straight line on the CIE 1931 chromaticity diagram that joins the neutral point with the purple boundary, through the white used for the match. As long as there is no perceived lightness difference, all these colours look the same as each other and the same as neutral grey.

**Neutral point**: This is the spectral wavelength that matches equal energy white for colour deficients. Further specified by the colour temperature of the white light used for the match.

**Non-self-luminous colour stimulus**: Stimulus that consists of an illuminated object, which does not produce light.

**Normal trichromats**: Person with normal colour vision.

**Normal colour vision**: The ability that the majority (92%) of the population have of seeing and interpreting colour.

**Optical axis (of the eye)**: The direction defined by a line passing through the optical elements of the eye.

**Photometer**: Optical radiation detector constructed to mimic the spectral response of the eye.

**Photometry**: Photometry is the measurement of light, which is defined as electromagnetic radiation which is detectable by the human eye. It is thus restricted to the wavelength range from about 360 to 830 nanometres. Photometry is just like radiometry except that everything is weighted by the spectral response of the eye (Vl and V'l function). Visual photometry uses the eye as a comparison detector, while physical photometry uses either optical radiation detectors constructed to mimic the spectral response of the eye, or spectroradiometry coupled with appropriate calculations to do the eye response weighting. Typical photometric units include lumens (luminous flux), lux (illuminance), candelas (luminous intensity).

**Photon**: A quantum of light or of other electromagnetic radiation.

**Photopic vision**: Vision by the normal eye when it is adapted to levels of luminance of at least several candelas per square metre (daylight). (The cones are the principle photoreceptors that are active in photopic vision.)

**Photoreceptors**: Light receptors in the retina of the eye; either rods or cones.

**Photopigments (light-sensitive pigments)**: Pigments in the photoreceptors. There are three types of cone photopigments. It is the interaction of these pigments and light that initiates the visual process.

**Power**: Energy per unit time.

**Primary colour stimuli (primaries)**: Colour stimuli by whose additive mixture nearly all other colour stimuli may be completely matched in colour. These colour stimuli are often chosen to be either red, green, and blue, or red, green, and violet.

**Primary visual cortex**: A region at the back of the brain to which all visual information is initially sent for basic processing e.g. shape, before being sent on to other regions for more specialised processing, e.g. colour and motion.

**Protan**: Adjective denoting protanopia or protanomaly.

**Protanomaly (protanomalous trichromatism)**: Congenital defective colour vision in which discrimination of the reddish and greenish contents of colours is reduced, with reddish colours appearing abnormally dim. The L-cone ('red') is abnormal.

**Protanope**: Person with protanopia.

**Protanopia**: Congenital defective colour vision in which discrimination of the reddish and greenish contents of colours is absent, with reddish colours appearing abnormally dim. The L-cone ('red') is missing.

**Purity**: A measure of the proportions of the amounts of the monochromatic stimulus and of the specified achromatic stimulus that, when additively mixed, match the colour stimulus considered. (In the case of purple stimuli, the monochromatic stimulus is replaced by a stimulus whose chromaticity is represented by a point on the purple boundary.)

**Purple boundary**: The line in a chromaticity diagram that represents additive mixture of monochromatic stimuli from the two ends of the spectrum, according to wavelengths of approximately 380 and 780 nm.

**Purple stimulus**: Stimulus that is represented in any chromaticity diagram by a point lying within the triangle defined by the point representing the specified achromatic stimulus and the two ends of the spectral locus, which correspond approximately to the wavelengths 380 and 780 nm.

**Radiometry**: The measurement of optical radiation, which is electromagnetic radiation within the frequency range between 3×1011 and 3×1016 Hz. This range corresponds to wavelengths between 10 and 106 nanometres (nm), and includes the regions commonly called the ultraviolet, the visible and the infrared. Two out of many typical units encountered are watts/m2 (irradiance) and watts/steradian (radiant intensity).

**Radiant**: Adjective denoting measures evaluated in terms of power.

**Rayleigh match**: Involves matching a spectral (or nearly spectral) yellow light to a mixture of spectral (or nearly spectral) red and green lights. Although only two primaries are used, a perfect match can be achieved. The primaries and test light occur at wavelengths to which the S-cone photopigment is not sensitive. As only two photopigments (M-cones and L-cones) are active, for normal colour vision, only two primaries are required. This Rayleigh match system differentiates normal trichromats from observers with all types of congenital red/green colour defect and allows classification of congenital red/green defects and is used in instruments such as the Nagel anomaloscope.

**Red/green colour vision deficiencies - congenital**: Group term for protan and deutan deficiencies. The most common defects of colour vision, they share a common mode of inheritance and similar colour confusions in the red-yellow-green range. (See Congenital red/green colour defects.)

**Redundant coding**: The repetition of information provided in one code by another code. Values of the two codes can be correlated with each other either totally or partially. A multidimensional display combining numeric and colour codes provides a good example of redundant coding. If the numeric code consists of the digits one through six and the colour code consists of six different colours, then the unique assignment of one of the six colours to each of the six digits would produce complete redundancy. Knowing either the digit or the colour would provide complete information. However, if only three colours were used and each colour was assigned to two of the six digits, then the colour code would be only partially redundant with the numeric code. Knowledge of the colour of a symbol would only constrain the range of possible numeric values, thus providing only partial information as to the exact numeric value.

**Reflection**: Return of radiation by a medium without change of frequency (that is without fluorescence).

**Relative spectral power distribution**: Spectral power per small constant-width wavelength interval throughout the spectrum relative to a fixed reference value.

**Retina**: Light sensitive layer on the inside of the back of the eye; it contains the photoreceptors and nerve cells that transmit the visual signals to the optic nerve.

**Rods**: Photoreceptors in the retina that contain a light-sensitive pigment (photopigment) capable of initiating the process of scotopic vision.

**S-cones**: Short wavelength cones. Commonly referred to as 'blue' photoreceptors.

**Saturation**: Colourfulness of an area judged in proportion to its brightness. The attribute of a visual sensation that permits a judgment to be made of the degree to which a chromatic stimulus differs from an achromatic stimulus regardless of their brightness.

**Scotopic vision**: Vision by the normal eye when it is adapted to levels of luminance less than some hundredths of a candela per square metre (darkness). (The rods are the principle photoreceptors that are active in scotopic vision.)

**Self-luminous colour stimulus**: Stimulus that produces its own light.

**Sensitivity**: The sensitivity of a colour vision test is the percentage of colour deficient subjects correctly identified as such.

**Signal**: Information conveyed to the brain, usually in a prearranged or recognisable format, e.g. visual, colour (chromatic) and audio signals are forms of information that the brain can interpret as having a certain meaning, from simply recognising what colour something is, to that colour having a certain meaning attached to it, such as red meaning danger.

**Signal light**: Light used in transport systems for conveying information to the observer. as defined by the CIE standards 0.2.2, 1975 and the updated S004/E-2001, 2001. These standards specify 'the allowable colours for steady signal lights and flashing signal lights where the duration of the on period is at least one second'. They are 'applicable to the colours of signal lights used in sea, road, air and rail transport systems including signal lights on ships, aircraft, motor vehicles and trains, where the recognition of colour is essential.' The standards 'can also be used for guidance on the selection of the colours of light signals and warning lights on instrument panels in vehicles and the colours used in visual display terminals when recognition of the colour code is important to interpreting the information displayed.' (CIE S004/E-2001, 2001)

**Specificity**: The specificity of a colour vision test is the percentage of normal colour vision subjects correctly identified as such.

**Spectral**: Adjective denoting that monochromatic concepts are being considered.

**Spectral hues**: Monochromatic stimuli throughout the spectrum represented as the spectral locus in a CIE chromaticity diagram. (See spectrum colours.)

**Spectral locus**: Locus in a chromaticity diagram of the points that represent monochromatic stimuli throughout the spectrum. (See spectrum colours and spectral hues.)

**Spectral luminous efficiency, V(λ), V'(λ)**: Weighting functions used to derive photometric measures from radiometric measures in photometry. Normally the V(λ) function is used, but, if the conditions are such that the vision is scotopic, the V'(λ) function is used and the measures are then distinguished by the adjective 'scotopic' and the symbols by the superscript '.

**Spectral power distribution**: Spectral power per small constant-width wavelength interval throughout the spectrum.

**Spectrum colours (spectrum)**: Those colours that are produced by passing white light through a prism and appear on the boundaries (spectral locus) of the CIE chromaticity diagrams. (See monochromatic stimulus and spectral hues.)

**Stimulus**: A thing that evokes a specific functional reaction in an organ or tissue (usually a visual stimulus in this report).

**Subtractive mixing of colorants**: Production of colours by mixing colorants in such a way that they each subtract light from some parts of the spectral power distribution used to illuminate them.

**Système International d'Unités**: International System of Units (international abbreviation SI), for the recommended practical system of units of measurement. The base units are a choice of seven well-defined units that by convention are regarded as dimensionally independent: the metre, the kilogram, the second, the ampere, the kelvin, the mole, and the candela. Derived units are those formed by combining base units according to the algebraic relations linking the corresponding quantities. The names and symbols of some of the units thus formed can be replaced by special names and symbols which can themselves be used to form expressions and symbols of other derived units.

**Trichromatic matching**: Action of making a colour stimulus appear the same colour as a given stimulus by adjusting three components of a colour mixture.

**Tristimulus values**: Amounts of the three additive matching stimuli (see Additive mixing), in a given trichromatic system, required to match or to specify the stimulus considered.

**Tritan**: Adjective denoting tritanopia or tritanomaly.

**Tritanomaly**: Congenital defective colour vision in which discrimination of the bluish and yellowish contents of colours is reduced. The S-cone ('blue') is abnormal.

**Tritanopia**: Congenital defective colour vision in which discrimination of the bluish and yellowish contents of colours is absent. The S-cone ('blue') is missing.

**Unique hues**: Hues that cannot be further described by the use of hue names other than its own (also referred to as unitary hue). There are four unique hues, each of which shows no perceptual similarity to any of the others; they are: red, green, yellow, and blue. A light (colour stimulus) perceived to be unique red is judged to be neither yellow nor blue. Similarly, unique yellow is neither red nor green; unique green is neither yellow nor blue; and unique blue is neither green nor red. The hueness of a light (colour stimulus) can be described as combinations of two unique hues; for example, orange is yellowish-red or reddish-yellow. Sometimes, non-unique hues such as orange are referred to as binary hues.

**V(λ) function**: Weighting function used to derive photometric measures from radiometric measures in photometry.

**V'(λ) function**: Weighting function used to derive scotopic photometric measures from radiometric measures in photometry.

**Visual axis**: The direction defined by a line joining the centre of the fovea to the centre of the pupil of the eye; the visual axis is offset from the optical axis of the eye by about 4°.

**Wavelength**: The distance between two successive points of a periodic wave in the direction of propagation in which the oscillation has the same phase. The wave propagates a distance equal to one wavelength during every period. Thus, the product of wavelength and frequency is equal to the velocity of the wave.

**Whiteness**: Attribute of a visual sensation according to which an area appears to contain more or less white content.

**x,y diagram**: Chromaticity diagram in which the x,y chromaticity co-ordinates of the CIE XYZ system are used. (See CIE 1931 x,y chromaticity diagram.)

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