Colour vision standards in aviation

Anthony D B Evans and John L Barbur

INDIVIDUALS WITH SOME FORM of red–green colour deficiency (the most common type) seem to function adequately in society and many men (the deficiency occurs in around 8% of males, and only 0.5% of females) apply for a Class 1 medical certificate unaware of any problem. It is only when they are rejected for commercial flying that they become aware of any deficiency.

Congenital colour-deficient observers vary enormously in their ability to discriminate different colours, and they often perform quite differently on various occupational colour vision tests.[1] This is largely because several factors can change chromatic sensitivity[2] and these affect the individual's ability to name colours, to recognise colour-defined patterns when camouflaged in spatial noise, to order colour patches in minimum detectable steps or to discriminate the colour of small lights when no other cues are present.[3] Most congenital colour deficiencies affect red–green discrimination. Loss of yellow–blue discrimination is mostly acquired.

Colour is often used to enhance conspicuity, to code functional information and to group objects into categories. Visual performance can be improved and the visual load significantly decreased when colour information is used appropriately in demanding visual tasks. This is particularly relevant in air traffic control, where the visual task is complex and extends over long periods. Although occupational colour vision tests often produce some form of grading of the severity of colour vision loss, the use of such information in relation to the requirements of specific visual tasks remains a difficult problem.[1]

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Abstract

- Many individuals with colour vision deficiency function adequately in society and often are not aware of any deficiency until they are rejected for commercial flying.
- The standards for aviation colour vision require a pass on a screening test (pseudoisochromatic plates) or a pass on a secondary test.
- Various secondary tests are accepted by different states, and protocols are not standard, so an individual's pass/fail result depends both on the level of deficiency and on the state where the test is conducted.
- There is a need for an accurate colour vision test and pass/fail criteria, based on an up-to-date task analysis of the requirements of modern flying, to be developed for international use by regulatory authorities.

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We explore the most common methods of colour vision testing in aviation and discuss the associated problems. The emphasis is on colour vision requirements for professional pilots.

Regulatory requirements for colour vision

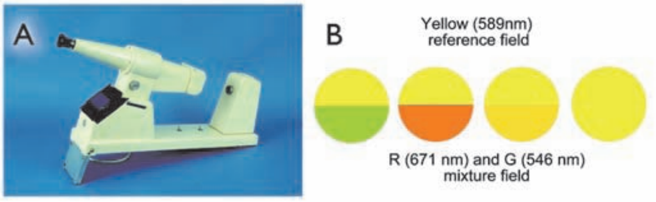
The International Civil Aviation Organisation (ICAO) sets standards for colour vision. These require that: "The applicant shall be tested for the ability to correctly identify a series of pseudoisochromatic plates."[4] However, an applicant who fails this test can be assessed as fit if he is "able to readily distinguish the colours used in air navigation and correctly identify aviation coloured lights".[4] This two-stage process can be summarised as a requirement to use a screening test, followed by a secondary test for any who should fail this. A pass at either stage is required for Class 1 aeromedical certification.

Most aviation colour vision tests do not assess yellow–blue colour discrimination. Testing for yellow–blue deficiencies is under special consideration in military flying applications and in air traffic control, where even a small deficiency is not acceptable.

Screening tests

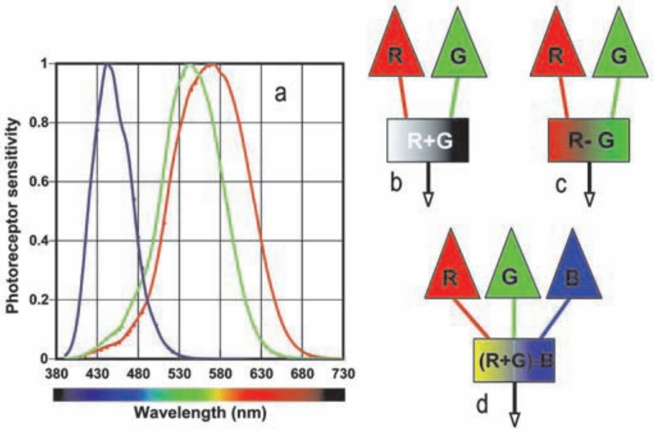
The ICAO does not specify the type of pseudoisochromatic plates (patterns falsely perceived by colour-deficient observers as being indistinguishable from the background). There are many types of plates and they vary in their efficiency at detecting people with reduced colour sensitivity. Different tests can produce different results for the same individual and, even

1: The Nagel anomaloscope



A: The Nagel anomaloscope.
B: The stimulus seen by the subject . The task is to adjust the mixture of red (wavelength, λ = 671 nm) and green (λ = 546 nm) in the lower "test" half of the field to match the perceived colour of the yellow "reference" field (λ = 589 nm). A normal trichromat can only match the colour appearance of the yellow field with a narrow range of red–green mixtures. Subjects who lack functioning red or green cone photoreceptors in the eye can match the yellow field with any red–green mixture. Abnormal functioning of either the red or the green photoreceptors results in a larger range of red–green mixture ratios that match the perceived colour of the reference field. A subject with green cone deficiency (deuternanomalous) requires more green light, and a subject with red cone deficiency (protanomalous) requires more red light to make the match. A complete match also requires adjustment of the brightness of the yellow reference field. Red cone deficiency can make the subject less sensitive to long wavelength light and this causes the red–green mixture field to appear dark. Thus, protanomalous observers need less light (ie, lower luminance) in the yellow field to produce an identical match to the test field. This observation, in addition to the mean and range of red–green ratios that match the yellow field, makes it possible to distinguish between protanomalous and deuteranomalous observers.

2: Colour and luminance channels



Normalised spectral responsivity functions of cone photoreceptors in the eye (a).[5] Light to which the normal eye responds is detected within three spectral bands described as long, medium and short wavelength light, which correspond to colour sensations described as red, green and blue, respectively. The luminance channel is formed largely through the addition of red and green cone signals (b). The difference between red and green cone signals produces the red–green colour channel (c). The yellow–blue channel is achieved by subtracting the blue cone signal from the sum of the red and green cone signals (d).

if the same test is used, the conditions of use can vary and the pass criteria are not standardised. For example, European member states of the Joint Aviation Authorities (JAA) use the 24-plate Ishihara test. The applicant is shown the first 15 plates (plate 1 is for demonstration and will be passed by anyone with adequate visual acuity, and plates 16–24 are for children or illiterates) and the JAA requires correct identification of all 15 plates. On the other hand, the United States Federal Aviation Administration accepts several pseudoisochromatic test formats, of which Ishihara is but one. If the Ishihara test is used, the pass requirement is correct identification of nine of the first 15 plates. In Australia, 13 correct responses constitute a pass.

It is possible to learn, to a certain extent, the correct responses. This difficulty is only partly overcome by presenting the plates in a random fashion. Furthermore, normal individuals can misread a plate — according to the JAA requirements this constitutes an error and will result in secondary testing. However, the requirement to undergo a secondary test would not be a problem if it could be assumed that the secondary tests produce valid results, consistently passing those with normal colour vision (or with an acceptable deficiency) and failing others.

Secondary tests

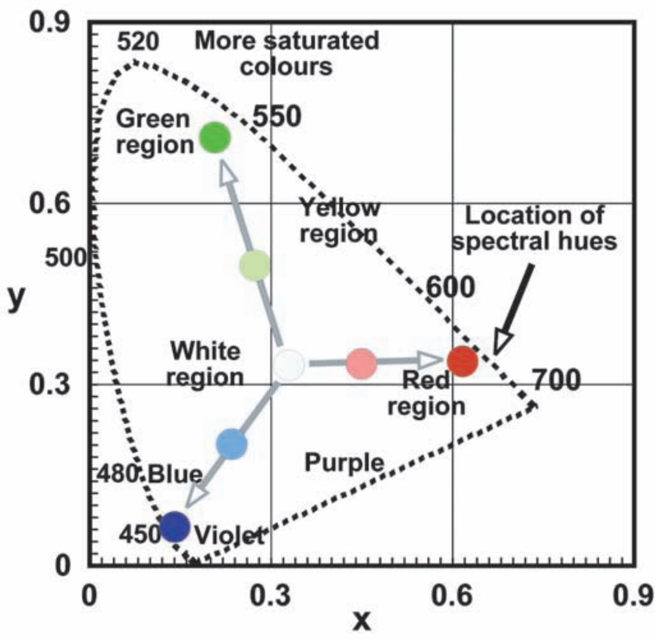
As with the pseudoisochromatic plates, various secondary tests are used by different regulatory authorities. The JAA permits four tests, reflecting the historical practice in different groups of member states before harmonisation. Three different "lantern" tests are acceptable. The Holmes-Wright and the Spectrolux lanterns use lights in hues of red, green and white, and pairs of lights are presented to the applicant. The Beyne lantern shows red, green and white hues, but also shows yellow and blue. It differs from the other two in presenting only one light at a time.

The fourth secondary test is the Nagel anomaloscope (Box 1), which is based on a normal trichromat's ability to match a spectrally pure (ie, single frequency) yellow with a mixture of red and green lights (Box 1).

The Nagel anomaloscope can be used to quantify the severity of colour vision loss. However, the grading of anomaly does not always correlate with the subject's ability to discriminate colour differences under more natural viewing conditions.[3] Thus, even the results of the Nagel anomaloscope, regarded by many as the gold standard for diagnosing and quantifying red–green colour deficiencies, are not sufficient to predict the subject's loss of red–green colour discrimination sensitivity in normal activity.

It is not surprising that individuals produce different results on different secondary tests, as even if an identical test is used by different authorities the protocol may not be identical. To understand some of the reasons why differences in results can

3: The Commission Internationale de l'Eclairage (CIE) chromaticity diagram



The three phosphors of a typical visual display (saturated red, green and blue dots) plotted on the CIE chromaticity diagram, together with less saturated colours that plot closer towards the centre grey dot (the location of an "equal energy" white). Each point in this diagram represents the relative proportions of red, green and blue cone signals generated when light of a given spectral composition illuminates the retina. Monochromatic wavelengths plot along the dotted line (known as the spectrum locus), with "purples" representing the different proportions of red and blue light. An important property of this diagram is that lights of two different chromaticities that are joined by a line (eg, the line formed by joining the green and red phosphor chromaticities) can be combined together in different proportions to form a range of colours that plot along this line. For example, light from the red phosphor can be added to light from the green phosphor to produce new colour that appears yellow to the eye (the principle of the Nagel anomaloscope).

be expected, it is useful to examine the characteristics of these tests and their differences in relation to luminance and colour channels in human vision.

The processing of luminance and colour signals

The underlying mechanisms of vision are not fully understood. A simplified theory postulates the existence of different "channels" for the processing of different stimulus attributes (Box 2). In good ambient illumination, luminance information is derived from all three cones, but mainly red and green. In poorer lighting, cone photoreceptors contribute less to vision, and this causes reduced colour discrimination and poorer visual acuity.

The signals generated in red, green and blue cones combine to form three channels that extract the spatial variations in intensity and spectral content in the retinal image (Box 2). These correspond loosely to what we perceive as luminance edges and colour variations. In the red–green region of the spectrum, colour information is extracted by comparing red and green cone signals. Lack of functioning green or red cones abolishes the red–green colour channel. Yellow–blue discrimination is achieved by comparing the signals generated in blue cones against the output of red and green cones. Lack of blue cones abolishes the yellow–blue channel, whereas the absence of either red or green cones (but not both) changes the characteristics of the yellow–blue channel (but does not abolish it).

Using the channel theory of colour discrimination, there are two types of colour vision deficiency. Congenital absence or deficiency of the red or the green photoreceptors is relatively common, whereas congenital deficiency of blue photoreceptors is very rare. However, loss of yellow–blue sensitivity as a result of damage to blue cones is the most common acquired colour vision deficiency. Yellow–blue loss is often observed in glaucoma, optic neuritis, damage following treatment of compressive optic neuropathies, and other pathological conditions. Some indications of a medical problem are usually apparent before the subjects notices any colour vision loss, although, with improved techniques for assessing loss of colour sensitivity, the earliest sign of pathology can be determined by an increase in thresholds for detection of colour changes.

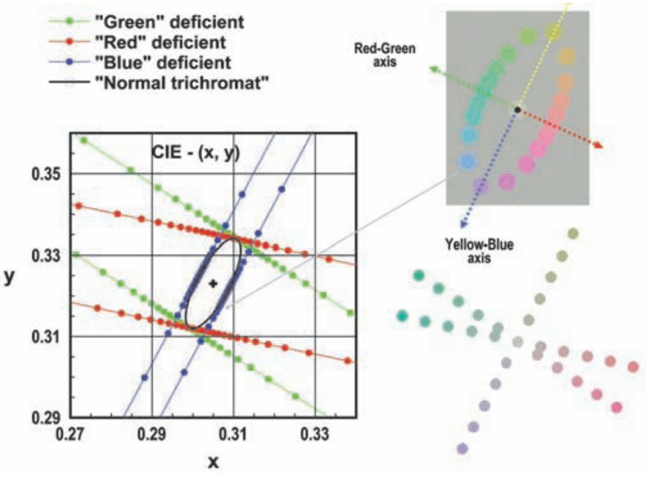
The principal reason why colour-deficient individuals can cope with demanding visual tasks is because most objects are defined by both luminance and colour contrast. Most visual functions, in particular the detection of small, faint objects, involve mostly the luminance channel. The effects of poor colour discrimination can be minimised using other cues. For example, discrimination of traffic lights does not usually present a problem because when one is illuminated it appears brighter than the others, and can be identified because the orientation of the lights is standard. Thus, when designing tests to identify colour vision deficiencies it is important to ensure that the subject cannot use luminance contrast.

An additional cue that can be used by protanopes is that red objects appear dark in comparison to objects in other colours. Above 650 nm, only red photoreceptors have sufficient sensitivity to register light, so if these receptors are absent or insensitive, red colours will appear dark or, in extreme cases, black. This is functionally important, as protanopes may not see red lights against a dark background.

Commission Internationale de l'Eclairage (CIE) chromaticity diagram

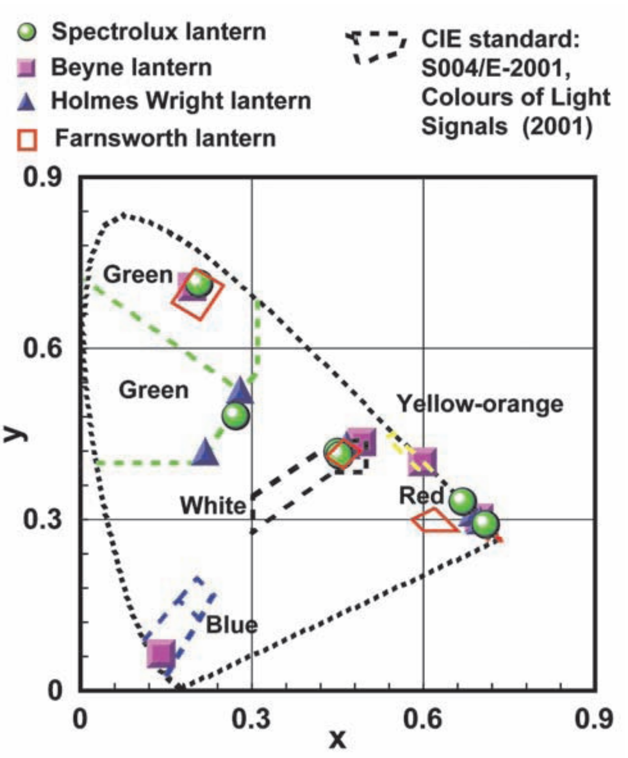
Different colours and the action of the red–green and yellow–blue channels can be represented by means of the CIE chromaticity diagram (Box 3). Each point in this diagram

4: Colour confusion bands



Chromaticity diagram showing the "colour confusion bands" of deuteranopes (green lines), protanopes (red lines) and tritanopes (blue lines), together with the threshold ellipse for the average normal trichromat. The CIE D_{65} standard illuminant plots at the centre of the ellipse. A normal trichromat cannot discriminate between the grey background and any test colour that plots within the black ellipse. In the absence of luminance contrast cues, dichromats cannot discriminate the test colour from the background for any colour that plots along the relevant colour confusion band. The arrows indicate the directions in colour space when colour discrimination is mediated entirely by the by the yellow–blue and the red–green chromatic channels. The colours around the ellipse shown in the upper right section illustrate what a normal trichromat sees when presented with equal, above threshold, colour signal strengths. The lower right section shows the appearance of colours that are confused by each class of dichromat when discrimination is against a D_{65} background.

5: Aviation colours tests and Commission Internationale de l'Eclairage (CIE) recommendations



The regions surrounded by dashed lines indicate the CIE recommended colours for tasks requiring colour discrimination. The lights used in the various lantern tests used for aviation testing are also plotted, and are within the recommendations (except for Farnsworth red).

corresponds to a unique proportion of red, green and blue cone signals. Lights that differ in spectral composition can yield identical proportions of cone photoreceptor signals (ie, the observed colours appear identical and plot at the same location in the chromaticity diagram). These are known as metameric colours.

Box 3 also shows the locations of the lights produced by the red, green and blue phosphors (light-emitting elements) of a typical visual display. Any colour within the triangle formed by these phosphors can be produced by appropriate amounts of light generated by the display phosphors. The ease with which different colours can be generated makes it possible to test for red–green and yellow–blue chromatic sensitivity using such a display.

Colour confusion lines

The common colour vision tests used in aviation detect only deficiencies associated with red–green colour discrimination. New developments in colour vision testing make it possible to isolate the use of red–green and yellow–blue colour signals to classify deficiency and quantify the loss of chromatic sensitivity. Using the CIE diagram, it is possible to measure any deficiency and indicate the colours that an individual will be unable to discriminate.

Box 4 shows the colour confusion "bands" near the centre of the CIE diagram. Within the ellipse at the centre, different colours cannot be discriminated against the grey background by a normal trichromat. Protanopes, deuteranopes and tritanopes are unable to distinguish colours that lie between the relevant pairs of parallel lines.

An individual lacking functional red or green photoreceptors is unable to discriminate between the colours lying along the corresponding colour confusion line (see Box 4, lower right). Anomalous trichromats, on the other hand, have increased thresholds that vary with the severity of colour vision loss. Hence, there is a range of ability to detect colour differences along the red and green confusion lines, ranging from those unable to detect even the largest changes (protanopes, deuteranopes) to those who can do so to varying degrees (protanomalous, deuteranomalous and "normals").

Colour lanterns

The CIE specifies colours (in terms of coordinates on the chromaticity diagram) that should be used when designing tasks that rely on colour recognition (Box 5). In specifying lights to be used for aviation purposes, ICAO follows these recommendations.

The three JAA colour lanterns, and the Farnsworth lantern, use different chromaticities for each test (Box 5). All lights, apart from the Farnsworth red, use colours within the recommended CIE chromaticity values. Differences between the tests are apparent in red, white and green, and are particularly marked in the green. Only the Beyne lantern assesses ability to distinguish blue and yellow lights.

As the various tests use different colours, geometries and presentation times, different outcomes are possible when the same individual is tested on the various lanterns. If different protocols are also used (standard protocols are often not specified) and different pass criteria or levels of discretion are applied, this will inevitably lead to inconsistencies of outcome.

Conclusion

Most aviation regulators accept that a minimum level of ability to discriminate between different colours is necessary for safe professional flying operations. Less certain is the degree of acceptable colour vision deficiency that is compatible with flight safety, and different states currently apply various pseudoisochromatic plate types, colour lanterns, anomaloscopes and signal light tests. Even when the same test is used, this does not guarantee consistency between states in aeromedical decision-making, as different protocols with different pass/fail criteria are used. This can result in a fit/unfit decision for a mildly colour deficient applicant being dependent not only on the degree of his colour deficiency, but also on the country in which he applies for a medical certificate.

There is a need for an accurate colour vision test and pass/fail criteria, based on an up-to-date task analysis of the requirements of modern flying, to be developed for international use by regulatory authorities.

Competing interests

None identified.

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