# An update on diagnostic tests for colour vision defects in individuals working in the aviation industry

**PS Makunyane**
Department of Ophthalmology, University of Pretoria, Steve Biko Academic Hospital, Pretoria, South Africa

*Correspondence:* Dr Seipati Makunyane, Acting Academic Head of Ophthalmology, Steve Biko Academic Hospital, Private Bag X169, Pretoria, 0001, South Africa. e-mail: drseipati@iafrica.com; prisilla.makunyane@up.ac.za

## ABSTRACT

***Background:*** Colour vision is a function of the visual system and is important in visually-demanding environments such as aviation. There is no international consensus on minimum colour vision standards or on colour vision assessment protocols for use in aviation.
***Objective:*** To provide an update on colour-vision tests approved by the International Civil Aviation Organization and to highlight the importance of choosing appropriate colour-vision tests that can be used with confidence to detect colour-vision deficiency, to classify the type of deficiency involved, and to quantify the severity of loss.
***Methods:*** Available English literature was reviewed. The articles reviewed focused on the colour-vision tests recommended by the International Civil Aviation Organization.
***Findings:*** Comparisons of conventional colour-vision tests revealed the enormous variability and inconsistency of outcomes. Novel techniques of colour-vision assessment referred to as precision tests provide more description of the class and severity of colour vision loss. These techniques go a long way towards establishment of an objective and less variable colour-vision assessment within aviation.
***Conclusion:*** There is a clear need for the development of an internationally recognised system of colour-vision assessment that is less variable and can be used to accurately classify the class of colour deficiency and severity of loss of vision. There is an even greater need to establish the level of residual colour vision that can be classed as safe within well-defined working environments to ensure that applicants who can carry out safety-critical, colour-related tasks, as well as normal trichomats, are not discriminated against on the basis of their colour deficiency.

***Keywords:*** colour-vision defects, colour assessments, precision tests, International Civil Aviation Organization, pseudo-isochromatic tests

## BACKGROUND

Human beings and other primates possess three distinct classes of retinal cone photoreceptors. These cones contain either short wave (S), medium-wave (M), or long-wave (L) sensitive photo-pigments. These S, M and L-photopigments have overlapping spectra with peaks of maximal absorption at 420, 530 and 560 nm, respectively. The 30 nm difference between the L and M cones is accounted for by the differences in amino acids positions. The trichomatic colour perception relies on interplay among outputs from these three cone photoreceptor classes.[1]

Colour vision is an important attribute and of utmost importance in a visually-demanding work environment such as that in which aviators work. Many of the features and cues in their environment, e.g. cockpit lights, maps, external airborne lighting, air traffic control instruments and radar screens, are colour-coded. Aviation personnel, especially pilots and air traffic controllers, need to be able to distinguish colours on charts and control panels, and on the terrain.

## COLOUR-VISION DEFECTS

Colour-vision defects occur when there is a deficiency or absence of one or more of the cone types. There are various grades of colour-vision defects, ranging from mild to severe. Subjects with protanopia, deuteranopia and tritanopia are referred to as dichromats (see Table 1). Subjects with protanomaly, deuteranomaly and tritanomaly are called anomalous trichromats.

Because of the extensive use of colour information in many visual environments, it is of greater interest to establish accurately how reduced colour discrimination can affect visual performance, with emphasis on safety-critical tasks. Comparison of results from conventional tests has revealed enormous variability and inconsistency. Consequently, individuals with mild colour-vision defects failed normal trichromacy tests and were therefore prevented from becoming pilots. Individuals with mild colour-vision defects often fail normal trichomacy tests as do some normal trichomats (individuals with three classes of cone receptors; considered normal), and are therefore prevented from choosing certain

**Table 1. Expression of cone-specific pigments in colour vision**

| | Photo pigment expression | | |
|---|---|---|---|
| **Condition** | **L-cone** | **M-cone** | **S-cone** |
| Protanopia | Missing | Normal | Normal |
| Protanomaly | Malfunctioning/defective | Normal | Normal |
| Deuteranopia | Normal | Missing | Normal |
| Deuteranomaly | Normal | Malfunctioning/defective | Normal |
| Tritanopia | Normal | Normal | Missing |
| Tritanomaly | Normal | Normal | Malfunctioning/defective |

career paths. These individuals with mild colour-vision defects might well be able to perform tasks that are critical to safety in aviation, as might normal trichromats, when presented with the same colour signals.[2]

In an attempt to include these individuals in aviation, some authorities either relaxed the pass limits on colour-vision screening tests or used less demanding colour-vision tests. These attempts compromised the required trichromatic performance in the most safety-critical tasks that are colour-coded.[1]

No consensus exists on standard medical requirements and colour-vision protocols in aviation internationally. Conditions under which colour-vision tests are done and the interpretation thereof vary from country to country. Different International Civil Aviation Organization (ICAO)-affiliated countries have set different requirements and use different tests for colour-vision testing. These inconsistencies make it possible for an applicant to fail colour-vision testing in one country and pass it in another.[3] These challenges are further compounded by the fact that significant variability in colour vision exists within normal trichromats, with much greater variability in individuals with congenital colour deficiency.[2]

A question is often asked by aviation personnel as to how severe a colour-vision defect should be before an individual is considered unable to operate safely in the aviation environment. In the text book, Adler's Physiology of the Eye – Clinical Application, the author cautions healthcare workers to not over-diagnose colour-vision defects and consequently exclude individuals from occupations that they could manage.[4]

In the executive summary of the aircraft accident report of Fedex Express flight 1478 in Tallahassee Florida 2002, by the National Transportation Safety Board, one of the cited contributing factors was the first officer's colour-vision deficiency. The safety concerns in this report focused on, among other things, certification of pilots with colour-vision deficiency.[5] The need for the development of an internationally accepted, defensible, objective and standardised set of colour-vision tests that can accurately classify and quantify severity of colour-vision defects was addressed by Milburn et al. in their paper entitled "Pilot colour vision – research and recommendations".[6] Linda Werfelman also addressed the same need in her article that summarised Dougal Watson's study of colour-vision testing in aviation in 78 countries.[3] In the eleventh edition of the text book, Adler's Physiology of the Eye, Adler states that performance of a battery of tests is preferable over performing one type of colour-vision test to provide the most complete assessment of colour-vision defects.[7]

The need for a better understanding of colour-vision requirements was also addressed by the United Kingdom Civil Aviation Authority (UKCAA), supported by the United States FAA together with City University London, when this collaborative team embarked on a study to find the minimum colour-vision requirements for modern flight crew, and designed the 'Colour Assessment and Diagnosis' (CAD) test.[8]

The aim of this review is to give an update on colour-vision tests that are approved by ICAO and to highlight the importance of choosing appropriate colour-vision tests that can be used with confidence to detect colour-vision deficiency.

## METHODS

The search words 'colour vision', 'colour-vision testing in aviation' and 'ICAO-approved colour vision tests' were used on the Internet. All colour-vision tests that were not approved by the ICAO were excluded from this review. Various ophthalmology text books were also consulted. The literature reviewed was written in English and much was published in peer-reviewed journals. The articles focused on colour-vision test methods that have been developed in the last century and recommended by the ICAO. The advantages and limitations of these tests are addressed

**Deuteranopia** **Normal Colour Vision** **Protanopia** **Tritanopia**

> "Colour-vision defects occur when there is a deficiency or absence of one or more of the cone types"

in this paper. Newly-developed precision tests used in assessing colour vision are presented. Recommendations are also discussed.

## DISCUSSION

### The role of colour vision in aviation

Because of the demands on visual acuity and colour perception, and the increased need for aviation safety and advancement in aircraft technology, the need to accurately classify the class of colour vision defect and to quantify the severity thereof in applicants with colour deficiency is of utmost importance. The complexity of aerodromes also plays an important role in colour-vision testing.

The aims of colour-vision testing are grouped into three broad categories:

- Screening for the presence of a congenital or acquired colour vision deficiency
- Diagnosis of the type and severity of colour vision deficiency
- Assessment of the importance of the colour vision deficiency in a particular vocation, employment or occupation

In aviation, colours that are most widely used in cockpits of both civil and military aircrafts, on the flight deck, in the aircraft cabin, on external airborne lighting, in air traffic control instruments, and on radar screens, are red, green, yellow, orange, blue, cyan, magenta and white.

Three types of tests are used in aviation:

- Pseudo-isochromatic plates
- Colour lantern tests
- Anomaloscopes

The fourth and the most recently developed tests are called precision tests and include the CAD, Waggoner's Computerized Colour Vision Test (Waggoner CCVT), and the Cambridge Colour Test (CCT).

### Pseudo-isochromatic plates

These plates are used as screening or primary tests. Pseudo-isochromatic plates are the simplest to use and are based on the principle of colour confusion and colour saturation.[9] The plates are usually presented in book form and require verbal identification of a coloured figure. The design of plates for yellow-blue (YB) defects is particularly difficult due to large variations among normal observers and the rareness of YB colour defects.

There are many types of pseudo-isochromatic plate tests available; the well-known ones are the Ishihara plates, the Dvorine plates and the American Optical Hardy, Hand and Rittler (AO-HRR) plates.The Ishihara test (IT) is the most widely accepted screening test for congenital red-green (RG) defects. The IT was first published in 1917 and since then has been reprinted in many different editions.[8]

*Limitations of pseudo-isochromatic plates*

Errors of interpretation related to pseudo-isochromatic plates may be a result of weak or varying chromatic signals, resulting in poorly defined contours. This form of error can occur if the plates are stored in bright sunlight, resulting in fading of the plate colours. Individual factors, such as advanced age, length of observation time, and the intensity of the background lighting in the examination room, have been reported as causes of errors.[8]

A study aimed at investigating the possibility of attaching appropriate weights to each IT plate as a measure of severity of colour vision defect was conducted in City University, London.[8] The results demonstrated inconsistencies wherein some colour-deficient individuals passed the test as if they were normal trichromats. Moreover, when no errors were allowed during testing, 19% of subjects with normal trichromatic vision also failed. The conclusion was that IT plates are able to detect very mild colour-vision defects but cannot quantify them.[8]

In a study that compared results obtained from IT and other isochromatic plates, inter-subject variability and inconsistency was demonstrated even though, in principle, the tests are similar.[10]

The City University study conclusion is confirmed in Adler's Physiology of the eye – Clinical application: 8th edition. In this book it is stated that RG defects can be easily detected with the pseudo-isochromatic plates, but classification thereof is difficult. It is further stated that the illumination of the plates must be carefully controlled when testing is done.[4] In the text book, Basic and Clinical Science Course 1991-1992, Section 11 Retina and Vitreous, of the American Academy, it is stated that pseudo-isochromatic plates have unfortunately not always been reliable in detecting acquired colour vision defects.[9]

### Lantern tests

These are used to determine whether the subject can detect and correctly name the colours of signal lights. Lantern tests have a high practical value in aviation because they employ supra-threshold signal lights that are used in aviation and maritime environments.[2,4] Lantern tests, together with anomaloscopes, are classified as secondary tests. The lantern tests that are approved by the ICAO are the Farnsworth Lantern test (falant), the Spectrolux, the Beyne lantern, the Optec 900 test, and the Holmes Wright which has two versions: Holmes Wright A and B.

### Anomaloscopes

Anomaloscopes provide the most accurate method to test the severity of colour-vision defects. Anomaloscopes are able to distinguish between dichromats and anomalous trichromats, and use the principle of colour matching in diagnosing colour-vision deficiencies. The anomaloscope's mode of action is based on the Rayleigh match: a mixture of red and green light sources has to be matched with a yellow light source. Through the matching range, it is possible to discover all different types of RG colour-vision deficiency. Some of the advanced anomaloscopes include the Moreland match (blue-green) to test for tritan defects but these are said to be difficult to use because of the differences in macular pigmentation and the lens colours in individuals. These differences lead to a wide distribution of acceptable settings when testing for blue wavelength detection.[4]

*Limitations of lantern tests and anomaloscopes*

Adler states that accurate diagnosis of colour-vision defects is difficult because tests that are easy to do can give inaccurate results, whereas the more accurate tests require rigorous training for the examiner.[4] A study to compare results obtained from testing 55 subjects with colour-vision defects and 24 subjects with normal colour vision was conducted. The IT, the Nagel anomaloscope and three lantern tests were used as Joint Aviation Authorities (JAA)-approved test methods. The results convincingly showed that currently approved tests do not yield consistent results in passing and failing the same individuals. These approved conventional tests do not assess the nature and severity of colour vision defects. There was poor correlation of outcomes of the different tests and they did not give reliable information about safe minimum colour vision required for flying.[10]

## Precision tests

*1. The Colour Assessment and Diagnosis (CAD) Test*

The South African Civil Aviation Authority has selected the CAD test as the precision test of choice. This test was enhanced and optimised for use in aviation when the UKCAA supported by the United States FAA, together with City University London, embarked on a project to establish minimum colour vision requirements for commercial pilots. The CAD employs a carefully calibrated visual display and consists of coloured stimuli which are embedded in a background of dynamic luminance contrast noise. The coloured stimulus moves along each diagonal direction and the subject indicates the direction of motion of the coloured stimulus. The CAD test cannot be learnt and has high sensitivity. It provides automatic classification of colour vision deficiencies and separates normal subjects from congenital and acquired colour-deficient subjects, with 100% sensitivity and 100% specificity.[2]

The CAD has two programmes, namely, the 'fast screening' option and the full RG and YB CAD test programmes which establish the class of colour vision loss and whether the candidate passes (colour-safe) or fails (colour-unsafe) within selected environments.

In the UK, the CAD test is used in occupational medicine for certification in departments of aviation, the fire service, the police and the department of transport for train drivers. The CAD is also used in clinical settings for early detection and monitoring of eye diseases such as sight-threatening diabetic retinopathy. For research purposes, the CAD has been valuable for studies in chromatic mechanisms, ophthalmology and neurology, and in drug trials.

"Comparison of results from conventional tests has revealed enormous variability and inconsistency"

*2. Waggoner Computerized Colour Vision Test (Waggoner CCVT)*

The Waggoner CCVT is used for colour-vision screening and testing for individuals of all ages and was created by Terrace L Waggoner together with his colour-deficient son, TJ Waggoner. The test provides automatic screening and test results by having the subject look at a coloured test plate and selecting an answer from a table of symbols or numbers that appear after the test plate has disappeared. The length of testing time ranges from two to 17 minutes, depending on whether it is used for screening or diagnostic purposes. Test plates are standardised, allowing each subject the same maximum exposure time, and are randomised each time the test starts, to prevent memorisation.[11]

*3. The Cambridge Colour Test (CCT)*

The test was developed by John Mollon and colleagues to determine discrimination ellipses in colour-deficient subjects, by probing chromatic signals along colour confusion lines. Ellipses measured in these individuals are characteristically oriented and enlarged. The test uses the Landolt C stimulus defined by two test colours that are to be discriminated, on an achromatic background.[12]

## RECOMMENDATIONS

Milburn and colleagues examined whether individuals with colour vision deficiency, as well as individuals with

“The South African Civil Aviation Authority has selected the CAD test as the precision test of choice”

normal colour vision, could discriminate job sample tests, and made the following recommendations:[6]

a. The Richmond HRR (4th edition), the Waggoner HRR, the Waggoner pseudo-isochromatic plates, Ishihara Compatible (PIPIC) plates, the Ishihara 38, 24 and 14 plates with HRR YB plates, or the Optec 900 with HRR YB plates should be used as screening tests to classify the colour-vision defect
b. The Waggoner CCVT or the CAD should be used as secondary precision tests. The precision tests quantify the colour-vision deficiency and identify 83% of subjects with colour vision defects who pass all job tests
c. Colour-vision screening should be limited to a single attempt per medical examination because testing multiple times increases measurement errors
d. HRR YB plates should be added to the RG-only tests because numerous eye conditions can cause YB colour-vision defects
e. Tests with limited trials should be removed because they can be memorised
f. All pilots that fail any of the screening tests need to pass a precision test to be cleared without restrictions

Linda Werfelman highlighted Watson’s findings that, in 78 countries studied, the colour-vision assessment process begins with primary screening, with most countries using the IT. If the subject is unsuccessful during primary screening, secondary screening is undertaken, using lantern tests. Secondary screening may be followed by further investigation. Applicants are then licensed appropriately.[3]

## CONCLUSION

Colour vision is of great importance in visually-demanding work environments. Challenges of inconsistency and variability of results have been demonstrated. It is recommended that a standardised list of tests that are internationally accepted to diagnose and quantify colour vision, be compiled. Novel techniques of colour vision assessment, called precision tests, have been designed for this purpose. Further studies are, however, needed to analyse each of these tests for each class of colour vision.

### LESSONS LEARNED

- Aviators can fail colour vision testing in one country and pass in another due to inconsistencies and variability of results and interpretation of the conventional tests
- The commonly used pseudo-isochromatic tests can diagnose colour-vision defects with high sensitivity, but poor specificity. In general, these tests cannot be used to quantify severity of colour vision loss
- Multiple tests and varied protocols yield inconsistent results which are difficult to interpret
- Precision tests, even though more time-consuming, offer the most reliable means of detecting the presence of congenital deficiency and of quantifying the severity of loss. These tests are also useful in healthcare and eye-related clinical use

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