Safety Regulation Group

CAA Paper 2009/04

Minimum Colour Vision Requirements for Professional Flight Crew

Recommendations for new colour vision standards

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Civil Aviation Authority

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Minimum Colour Vision Requirements for Professional Flight Crew

Recommendations for new colour vision standards

Based on a report prepared for the CAA by:

Prof John Barbur & Dr Marisa Rodriguez-Carmona
Applied Vision Research Centre,
The Henry Wellcome Laboratories for Vision Sciences,
Northampton Square,
London EC1V 0HB.

Dr Sally Evans,
UK Civil Aviation Authority,
Safety Regulation Group,
Aviation House,
Gatwick Airport South, RH6 0YR, UK.

Dr Nelda Milburn
FAA, Civil Aerospace Medical Institute, AAM-510
PO Box 25082
Oklahoma City, OK 73125, USA.

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Enquiries regarding the content of this publication should be addressed to:
Medical Department, Safety Regulation Group, Civil Aviation Authority, Aviation House, Gatwick Airport South, West Sussex, RH6 0YR.

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Foreword

This report describes the third phase of a project to determine 'Minimum Colour Vision Requirements for Professional Flight Crew'. It is a study to produce standards and a new test for chromatic sensitivity that can be used to quantify the severity of an individual's colour deficiency. The research was necessary because of the lack of reliable, standardised tests and the absence of information on the specific colour vision needs of professional flight crew.

The project was initiated by UK CAA who published the first two phases as CAA Paper 2006/04. Part 1 'The Use of Colour Signals and the Assessment of Colour Vision Requirements in Aviation' details an examination as to whether the current colour vision tests and standards for professional pilots are still appropriate for modern aviation. Part 2 'Task Analysis' determines the colour vision demands on the flight crew when operating modern aeroplanes, taking two aircraft types as case studies: the Airbus A321 and Boeing 757.

This third phase of the work has been co-sponsored by the FAA. It has produced the minimum colour vision requirements for modern flight crew, and a new colour assessment and diagnosis test. The new test provides an accurate assessment of the applicant's colour vision and excludes only those applicants with colour deficiency characteristics that are likely to affect performance on the flight crew task. If the new standard and tests were to be adopted, it is anticipated that, on average, 35% of applicants currently excluded on the basis of conventional colour vision tests would be accepted as safe to fly.

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Executive Summary

This report describes the findings of the third phase of the project sponsored by the United Kingdom Civil Aviation Authority (CAA) on "Minimum Colour Vision Requirements for Professional Flight Crew". Parts I and II have already been published[1] and cover "The Use of Colour Signals and Assessment of Colour Vision Requirements", and "Task Analysis", respectively. This third part of the project, "Recommendations for New Colour Vision Standards", involved collaboration and co-sponsorship by the Federal Aviation Administration (FAA).

Minimum colour vision requirements for professional flight crew have been established by assessing the level of colour vision loss above which subjects with colour deficiency no longer perform the most safety-critical, colour-related tasks within the aviation environment with the same accuracy as normal trichromats.

The new CAD (Colour Assessment & Diagnosis) test provides accurate assessment of the applicant's colour vision. The results of the test establish with high specificity whether the subject's red-green and yellow-blue colour vision falls within the normal range and the class and severity of colour vision loss in subjects with colour deficiency. The results of the test also indicate whether the applicant's colour vision meets the minimum requirements for safe performance that have emerged as necessary from this investigation. If the new, experiment-based, pass / fail colour limits were adopted as minimum requirements for professional flight crew, 36% of deutan subjects and 30% of protan subjects would be classed as safe to fly. Given the higher prevalence of deutan deficiencies, these findings suggest that 35% of colour deficient applicants would be classed as safe to fly.

Background

The use of colour in aviation for coding of signals and information is important, hence the need to set adequate colour vision requirements to ensure that flight crew are able to discriminate and recognise different colours, both on the flight deck and externally. Concern has, however, been expressed during the past few years that the current colour vision standards, at least within JAA (Joint Aviation Authorities) member states[2] are not appropriate since most tests and pass limits only screen for normal red/green colour vision. Since the incidence of congenital yellow/blue deficiency is extremely low (see Table 1), the absence of red/green deficiency is virtually equivalent to normal trichromacy. Subjects with minimal colour deficiencies often fail normal trichromacy tests and the great majority are therefore prevented from becoming pilots, although many of these subjects may well be able to perform safety-critical tasks, as well as normal trichromats, when presented with the same, suprathreshold colour signals. In principle, these subjects should be allowed to fly. To include some individuals with minimum colour deficiency that may well be safe to fly, some authorities have either relaxed the pass limits on tests designed to screen for normal colour vision (e.g. Ishihara, Dvorine) or they have introduced less demanding tests that applicants with mild colour vision deficiency can pass. This approach does justice to some applicants, but not to others. Existing, conventional colour screening tests employed by most authorities cannot be used to quantify accurately the severity of colour vision loss and this makes it difficult to set reliable pass / fail limits. With very few exceptions, no red/green colour deficient applicants pass either the Ishihara or the Dvorine colour screening tests with zero errors. The same applies to anomaloscope matches when strict criteria are employed (e.g. when the applicant sets an appropriate red/green mixture field to match the colour appearance of a yellow,

1. CAA Paper 2006/04, published August 2006.
2. JAR requirements on this subject are still applicable under EASA, transition of the relevant text to an EASA document is anticipated by 2012.

monochromatic field, as in the Nagel anomaloscope). In this respect these tests are excellent, but as has been shown in several studies, neither the anomaloscope results (Barbur et al., 2008) nor the Dvorine / Ishihara plates (Squire et al., 2005) can be used to quantify reliably the severity of colour vision loss.

When the pass limits are relaxed, the outcome of such tests no longer guarantees normal trichromatic performance in the most safety-critical, colour-related tasks. The FAA guidelines for aviation medical examiners in relation to colour vision tests, testing procedures and pass limits are different to those practised in Europe. The JAA member states employ the Ishihara screening test to identify applicants with red/green deficiency. No errors on any of the first 15 plates of the 24-plate Ishihara set are allowed in order to pass. Most colour deficient observers (both deutan and protan) fail this stringent use of the Ishihara test, except for a very small number of minimum deuteranomalous that pass. In addition, ~15% of normal trichromats (an estimate based on 202 normal trichromats examined at AVRC) also fail the Ishihara, when one employs the strict CAA/JAA pass / fail criteria. Secondary tests such as the Holmes-Wright Type A (HW) lantern (used in the United Kingdom) are employed and although some colour deficient observers (mostly deuteranomalous subjects, see discussion section) pass these tests, the severity of their colour vision loss remains unknown. One advantage of using the HW lantern as a secondary test is that normal trichromats pass this test and are therefore not disadvantaged when they fail the Ishihara test. Mild deuteranomalous subjects that pass the lantern tests cannot be distinguished from normal trichromats on the basis of these tests. These subjects (i.e. the deutan applicants that pass the HW lantern) are therefore allowed to fly. All protan subjects fail the HW test, but some may have sufficient chromatic sensitivity to carry out safety-critical colour tasks as well as normal trichromats. It is therefore clear that, at least in the UK (which employs the HW lantern as the secondary test), protans are very likely to be excluded.

The current procedures within JAA are therefore unsatisfactory for at least two reasons. First, there is no guarantee that the deutan subjects that pass secondary tests can cope with safety-critical, colour-related tasks, since the severity of their colour vision loss remains unquantified, and second, many colour deficient subjects that can carry out such tasks safely fail the lantern tests and will not therefore be allowed to fly. There are also other additional problems. The pass / fail variability of different conventional, colour screening tests is high (Squire et al., 2005). Although subjects with minimum colour deficiency may sometimes pass these tests, the results provide no reliable information as to the minimum colour vision requirements that can be considered safe within the aviation environment.

Another important, practical aspect of regulatory testing of colour vision is that aspiring pilots are often highly motivated to pass a screening test. The context in which the test is undertaken is therefore very different to the clinical setting. It is known that, in order to pass the Ishihara test, or similar pseudoisochromatic tests, colour deficient applicants have been known to have learned the correct responses, so as to maximize their chances of passing the test. It is for that reason important to eliminate any opportunity of learning the right answers to pass a screening test. When used in the recommended clinical settings, most of the popular occupational colour tests exhibit large within-subject and inter-subject variability, even within normal trichromats (Squire et al., 2005).The recommended surround, ambient viewing conditions, measurement procedures and interpretation of results can vary significantly from country to country, even when the same tests are employed. Many International Civil Aviation Organization (ICAO) member states have different requirements for colour vision assessment and use different tests. Within the JAA the HW (United Kingdom), the Spectrolux (Switzerland), the Beyne (France, Belgium and Spain) lanterns and the Nagel anomaloscope (Germany) are recognised secondary tests. Since the correlation between the outcomes of different tests is poor (Squire et al., 2005), it is not uncommon for pilot applicants to fail the colour vision assessment in one country and to pass in another. Although such occurrences have not passed unnoticed, no adequate solutions have emerged to set minimum limits of colour vision sensitivity that can be considered operationally “safe” within specified environments. The lack of adequate solutions to this problem explains why some authorities unknowingly insist on normal trichromacy (which is largely what is achieved when current pass/fail limits are employed with Ishihara as the primary test and HW lantern as the secondary test).

The FAA guidelines are more liberal and allow for the use of various pseudoisochromatic plates (e.g. Ishihara, Dvorine, AOC-HRR, Richmond 1983-edition, 15 plates, etc) with relaxed pass/fail limits (e.g. the applicant has to make seven or more errors in order to fail the Ishihara or Dvorine tests). Alternative tests such as Farnsworth lantern (FALANT), Keystone Orthoscope, etc can also be used as acceptable substitutes. As far as the FAA guidelines are concerned, the analysis of results is restricted to the FAA approved tests that have been included in this investigation (i.e. Ishihara and Dvorine). In addition, the Aviation Lights Test (i.e. a modified Farnsworth lantern that has been developed to screen air traffic controllers, see Figure 7 in full report) was also included in this investigation.

New developments

Advances in understanding human colour vision (Barbur, 2003) and the development of novel methods to measure accurately the loss of chromatic sensitivity (Barbur et al., 1994) have prompted the CAA to sponsor new studies to examine how colour vision loss can be measured accurately and also to establish minimum colour vision requirements for civil aviation professional pilots. As a result of the progress made in these studies it is now possible to define the variability that exists within normal colour vision and to detect with confidence and classify accurately even the smallest congenital colour vision deficiencies that sometimes pass undetected in conventional, occupational colour vision tests. More importantly, it is now possible to achieve the aim of the project, i.e., *to quantify the severity of colour vision loss and to recommend minimum colour vision requirements by establishing the level of colour vision loss when colour deficient observers can no longer perform the most safety-critical, colour-related tasks with the same accuracy as normal trichromats.*

A number of developments that have emerged from the studies carried out during the last few years have made it possible to achieve the aim of this project:

- A Colour Assessment and Diagnosis (CAD) test that employs novel techniques to isolate the use of colour signals and measures accurately both red-green (RG) and yellow-blue (YB) chromatic sensitivity has been developed and validated (see Figure 9).
- A study that compared outcome measures in the most common, occupational colour vision tests, in both normal trichromats and in a large number of colour deficient observers, has improved our understanding of current limitations. The findings from this study also justify the need for a test that can be used to measure accurately the subject’s chromatic sensitivity and the variability expected within the colour normal population (Squire et al., 2005).
- The establishment of colour discrimination limits for normal vision i.e., the standard normal CAD observer based on RG and YB colour detection thresholds measured in ~250 normal trichromats provides a template for detection of abnormal sensitivity (Rodriguez-Carmona et al., 2005) (see Figure 8). In addition, similar measurements in over 300 colour deficient observers that participated in several projects related to colour vision provided the data needed to describe the differences in the severity of colour vision loss within deuteranomalous and protanomalous observers (see Figure 12).
- Identification of the most important, safety-critical, colour-related tasks for pilots and faithful reproduction of such tasks in the laboratory made it possible to establish experimentally the safe limits of colour vision loss. The visual task analysis carried out as part of this study identified the Precision Approach Path Indicator (PAPI) as the most important, safety-critical task that relies largely on colour vision. At some airports, colour signals are also used for

aligning the aircraft when approaching the parking area, and in such cases correct colour recognition is critical to the safe accomplishment of this task. There are many other tasks that involve the use of colour signals, but they involve larger stimuli, the viewing is under more favourable conditions of light adaptation and other cues make the colour coding less critical. In the case of the PAPI lights, it is essential that the pilot distinguishes accurately the number of "white" and "red" lights. Moreover, the pilot needs to recognise the four adjacent lights as "white", when too high, and as "red", when too low. The PAPI lights task is demanding since the lights can be very small (i.e. subtend a very small visual angle at the eye) and are often seen against a dark background (see Figure 18) when colour discrimination sensitivity is known to be poor.

- Colour discrimination limits (based on the CAD test) that can be classified as safe for pilots in civil aviation have been established. This was achieved by measuring and relating PAPI task performance and colour discrimination sensitivity as assessed on CAD, signal lights and a number of other colour vision tests (see description below) in 40 protanomalous, 77 deuteranomalous and 65 normal trichromats. There are other visual tasks that can be classed as safety-critical, but in general these involve larger and brighter lights and are therefore easier to carry out. These tasks either rely on colour discrimination (such as the red-green parking lights) or, in some cases, the tasks benefit from the use of colour signals as redundant information (such as the "green" runway threshold lights). In addition to the red-green parking and the green runway threshold lights there are also a number of other runway lights; the red-white centre-line lights, the green-yellow lead-off lights and the red stopway lights. The tasks that involve these additional lights have not been simulated in the laboratory, but as argued in the main report, they are either less demanding in terms of colour discrimination or the colour signals are only used to reinforce the functional significance of the lights.
- Data showing correlation between PAPI scores and CAD sensitivity thresholds are shown in Figure 23 for normal, deuteranomalous and protanomalous observers.

Principal conclusions

- Subjects with red/green congenital colour deficiency exhibit an almost continuous loss of chromatic sensitivity. The loss of sensitivity (when expressed in Standard Normal (CAD) units (SN units) is greater in protanomalous than deuteranomalous observers (Figure 12).
- When the ambient level of light adaptation is adequate, normal aging does not affect significantly either RG or YB thresholds below 60 yrs of age (see Figure 13).
- Analysis of PAPI results shows that the use of a modified "white" light results in significant, overall improvements in PAPI performance, particularly within normal trichromats and deuteranomalous observers. The modified (or colour corrected white) is achieved simply by adding a colour correction filter to the standard white lights produced by the source. The filter employed in this study decreased the colour temperature of the standard white (used in PAPI systems) by 200 MIREDS (micro reciprocal degrees).
- The deuteranomalous subjects investigated in this study with CAD thresholds < 6 SN units and the protanomalous subjects with CAD thresholds < 12 SN units perform the PAPI test as well as normal trichromats.
- 43 of the 77 deuteranomalous subjects failed the PAPI test. 29 out of the remaining 34 subjects that passed the PAPI test had CAD thresholds < 6 SN units.
- 20 of the 40 protanomalous subjects failed the PAPI test. 13 out of the remaining 20 subjects that passed the PAPI test had CAD thresholds < 12 SN units.
- A small number of deuteranomalous (5) and protanomalous (7) observers with thresholds higher than 6 and 12 SN units, respectively, passed the PAPI test. All these subjects do, however, exhibit poor overall, RG chromatic sensitivity in all the other colour tests

employed in the study and are therefore likely to be disadvantaged in many other suprathreshold visual performance tasks that involve colour discrimination.

- The results suggest that subjects with minimum colour deficiency that does not exceed 6 SN units for deuteranomalous observers and 12 SN units for protanomalous observers perform the PAPI test as well as normal trichromats. If these findings were adopted as pass / fail limits for pilots ~35% of colour deficient applicants would be classed as safe to fly.
- The administration of the CAD test eliminates the need to use any other primary or secondary tests. It is proposed that a rapid, reduced version of the CAD test (labelled fast-CAD) is administered first to establish whether the applicant passes with no errors the 6 SN limit established for deutan subjects. Deutans represent ~ 6% of colour deficients and 36% of deutan subjects pass the recommended CAD limit (see Table 3). When one includes normal trichromats, ~ 94% of all applicants will pass the fast-CAD screening test and be classified as safe to fly. This process is very efficient since the fast-CAD test is simple to carry out and takes less than 30 seconds to complete. The definitive CAD test (which takes between 6 to 8 minutes for RG sensitivity) is administered only when the applicant fails the fast-CAD screening test. The latter establishes the class of colour deficiency involved and whether the applicant's threshold is below the pass / fail limit established for protan subjects. In addition, the CAD test provides the option to test the applicants YB colour vision. This option reveals whether the applicant's YB discrimination sensitivity falls within the normal range. In view of the increased use of colour in aviation, testing for normal YB thresholds can also be of relevance to aviation safety.

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Glossary

1 Abbreviations

AGL	Aeronautical Ground Lighting
ALT	Aviation Light Test
ATC	Air Traffic Controller
ATCO	Air Traffic Control Officer
AVRC	Applied Vision Research Centre (City University)
CAA	Civil Aviation Authority
CAD	Colour Assessment and Diagnosis test
CIE	Commission Internationale de l'Eclairage
CS	Chromatic Sensitivity
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
JAA	Joint Aviation Authorities
JAR	Joint Aviation Requirements
L-cones	Long-wavelength sensitive cones
LC	Luminance Contrast
MIRED	Micro Reciprocal Degrees
M-cones	Medium-wavelength sensitive cones
NTSB	National Transportation Safety Board
PAPI	Precision Approach Path Indicator
RG	Red-Green
S-cones	Short-wavelength sensitive cones
SI	Système International d'Unités (International System of Units)
SN	Standard Normal
UK	United Kingdom
YB	Yellow-Blue

2 Nomenclature

°	degrees
cd m^{-2}	candelas per square metre
λ	wavelength (lambda), nm
λ_{max}	maximum (peak) wavelength of V(λ)
%	percent
2' arc	2 minutes of arc
A	ampere (amp) unit of electric current
km	kilometre
K	degrees Kelvin
mm	millimetres (1 mm=10^{-3} of a metre)
M	mired (unit of measurement to express colour temperature = 10^6 K)
nm	nanometres (1 nm=10^{-9} of a metre)
s	second (time)
μ	micro=x10^{-6}
V(λ)	Standard photopic luminous efficiency (for high ambient illumination) (CIE, 1924)
V'(λ)	Standard scotopic luminous efficiency (when very low light levels are involved) (CIE, 1951)

Minimum Colour Vision Requirements for Professional Flight Crew

1 Introduction

1.1 Occupational colour vision standards were introduced in aviation in 1919 (by The International Commission for Air Navigation). These standards reflected both the needs and the methods available for colour vision assessment at the time. Concern has been expressed during the last few years that the current JAR (Joint Aviation Requirements)[1] colour vision standards may be too stringent and, at the same time, also variable. The tests employed do not always reflect the tasks pilots encounter in today's aviation environment. An examination of current standards and techniques employed to assess colour vision requirements suggests the need for a more unified colour vision test to provide a measure of colour vision loss that relates directly to the most safety-critical, colour-related tasks within the aviation environment (Cole, 1993). The current colour vision standards and accepted JAA (Joint Aviation Authorities) colour vision tests for professional flight crew have been reviewed by the United Kingdom Civil Aviation Authority (UK CAA). This report follows other CAA documents published in 2006: "Minimum Colour Vision Requirements for Professional Flight Crew": Part I: The Use of Colour Signals and the Assessment of Colour Vision Requirements in Aviation and Part 2: Task Analysis.

1.2 The use of colour in aviation

1.2.1 The use of colour in the aviation environment is important since it makes possible the efficient coding of signals and information and this, in turn, enhances visual performance, provided the subjects can make use of colour signals. Humans with normal trichromatic colour vision possess three distinct classes of cone photoreceptors. These contain short (S), middle (M) and long (L) wavelength sensitive photopigments with appropriate peak absorption wavelengths (λ_{max}). Variant L- and / or M-cone genes can cause significant shifts in λ_{max} and this in turn can cause large changes in chromatic sensitivity. In addition to λ_{max} changes, other factors such as the amount of pigment present in photoreceptors can also affect chromatic sensitivity. Red/green deficiency is the most common type and is caused by either the absence of or the abnormal functioning of L- or M-cones. The corresponding condition is normally described as protan or deutan deficiency, respectively. Colour vision deficiency affects approximately 8% of men and less than 1% of women (see Table in Section 4.4).

1.2.2 Aviation accidents have high social and economic costs, especially if the accident involves large passenger aircraft. Rigorous safety standards have been established over decades to decrease the probability of aviation accidents. An important strategy in achieving high levels of safety in aviation is to build redundancy in equipment and the interpretation of signals and other information by pilots and other personnel. Colour is used extensively to code information in the aviation environment and pilots are normally expected to have good colour discrimination. Even when other cues are also available, the ability to use colour information increases redundancy and in some tasks this improves considerably the level of visual performance that can be achieved. Some accidents have been linked to loss of colour vision (National Transportation Safety Board, 2004)[2]. There is also some evidence to suggest that the likelihood of

1. JAR requirements on this subject are still applicable under EASA, transition of the relevant text to an EASA document is anticipated by 2012.

accidents is increased in pilots that are colour deficient (Vingrys & Cole, 1986). Other studies have shown that subjects with colour vision deficiencies make more errors and are slower in recognising aviation signals and colour coded instrument displays (Vingrys & Cole, 1986; Cole & Maddocks, 1995; Squire et al, 2005). There are also a small number of tasks in which colour information is not used redundantly and therefore the correct interpretation of colour signals becomes very important.

1.3 Current colour vision requirements and assessment methods in aviation

1.3.1 The International Civil Aviation Organization (ICAO) requires Contracting States to maintain a colour vision standard to ensure pilots can recognise correctly the colours of signal lights used in aviation: '*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, 2001b). Many ICAO member states have different requirements for colour vision assessment and employ different tests as the standard.

1.3.2 In Europe, there is agreement amongst the 38 members of the JAA to apply the same standards, at least in terms of primary tests. The current JAA colour vision requirements (Section 1; JAR-FCL 3, 2002) use the Ishihara pseudo-isochromatic test (Section 1.8.1 of this report) as a screening test for colour vision. The JAA use the first 15 plates of the 24-plate version of the Ishihara pseudo-isochromatic test, with no errors as the pass criteria. If the applicant fails this test then either a lantern test or the Nagel anomaloscope test is used. The three lanterns recommended by the JAA are the Holmes-Wright Type A (United Kingdom), the Spectrolux (Switzerland) and the Beyne (France, Belgium and Spain). The subjects pass when they make no errors on the corresponding lantern test. For the Nagel Anomaloscope (Section 1.8.3 of this report): *"This test is considered passed if the colour match is trichromatic and the matching range is 4 scale units or less…"* (See Appendix 14 to subpart B; JAR-FCL 3, 2000). The tests currently employed by JAA member states and the corresponding pass/fail criteria are fully described in the report by the CAA (Civil Aviation Authority, 2006a).

1.3.3 In the USA, the Federal Aviation Administration (FAA) guidelines are more liberal and the approved primary tests include Ishihara, Dvorine, AOC-HRR, Richmond, etc. The pass limits are also more relaxed which favours some applicants with mild colour deficiency. Other tests include the Farnsworth Lantern, Keystone Orthoscope, etc. In exceptional cases this can then be followed by the more practical Signal Light Gun Test (SLGT), usually carried out in an airport tower. This approach does justice to some applicants, but not to others (see Section 4). The disadvantage of this more liberal approach is that when the pass limits are relaxed, the pass / fail outcome of the screening tests no longer guarantees normal performance in the most safety-critical, colour-related tasks.

1.3.4 Follow up colour vision tests may be carried out for renewal of Class 1 medical certificates. Within the JAA, the Ishihara plates which screen only for red/green deficiency are normally used for this assessment. Any yellow-blue loss (either congenital or acquired) will not therefore be picked up by this test (Section 1.11 of this report). Since changes in chromatic sensitivity are often indicative of early stage systemic (e.g. diabetes) or ocular diseases (e.g. glaucoma, age-related macular degeneration), it is recommended that both red-green and yellow-blue colour sensitivity should be assessed with every medical examination and any significant changes noted. The data can then be used to detect when the progression of any inherent condition yields colour thresholds that fall outside the range established for normal vision.

2. NTSB Report AAR-04-02 concerning an accident in 2002, recommendations A 04-46 and A 04-47.

1.4 **Problems identified with current assessment methods and procedures**

Current colour vision requirements vary from country to country, even within the JAA member states. The correlation between the outcomes of different tests is poor and therefore it is not uncommon for pilot applicants to fail the colour vision assessment in one country and to pass in another (Squire et al, 2005). This is not completely unexpected given the large inter-subject variability, the different factors that can contribute to loss of chromatic sensitivity and the different characteristics of the various colour vision tests. The lack of standardisation often causes confusion amongst applicants and provides the opportunity to attempt several tests in order to pass one of the many colour vision standards.

1.5 **A new approach based on recent advances in colour vision testing**

Advances in the understanding of human colour vision (Barbur, 2003) and the development of novel methods to measure accurately the loss of chromatic sensitivity (Barbur et al, 1994) have prompted the UK CAA and the FAA of the USA to sponsor new studies to examine how colour vision loss can be measured accurately and also to establish minimum colour vision requirements for professional pilots. As part of the CAA funded study, the current accepted JAA colour vision requirements for professional flight crew have been reviewed and the variability associated with the most common occupational colour vision tests assessed, both in normal trichromats and in subjects with red/green colour deficiency. The aim of the current project was to establish minimum limits of colour vision sensitivity that can be considered to be operationally "safe" within the aviation environment. This joint report follows other CAA documents published in 2006 (CAA 2006/04): *'Minimum Colour Vision Requirements for Professional Flight Crew', Part I: The Use of Colour Signals and the Assessment of Colour Vision Requirements in Aviation and Part 2: Task Analysis.*

1.6 **A new colour vision test**

Ideal colour vision assessment requires a test that (i) provides true isolation of colour signals and quantifies the severity of colour vision loss, (ii) is based on data that describe the statistical limits of colour discrimination in "*norma*l" trichromats so as to be able to differentiate minimal colour vision loss due to congenital and acquired deficiencies from fluctuations expected within normal trichromats, (iii) has enough sensitivity to detect "minimal" deficiencies and to classify accurately the class of deficiency involved, and (iv) can be used to detect and monitor "significant changes" in colour sensitivity over time. The Colour Assessment and Diagnosis (CAD) test has been developed and improved over several years to fulfil these requirements (Section 1.9 of this report).

1.7 **Identification of the most safety-critical and demanding colour vision tasks**

1.7.1 An important aspect of this study was to investigate whether subjects with minimal colour vision loss were able to carry out the most demanding, safety-critical, colour related tasks with the same accuracy as normal trichromats. If the findings indicate that "normal" colour vision is not required to carry out such tasks, it then becomes important to establish the limits of colour vision loss that can still be considered safe within the aviation environment.

The Precision Approach Path Indicator (PAPI) signal lights that are used to inform pilots of the correct glide path for landing. This is an efficient system since it consists only of four lights, each of ~ 8″ diameters, spaced 9m apart. The angular subtense of the lights remains relatively unchanged beyond ~ 800m, but the retinal illuminance of the lights decreases. The output of the lamps can be adjusted using 6 preset lamp current settings. The disadvantage is that the correlated colour temperature of the lamp changes significantly and this affects mostly the colour of the "white" lights (see Section 2).

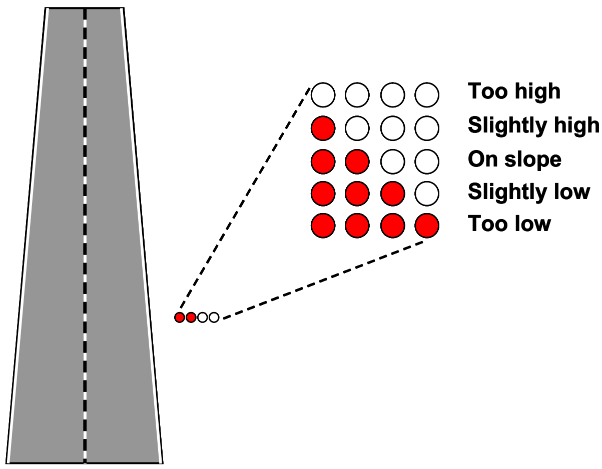

Figure 1a The Precision Approach Path Indicator (PAPI)

The Visual Approach Slope Indicator (VASI) and the more sophisticated T-VASI systems. The correct angle of approach is indicated as red over white. The T-VASI requires more space and is more expensive, but the use of colour provides only redundant information.

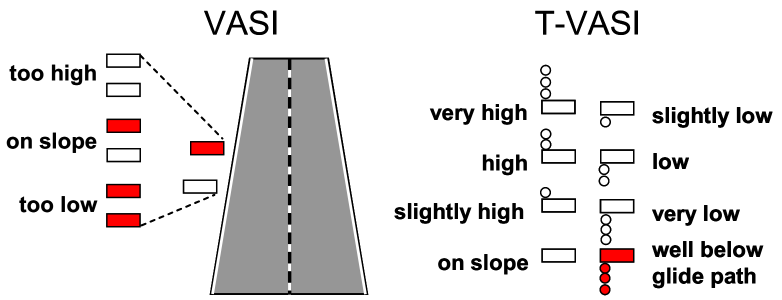

Figure 1b The Visual Approach Slope Indicator (VASI)

1.7.2 The approach adopted in this investigation was to relate the accurate assessment of colour vision loss to the subject's ability to carry out the safety-critical, colour based tasks within a specified environment when the use of other than colour cues was minimised. A visual task analysis was carried out (CAA, 2006a) to identify and characterise the most important safety-critical, colour-related tasks for flight crew. The PAPI and the parking signal lights were found to be the most safety-critical, colour-related tasks when no redundant information is available to carry out the task. An earlier study by Cole and Maddocks (1995) has also identified the PAPI lights as the most safety-critical, colour-related task. The PAPI lights provide the pilot with accurate glide slope information on final approach to landing using four lights each of which can be seen as either red or white. Two whites and two reds indicate correct approach path, too many reds indicate that the approach height is too low and too many whites indicate that the approach height is too high. The geometry of the PAPI signal system is shown in Figure 1a (see also Figure 2a).

1.7.3 An alternative system i.e. the VASI (Visual Approach Slope Indicator) is sometimes used in North America and Australia. The VASI is more expensive and requires more space. There are several versions of the VASI system, but the main task of the pilot remains the discrimination of horizontal bars of well defined red and white lights (see Figure 1b). The more favourable geometry and the greater angular separation of the lights make the VASI colour discrimination task less demanding than the PAPI. In the T-VASI version of the system the changing geometry of the lights provides the required approach slope information, hence the colour coding is used redundantly. The PAPI lights system is visually more demanding, the angular subtense of each of the four red / white lights corresponds to the smallest retinal image that can be produced by the optics of the eye and the red / white colour coding is used non-redundantly. This project has therefore focused on the PAPI lights as the most safety-critical, colour-coded task for pilots.

Figure 2a Photograph of PAPI lights viewed from ground level. Photograph taken at Sussex Flight Centre, Shoreham Airport (December 2006).

1.7.4 **Other uses of signal lights within the aviation environment**

There are many other colour signals that are used in the aviation environment to enhance conspicuity, code information and group objects of interest together. These situations are less safety-critical, involve the use of larger stimuli under more favourable conditions of light adaptation and the same information is also available in some other ways (e.g. text or audible signals). The PAPI signal system, on the other hand, offers no redundancy – at night there is no other unique cue in addition to colour discrimination to help the pilot recognise the red and white light signals reliably in order to determine visually whether the aircraft is on the correct approach path for landing.

a) **Parking Lights**

Parking the aircraft requires the correct alignment of the aircraft with the line of approach. The pilot is aided in this task by the red-green parking lights. Both lights are seen as green when the aircraft is positioned correctly for approach. A red-green combination (see photograph of parking lights in Figure 2b) signals that the aircraft has to veer slowly (towards the green light) to ensure that the pilot sees two green lights.

Photograph of the red and green parking lights that are used at airports to indicate to the pilot the correct line of approach for parking the aircraft at the stand. The pilot sees two green lights when the aircraft is positioned correctly for approach. A red-green combination (as shown in the photograph) signals that the aircraft has to veer slowly right (towards the green light) whereas a green on the left and a red on the right signals the need to veer slightly to the left (again towards the green light). This task description illustrates clearly that the pilot has to be able to discriminate between the red and green lights. The angular subtense of the parking lights is much larger than the PAPI and the retinal illuminance generated is also higher. This colour discrimination task is therefore likely to be less demanding.

Figure 2b Photograph of the red and green parking lights

This is a colour-related, safety-critical task simply because no other redundant cues are available; however, the lights are bright, the colour difference between the lights is large and the lights subtend a large visual angle at the eye. Consequently the colour discrimination task is less demanding and it is therefore expected that observers with minimum colour vision deficiency may well be able to carry out this task with the same accuracy as normal trichromats. This task was not investigated in this study.

b) **Runway and taxiway lights**

The lighting of runways and taxiways involves the use of colour signals, but the use of colour for coding is often redundant. The correct information is also provided by the geometry of the lights. Runway lighting is used for landing and take-off. On approach, the lighting of the runway provides essential information that yields outline views of the geometry of the runway. On touch-down the lights form unique geometric lines and shapes that convey specific information. A particular runway may have some or all of the following lights:

- *Runway Edge Lights* are white (or amber) and run the length of the runway on each side.
- *Runway Threshold Lights* are green and indicate the starting point for the available landing distance.
- *Runway End Lights* are red and delineate the extremity of the runway that is available for manoeuvring.
- *Runway Centre-line Lights* start white, become red-white intermittent and then red only, towards the end of available runway for take-off.
- *Touchdown Zone Lights* consist of rows of white light bars (with three in each row) on either side of the centre-line over the first 914 m of the runway (or to the midpoint, whichever is less).
- *Stopway Lights* are four unidirectional red lights equally spaced across the width to mark the end of any stopway associated with a runway used at night.

Runway edge lights provide perspective cues on approach and are less demanding than the PAPI light system; runway lighting becomes visible from several kms and often aids the pilot's visual search to locate the PAPI lights. The colour of the runway threshold lights is largely redundant because these green lights cannot be confused with any other similar lights in terms of location, geometry and shape, but the green colour may well reinforce their function. Touchdown zone lighting is added in order to improve texture and perspective and to give flight crew an indication of the area within which a landing must be initiated. The geometry and location of the runway end lights in relation to other lights is, again, sufficient to indicate their function. The colour of the runway centre-line lights changes from 'white' on touch down to alternating 'white-red' lights and then finally to 'red' lights when the aircraft advances towards the end of the runway. The colour of the lights indicates the position of the aircraft on the runway and this information is important in some situations (e.g. when take-off has to be abandoned, especially in conditions of poor visibility). Runway signal lights tend to be larger and brighter than PAPI lights and this makes the discrimination of colour differences less demanding. It has therefore been assumed that if the applicants can discriminate the red and white PAPI lights from 5kms, they should also be able to discriminate with no difficulty the red and white lights on the runway centre line.

For night operations, taxiways at most airports are equipped with lights that may include some or all of the following:

- *Taxiway Edge Lighting* is blue to outline the edges of taxiways during periods of darkness or restricted visibility.
- *Taxiway Centre-line Lighting* is green and provides centre-line guidance on taxiways and aprons and when entering or vacating a runway.
- *Stop-bar Lights* are a single row of red, flush or semi-flush inset lights installed laterally across the entire taxiway showing red towards the intended direction of approach. Following the traffic controller's clearance to proceed, the stop-bar is turned off and the centre-line lead-on lights are turned on.
- *Runway Guard Lights* are either a pair of elevated flashing amber lights installed on either side of the taxiway, or a row of in-pavement yellow lights installed across the entire taxiway, at the runway holding position marking at taxiway / runway intersections.

Taxiway lights are seen from much shorter distances when the aircraft moves slowly on the ground. The discrimination by the pilot of the centre taxiway line as green and the edge as blue is not an essential requirement to carry out the task safely, but the use of appropriate colours may well emphasise the function of the lights. There is therefore little doubt that an acceptable level of colour discrimination is needed which can enhance the conspicuity of light signals, even when colour is used redundantly and the tasks are less demanding or safety critical. The stop-bar and runway guard lights both play an important role in preventing runway incursions. In addition, the flashing aspect of the guard lights adds conspicuity to these signals, but may also distract the pilot from interpreting other signals. The most common causes of runway incursions do not involve the incorrect interpretation of colour signals since colour is used redundantly and it therefore simply adds to the conspicuity of the lights. Other factors such as lack of communication between ATC and pilot, lack of familiarity with airport layout, tiredness, lack of attention and poor cockpit procedures for maintaining orientation in low visibility conditions (*ICAO NAM / CAR / SAM Runway Safety/Incursion Conference, Mexico City, October 2002*) can all contribute to runway incursions.

1.7.5 **Analysis of the PAPI lights task**

The PAPI task is a simple, efficient, red-white two-colour code (and the white and red lights generate both red-green and yellow-blue colour signals in the eye). Red/green colour deficient observers will continue to have full use of their yellow-blue channel, although the properties of this channel will differ between deutan and protan subjects. The PAPI system is efficient since it takes a small amount of space and the size of the image of each light generated on the retina remains largely unchanged as the viewing distance increases beyond ~ 0.8km (although the lights become less bright as the viewing distance is increased). The geometry of the lights carries no information and hence the need to use coloured signals. It has been suggested that dichromats (who exhibit severe red/green colour vision loss) may be able to interpret correctly differences between two colours, at least under some conditions (Heath & Schmidt, 1959). In addition, colour deficient observers can usually recognise red signals with few errors (Vingrys & Cole, 1993; for a review, see Cole, 2004). It is likely that some subjects with severe colour deficiency may be able to carry out the PAPI task with no errors, but it is essential to ensure that the subjects recognise and name all four lights as red when too low and as white when too high. Any simulation of the PAPI test must include all conditions and must also ensure that the use of brightness difference cues is minimised.

On the other hand, the recognition of the red and white PAPI lights is not always an easy task. Atmospheric scatter and the use of reduced lamp current settings at night to dim the lights can shift the white signal toward the yellow region of the spectrum locus (see Figure 17). This often causes problems for colour normal observers and may cause even greater problems for colour deficient observers. In the case of large passenger aircrafts, the PAPI lights are seen from large distances (> 5kms) at night when both the angular subtense of each light and the angular separation between adjacent lights is very small. Adjacent lights tend to overlap visually and this is particularly troublesome at night when the pupil size is large. Subjects with large higher order aberrations and increased light scatter in the eye will be disadvantaged at night. Although most subjects will have high visual acuity (< 1 min arc) under photopic conditions, subjects with large higher order aberrations and scattered light may have very poor visual acuity under mesopic conditions when the pupil size is large. Visual acuity at low light levels in the mesopic range is not normally assessed for certification purposes. Partial overlap of adjacent lights makes the task of discriminating the number of red and white lights even more difficult. These additional factors explain why the PAPI task (which involves only two colours) is considered to be more critical than other colour based tasks.

1.7.6 **Disability discrimination**

There are also further considerations that justify the need to establish safe, minimum requirements for colour discrimination (when appropriate) and to avoid the easier alternative (from a regulatory viewpoint) of requiring every applicant to have normal colour vision. The recent UK Disability Discrimination Act (2004) has to a certain extent exposed weaknesses in the current standards and procedures. Companies need to justify refusal to employ an applicant on the basis of his/her defective colour vision and this requires scientific evidence to demonstrate convincingly that the applicant will not be able to carry out necessary occupational tasks that involve colour vision with the accuracy and efficiency expected of normal trichromats. In view of these arguments, we have developed a PAPI simulator and a PAPI Signal Lights test that can be used under controlled laboratory conditions. The simulators reproduce both the photometric and the angular subtense of the real lights under demanding viewing conditions when the lights are viewed against a dark background. The aim was to correlate the measured loss of chromatic sensitivity on the CAD test with the subject's performance on the most safety-critical, colour-related task identified in the aviation environment. Since other colour-related tasks such as seeing the colour of the parking lights or the discrimination of runway, centre-line, red and white lights are less demanding, it is assumed that the pilot will also be able to perform correctly these tasks. In principle, this approach should make it possible to recommend pass/fail limits based on the observer's ability to carry out the most safety-critical and demanding PAPI task.

1.8 Brief description of the most common occupational colour vision tests

For a full description of colour vision tests used in aviation please refer to CAA Paper 2006/04 (2006a) and for a list of tests accepted by the FAA see the FAA guide for Aviation Medical Examiners (2008). The following colour vision tests will be described here since they have been used along with the CAD test in this study. These are the Ishihara and Dvorine pseudoisochromatic plate tests, Nagel Anomaloscope and the Aviation Lights Test (ALT). Measures of colour discrimination performance computed from the results of these tests will be examined and compared with the subject's scores on the PAPI simulator. The same PAPI simulator was also used to produce a more demanding signal lights test that required the subject to name one of six different coloured lights, as described in Section 2 of this report. The latter will be referred to as the PSL (PAPI Signal Lights) test.

1.8.1 Ishihara plate test

1.8.1.1 The Ishihara pseudoisochromatic plate test consists of a series of numbers outlined by different coloured dots as shown in Figure 3. This is the most widely accepted screening test for red/green colour deficiency and uses camouflage to exploit the colour confusions of colour deficient observers (Sloan & Habel, 1956; Belcher et al, 1958; Frey, 1958; Birch, 1997). The Ishihara test consists of single or double-digit numbers that have to be identified verbally and pathways for tracing for those who cannot read numbers. The 24-plate test version consists of the following: plate 1 for demonstration of visual task, plates 2-15 for screening, plates 16-17 for protan/deutan classification. The Ishihara test employs a range of designs, such as transformation, vanishing or hidden digit. In the vanishing type plate (Figure 3, middle) a figure is seen by colour normals, but not by colour deficients; the reverse of this, the hidden figure design, is harder to design and not always so effective. More complex patterns are contained in transformation plates (Figure 3, left), 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. In the classification plate design (Figure 3, right), protans only see the number on the right side of each plate and deutans only see the number on the left.

1.8.1.2 The test is limited to red/green deficiency and cannot be used to assess loss of yellow-blue sensitivity.

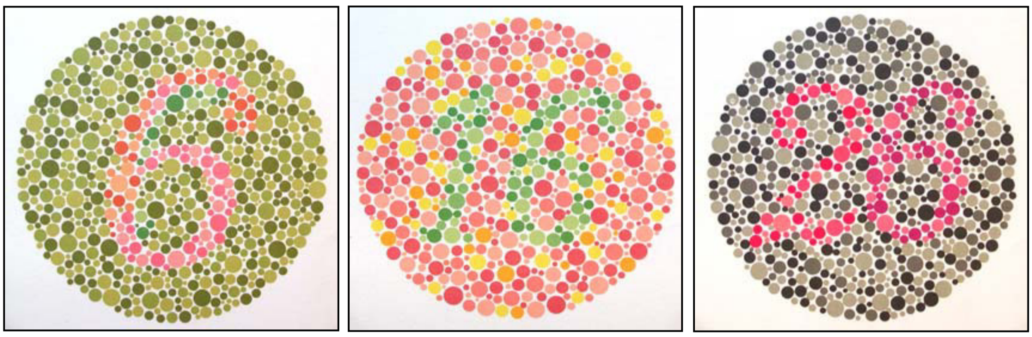

Figure 3 Ishihara pseudoisochromatic plates; left, transformation design; middle, vanishing design; right, protan/deutan classification plate. Please note that these may not be reproduced accurately here as the printed colour and the viewing illuminant will be different.

1.8.1.3 The test is viewed at about two-thirds of one metre (arm's length) distance using a MacBeth easel lamp for illumination. The first 25 plates of the 38-plate test version were used in this investigation. 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 illuminant used is important because the selected reflectances of the patches on the plates have been chosen with reference to this illuminant. The examiner instructs the person being tested to report the number they can see as the pages are turned, and warns the subject that on some occasions they may not see a number. The first introductory plate is used to demonstrate the visual task. This plate is designed so that anyone, including colour deficient subjects should see this number. With a viewing time of about 4 seconds allowed for each plate, undue hesitation on the part of the subject is the first indication of colour deficiency.

1.8.2 **Dvorine plate test**

1.8.2.1 The Dvorine test is based on pseudoisochromatic principles and is similar to the Ishihara test. It has 15 numeral plates, consisting of 1 initial plate that demonstrates the visual task, 12 plates for screening and 2 plates for protan/deutan classification (see Figure 4). These plates are of the vanishing type. The font of the numerals is slightly different to the Ishihara plates and is believed to be easier to read.

1.8.2.2 The Dvorine test is administered in a similar manner to the Ishihara test. The plates are positioned at arm's length, perpendicular to the line of sight, under daylight illumination or a Macbeth easel lamp. The subject is instructed to read the numerals (all plates have a numeral)

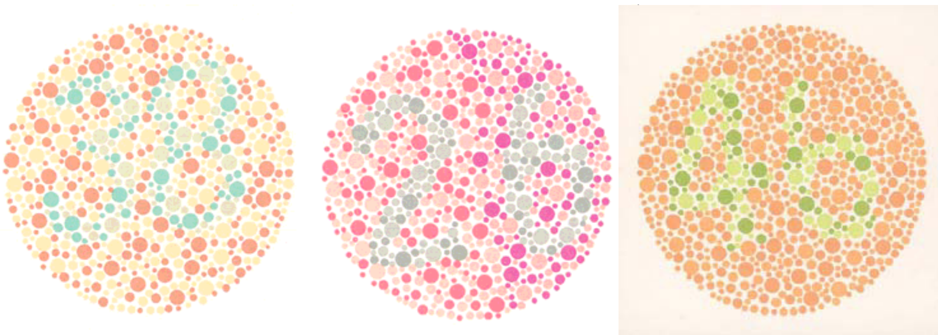

Figure 4 Dvorine pseudoisochromatic plates; left and right, vanishing design; middle, protan/deutan classification plate. Please note that the colour of the plates may not be reproduced accurately in this document or in print since the printed reflectances and the viewing illuminant will be different.

1.8.2.3 Pseudoisochromatic plate tests provide a simple, readily available, inexpensive and easy to administer screener mostly for red/green deficiencies. However, plate tests tend to be relatively easy to learn, and this encourages cheating. The spectral quality of the light source illuminating the plates is also important. Plates may be degraded by fingerprints, dust and excessive light exposure. In general, subjects with minimal colour vision loss tend to show greater variability on repeated tests by comparison with normal trichromats and on some occasions can even pass these tests (Squire et al, 2005).

1.8.3 Nagel Anomaloscope

1.8.3.1 The Nagel anomaloscope (Figure 5) is based on colour matching and is the standard clinical reference test for identifying and diagnosing red/green colour deficiency recommended by the National Research Council - National Academy of Sciences (NRC-NAS) Committee on Vision (1981). This instrument produces a disc stimulus that consists of two half fields and is viewed in an optical system. The top half of this disc is illuminated by a mixture of spectrally narrow red and green wavelengths, and the lower half is illuminated by spectrally narrow yellow light. Two control knobs 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 (see Figure 5). The test is administered in two stages. Usually only one eye (i.e. the dominant eye) is fully tested and the other eye is then checked to ensure the same deficiency. This confirms that the loss of colour vision is congenital. Following familiarisation with the instrument controls, the subject is then asked to alter both the control knobs until the two halves of the circle match completely in both colour and brightness. The subject is not asked to name the colours. A few matches are made, with the examiner "spoiling" the match after each setting. About ten seconds are allowed for each match and then, to minimize the effect of chromatic after images, the subject looks away from the instrument into the dimly lit room for a few seconds before the procedure is repeated. The second stage of the test is to determine the limits of the matching range. The initial matches made by the subject are used as a guide by 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 field is altered systematically by the examiner until the limits of the matching range are found. The matching range is recorded from the matching limits on the red/green mixture scale and the midpoint calculated.

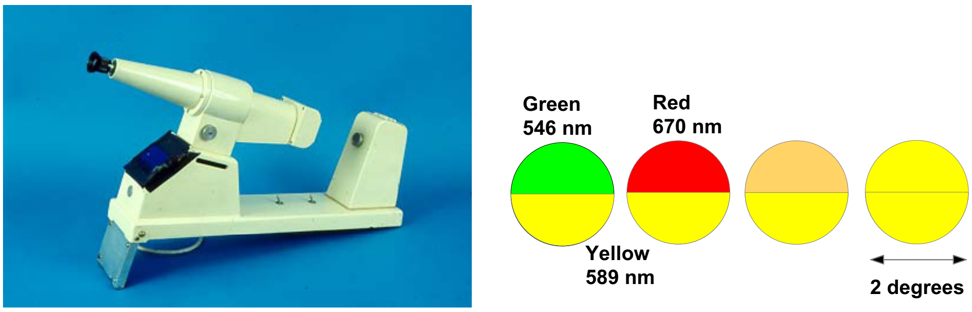

Figure 5 Photograph of the Nagel anomaloscope (Model I, Schmidt and Haensch, Germany) and illustration of the Nagel anomaloscope split field. The percentage mixture of red to green in the top half and the luminance of the yellow bottom field can be changed until a match of the two fields can be perceived.

1.8.3.2 Ideally, the red/green 'match' parameters should provide enough information to determine 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 (absence of a cone-type) or anomalous trichromat (anomalous cone-type). The size of the red-green matching range is often taken as an indicator of chromatic sensitivity loss. The red-green discrimination index (RGI), a parameter relating to the matching range, has been introduced in this study and provides an indication of the subject's ability to discriminate red-green colour differences:

$RGI = 1 - \frac{r_{subject}}{74}$, where $r_{subject}$ is the subject's mean matching range.

The RGI ranges from a value very close to 1 for normal sensitivity, to 0 for a dichromat that accepts any red/green mixture setting as a match to the yellow field.

1.8.3.3 A more appropriate measure of red/green sensitivity based on the Nagel is obtained simply by dividing the mean normal matching range (r_{mean}) obtained by averaging results for a large number of normal trichromats by the subject's range ($r_{subject}$). The mean normal matching range for the Nagel anomaloscope used in this study is approximately 4 scale units. Hence the new measure of chromatic sensitivity becomes:

$$\text{Nagel sensitivity} = \frac{r_{mean}}{r_{subject}}$$

1.8.3.4 A scatter plot of Nagel midpoints on the red-green scale versus RGI allows one to separate a clear cluster of subjects, with midpoints between 36 and 44 units, on the red/green mixture scale, that are likely to be normal trichromats (see Figure 6). Dichromats will accept the full range of red/green mixtures as a match with the yellow field (i.e. RGI=0), as they have only one photopigment in the spectral range provided by the instrument. Deuteranopes are distinguished from protanopes as the intensity 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. This is because protans tend to see red as fairly dark as they have reduced long wavelength sensitivity. If a colour match within the normal range is not achieved, the subject is classed as an anomalous trichromat. 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 (see Figure 6). The RGI or matching range provides some measure of the severity of the colour discrimination deficit on the Nagel anomaloscope, although it is well known that the correlation between the size of the matching range and the subject's ability to discriminate colours under more natural conditions is generally poor (Wright, 1946).

1.8.3.5 The principal advantage of the anomaloscope is that unlike the previous tests, the parameters of the yellow match can be used to classify accurately the type of colour deficiency involved.

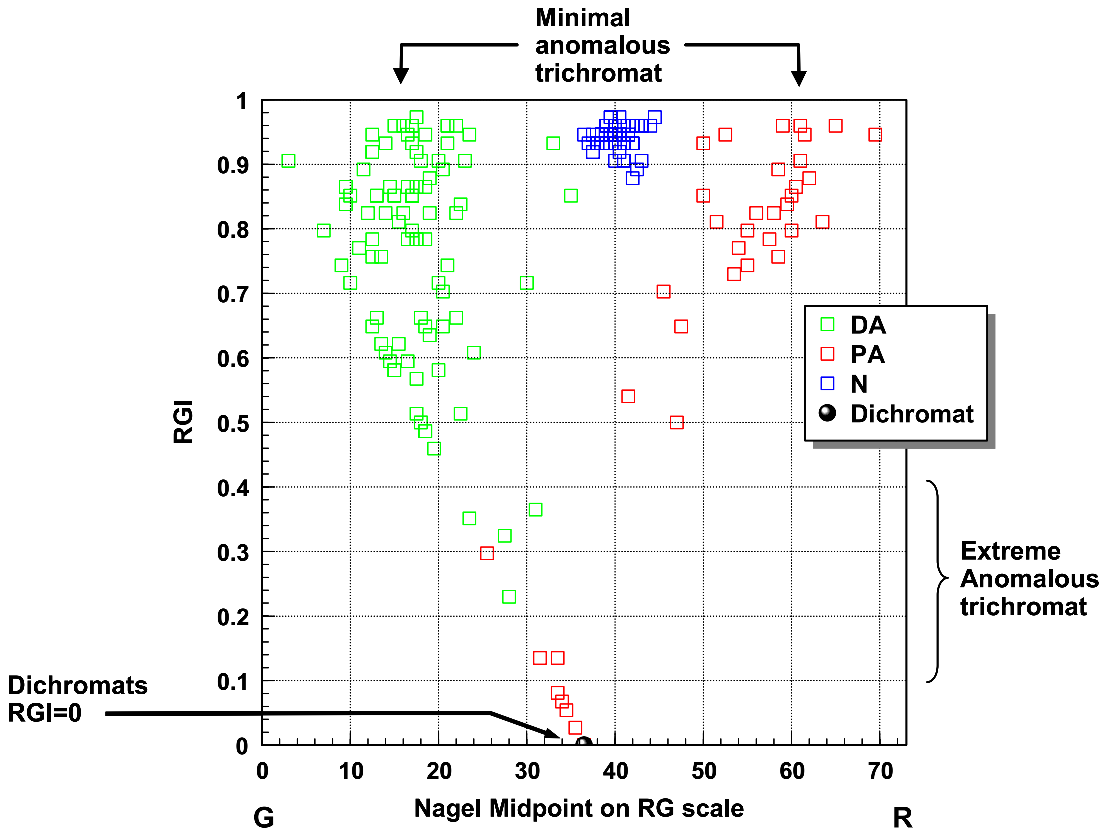

Figure 6 Scatter plot of matching midpoints versus RGI for 231 observers; 70 subjects formed a cluster that is separated from all other subjects by having a midpoint around 40 and a high RGI. The abbreviations in the legend refer to deuteranomalous (DA), protanomalous (PA), and normal trichromat (N) subjects. The value of the luminance setting on the yellow scale provides additional information to separate deutan and protan colour deficient observers. The data show clearly that according to the Nagel test, many deutan and protan subjects have RG chromatic sensitivity that is indistinguishable from the range of values measured in normal trichromats.

1.8.4 Aviation Lights Test (ALT)

1.8.4.1 The Aviation Lights Test is a modified Farnsworth Lantern (Milburn & Mertens, 2004) to meet the FAA's signal colour (USDOT-FAA, 1988) and International Civil Aviation Organization (ICAO, 1988) specifications for the red, green, and white signal light colours on aircraft. The chromaticity coordinates of the ALT are shown plotted in Figure 11. Originally the test was employed for secondary screening of air traffic control specialist applicants.

1.8.4.2 Nine vertically separated pairs of coloured lights (see Figure 7) are presented to the examinee, who is seated 8 ft (~ 2.4m) away from the lantern. The constant vertical separation of the 2 apertures is 13mm, or 18.3 minutes of arc at the recommended viewing distance. Each pair of lights subtends a visual angle of 3 min arc. There are three colours: red, green and white. Each series of nine pairs was presented three times in random order making a total of 27 presentations.

(b) (a)

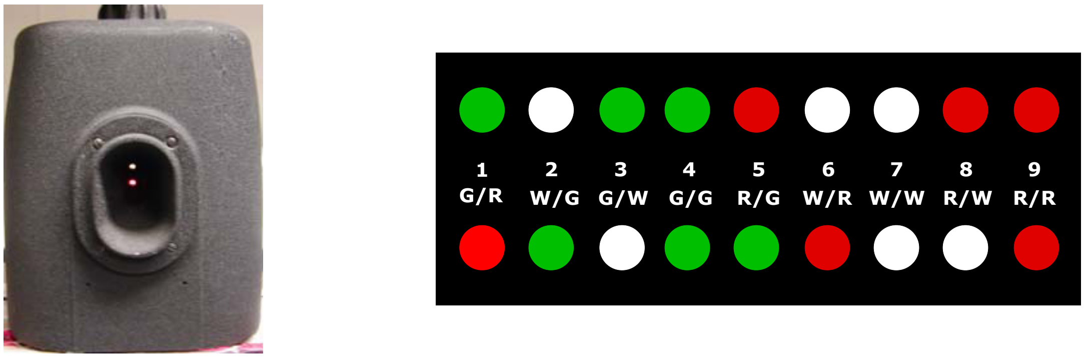

Figure 7 (a) Schematic representation of the different pairs of lights presented in the Aviation Lights Test (ALT). The lantern can show 9 different combinations (as shown) three times giving a total of 27 presentations, (b) Photograph of the ALT lantern.

1.8.4.3 Before the ALT test is carried out the subject is shown each of the three test light colours. Light pairs numbered 1 and 2 are shown (see Figure 7a) while saying: "this is green over red" and "this is white over green," respectively. The examinee has to name correctly the colours of the lights shown (with a pass criterion of not more than one error) in all 27 presentations. If the colour of either or both lights in a pair was identified incorrectly, this was counted as one error.

1.8.4.4 The ALT is administered in a very dim room that approximates the light level of the air traffic control (ATC) tower cab at night.

1.9 The CAD test

The Colour Assessment and Diagnosis (CAD) test has been described in an earlier CAA report (CAA, 2006a). The CAD test is implemented on a calibrated visual display and consists of coloured stimuli of precise chromaticity and saturation that are presented moving along each of the diagonal directions of a square foreground region made up of dynamic luminance contrast (LC) noise. The subject's task is to report the direction of motion of the colour-defined stimulus by pressing one of four appropriate buttons. Randomly interleaved staircase procedures are used to adjust the strength of the colour signals involved according to the subject's responses in order to determine the thresholds for colour detection in each direction of interest so as to establish reliable estimates of red-green and yellow-blue colour thresholds. The CAD test has a number of advantages over conventional tests both in terms of isolation of colour signals as well as sensitivity and accuracy:

a) **Isolation of colour signals**

It is very important to isolate the use of colour signals by masking any luminance contrast cues. Although the coloured stimuli generated are isoluminant for the standard CIE observer, the large variation in L:M spatial density ratio within normal trichromats (i.e. 0.6 to 13; Carroll et al, 2002) and the variation in cone spectral responsivity functions in colour deficient observers introduce variations in the perceived luminance contrast of most coloured stimuli. This is simply because the resulting luminance efficiency function V(λ) is likely to vary both amongst normal trichromats and within colour deficient observers. The CAD test employs dynamic LC noise and this masks effectively the detection of any residual luminance contrast signals that may be present in the coloured test target. The mean luminance of the foreground remains unchanged, both spatially as well as in time, and equal to that of the surround background field. The technique isolates the use of colour signals and ensures that the subject cannot make use of any residual LC signals. The dynamic LC noise does not affect the threshold for detection of colour signals, but masks very effectively the detection of luminance contrast signals (Barbur et al, 1994; Barbur, 2004).

b) **Measurement of chromatic detection thresholds**

An efficient, four-alternative, forced-choice procedure is used to measure subject's chromatic detection thresholds in a number of carefully selected directions in the CIE – (x,y) chromaticity chart. Thresholds are measured along 16 interleaved directions in colour space. These are grouped together so as to test red-green (RG) and yellow-blue (YB) colour sensitivity. Threshold ellipses are computed and plotted using the standard CIE 1931 chromaticity chart. The use of 16, randomly interleaved colour directions makes the technique statistically robust and eliminates any other possible cues, so that the subject has to rely entirely on the use of colour signals. The output of the CAD test also diagnoses accurately the class of colour deficiency involved. If the latter is not needed, one only needs to test two colour directions to screen for red/green colour deficiency.

c) **The statistical limits of chromatic sensitivity within "normal" trichromats**

Chromatic discrimination thresholds have been measured in over 450 observers, including 250 normal trichromats and 200 colour defective observers (Figure 12). Figure 8 shows the distribution of YB and RG chromatic thresholds obtained in the 250 normal trichromatic subjects. Figure 9 shows the statistical limits for the 'standard normal' (SN) observer on the CAD test plotted in the 1931 CIE-x,y colour chart (Rodriguez-Carmona et al, 2005; Rodriguez-Carmona, 2006). The variability in both RG and YB thresholds is shown by the grey shaded ellipse, which represents the region of the CIE chart where we expect to find 95% of normal trichromats. The 2.5% and 97.5% limits define the boundaries of this region. The median chromatic discrimination threshold ellipse is also plotted. The median threshold value is important since it represents the Standard Normal (SN) observer. A subject's thresholds can then be expressed in SN units and this makes it possible to assess the severity of colour vision loss, i.e. an observer with a RG threshold of 2 SN units requires twice the colour signal strength that is needed by the average standard CAD observer. Figure 9 is an extremely useful representation in that it provides a CAD test template for the SN observer. Any subject's results provide instant diagnosis of either normal or deficient colour vision when plotted on this template.

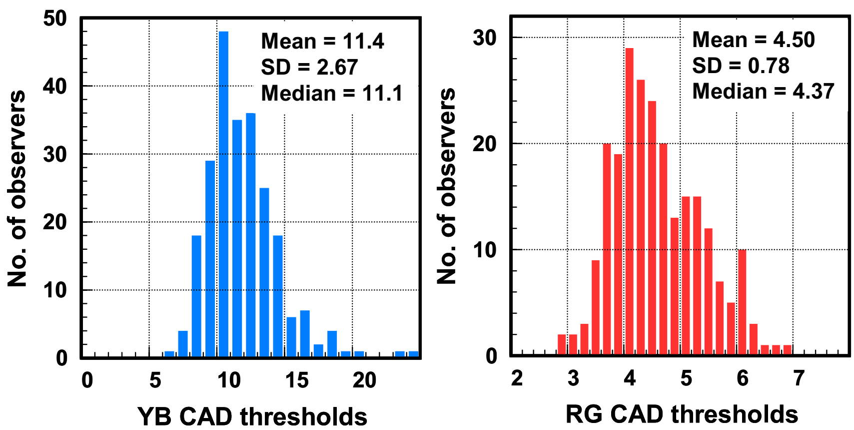

Figure 8 Frequency distributions of the YB and RG chromatic thresholds obtained in 250 observers with 'normal' trichromatic vision. The mean, standard deviation (SD) and median are shown

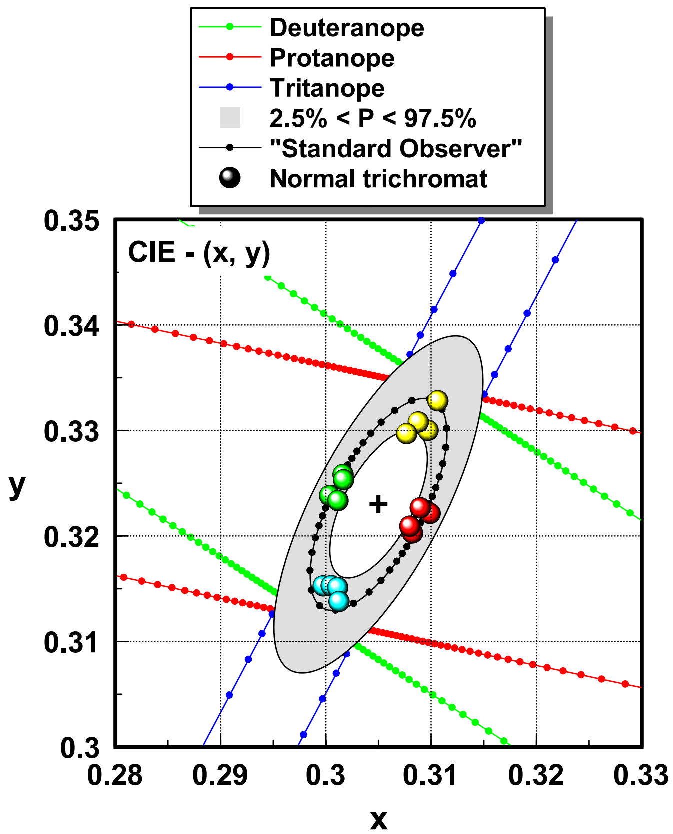

Figure 9 Data showing the 97.5 and 2.5% statistical limits that define the "standard" normal CAD test observer. The dotted, black ellipse is based on the median RG and YB thresholds measured in 250 observers. The grey shaded area shows the limits of variability of 95% of these observers. The deuteranopic, protanopic and tritanopic confusion bands are displayed in green, red and blue, respectively. The background chromaticity (x,y) is indicated by the black cross (0.305, 0.323). The coloured symbols show data measured for a typical normal trichromat.

d) **Detection of colour vision loss that falls outside normal range**

The distribution of thresholds along the directions examined provides enough information to classify even minimal deficiencies that would otherwise remain undetected using conventional colour vision tests. For example, Figure 10 shows results of two minimal colour vision deficient observers that fall just outside the normal range indicated by the shaded grey area. The subject on the left (subject CC) has a Nagel range of 16-18 and passes the Ishihara, whereas the subject on the right (subject SH) has a Nagel range of 40-42 units but fails the Ishihara with 2 errors. Although both subjects are classified as minimum deuteranomalous on the CAD test, their classification on the other two tests is less clear. The first subject is classified as normal on Ishihara and deuteranomalous on the Nagel (but with a mixture range that is smaller than the average normal trichromat). The second subject is classified as normal on the Nagel, but slightly red/green deficient on the Ishihara.

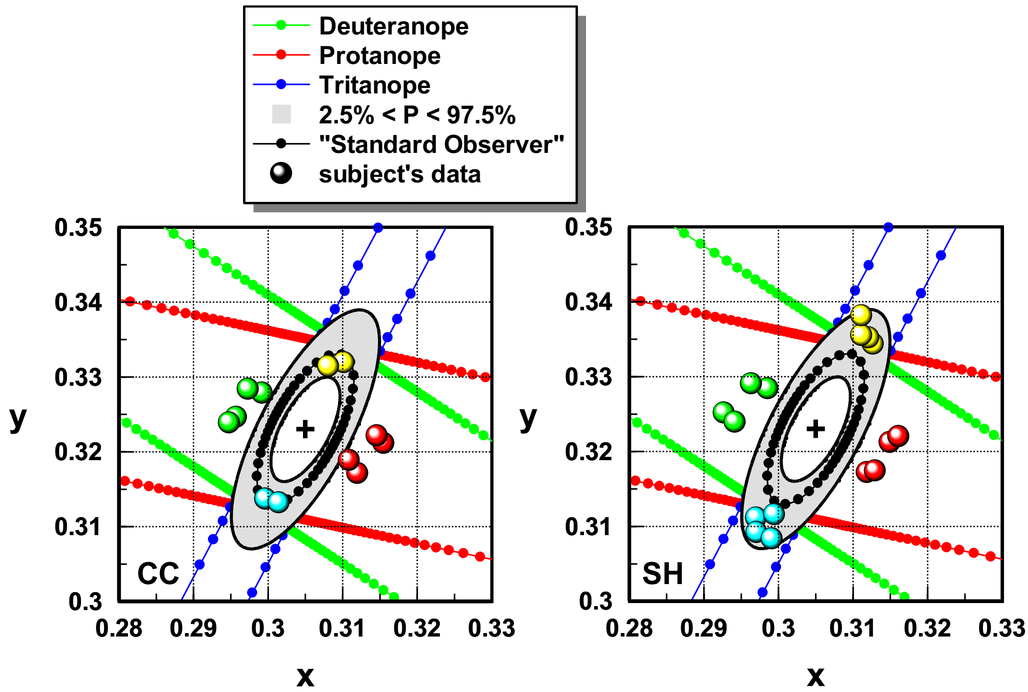

Figure 10 Chromatic thresholds for two colour vision deficient observers with minimal colour vision deficiency. The data for the average normal trichromat is shown as a black contour.

e) **Diagnosis of the type of deficiency involved**

The CAD test identifies the type of deficiency involved by the elongation of the subject's results either along the deuteranopic (Figure 11, left) or protanopic (Figure 11, right) confusion bands. In the case of absolute minimum deuteranomalous deficiencies the distribution of the thresholds is as shown in Figure 10. In the case of minimum protanomalous deficiencies the thresholds are much larger and extend sufficiently along in the protanopic direction indicating a diagnosis of minimum protanomaly with no ambiguity. The agreement with the Nagel for screening and classification of the class of congenital red/green deficiency is ~99%.

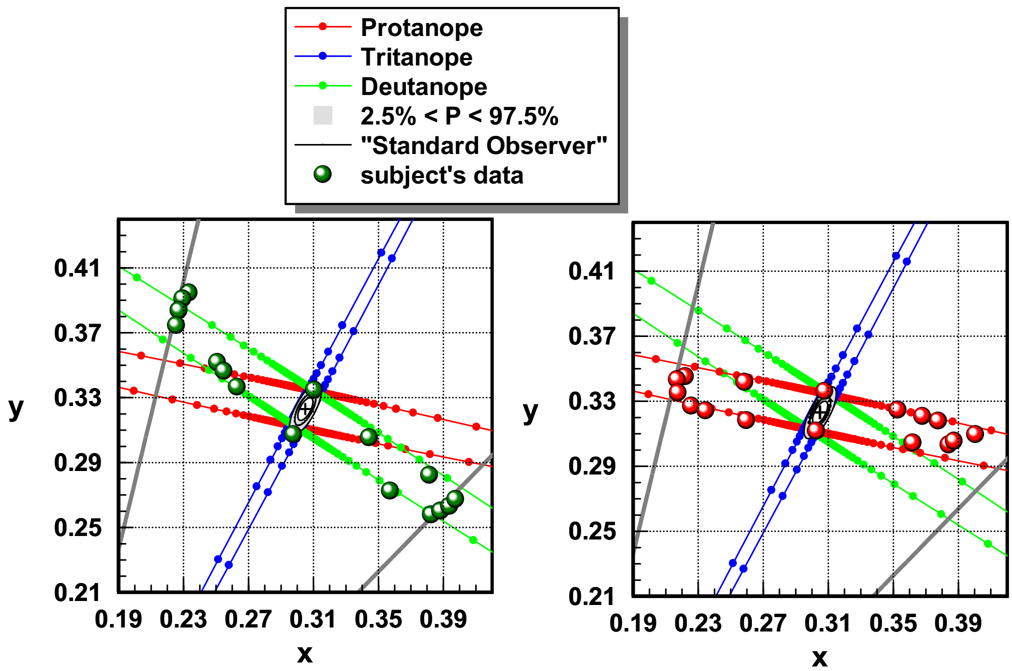

Figure 11 Chromatic thresholds for two colour vision deficient observers with severe colour vision deficiency. The largest chromatic displacements away from background chromaticity, as set by the isoluminant condition and the limits imposed by the phosphors of the display, are shown as grey lines. The extent of colour vision loss is related to the elongation along the protanopic or the deuteranopic confusion band and suggests that the greater the elongation, the lower the level of chromatic sensitivity.

f) Quantifying the severity of colour vision loss

The severity of red-green and yellow-blue loss of colour vision is proportional to the colour signal strength needed for threshold detection. For example, subjects in Figure 11 show more severe loss (i.e. higher thresholds or lower chromatic sensitivity) than the subjects shown in Figure 10. The severity of colour vision loss can be quantified with respect to the standard normal observer (Figures 8 and 9). Chromatic sensitivity varies greatly within colour deficient observers from complete absence of red-green discrimination, in the case of dichromats, to almost normal sensitivity in subjects with thresholds not much larger than 2 SN units. Figure 12 shows the subject's RG threshold in SN CAD units along the abscissa, plotted against the YB threshold along the ordinate in 450 observers. The results show that the RG thresholds vary almost continuously from very close to 'normal' to extreme values which can be 25 times larger than the standard normal threshold. The YB thresholds, on the other hand, vary very little as expected in the absence of yellow-blue loss or acquired deficiency. Interestingly, the RG thresholds show some correlation with YB thresholds in normal trichromats, suggesting that subjects with high RG chromatic sensitivity are also likely to exhibit high YB sensitivity. The loss of sensitivity (when expressed in Standard Normal (CAD) units (SN units) is greater in protanomalous than deuteranomalous observers (Figure 12)

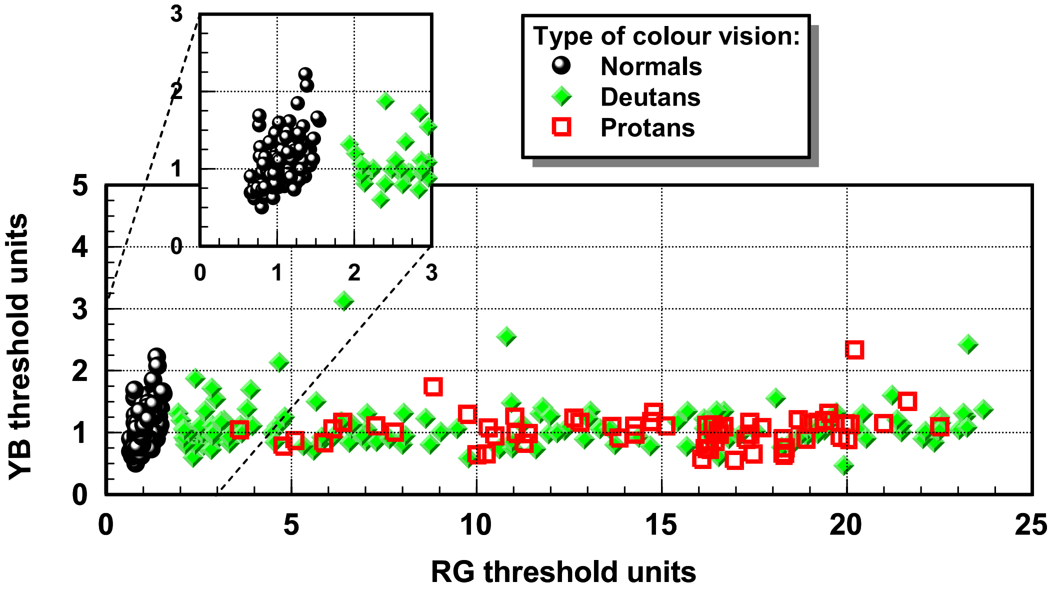

Figure 12 Graph showing Red-Green (RG) and Yellow-Blue (YB) thresholds expressed in CAD Standard Normal units for the population of subjects tested as part of this study. The spread of the data along the abscissa illustrates the large variation that exists amongst subjects with deutan- and protan-like deficiencies.

g) **Effects of light level and stimulus size**

Both the ambient light adaptation level and the size of the coloured stimulus can affect chromatic sensitivity. In general, as the light level is reduced and / or the stimulus size is decreased the RG and YB thresholds increase. The YB thresholds are affected most at lower light levels. Both background luminance and stimulus size have been optimised for the CAD test so that no significant improvement in chromatic sensitivity results by increasing either the light level or stimulus size. Any small variations in either light level or stimulus size will not therefore alter significantly the subject's RG and YB thresholds (Barbur et al, 2006). However, older subjects are likely to show more rapid effects as the light level is reduced simply because the retinal illuminance in these subjects is already low as a result of small pupil sizes and increased pre-receptoral absorption of blue light.

h) **The effects of aging on red-green and yellow-blue loss of chromatic sensitivity**

The effect of aging for YB and RG chromatic thresholds in normal trichromats is shown in Figure 13. These results show that up to the age of 60 years there is little correlation between the subject's age and chromatic sensitivity. A small effect can be observed when examining YB thresholds (but the correlation with age remains very poor) and virtually absent in the case of RG thresholds. The age range examined is representative of the typical working life of pilots. Colour vision is usually assessed in demanding occupational environments. Loss of colour vision later in life is described as acquired colour deficiency and can be caused by a number of factors including both systemic diseases and specific diseases of the eye (such as diabetes, glaucoma, age-related macular degeneration, etc.). Since loss of chromatic sensitivity usually precedes the reliable detection of any structural changes using fundus imaging, regular screening for acquired colour vision loss may be of great clinical value. In view of these findings, it makes sense to recommend that in addition to assessing colour vision at the start of the working career, periodic re-assessments should also be done, simply as a way of testing for acquired deficiencies.

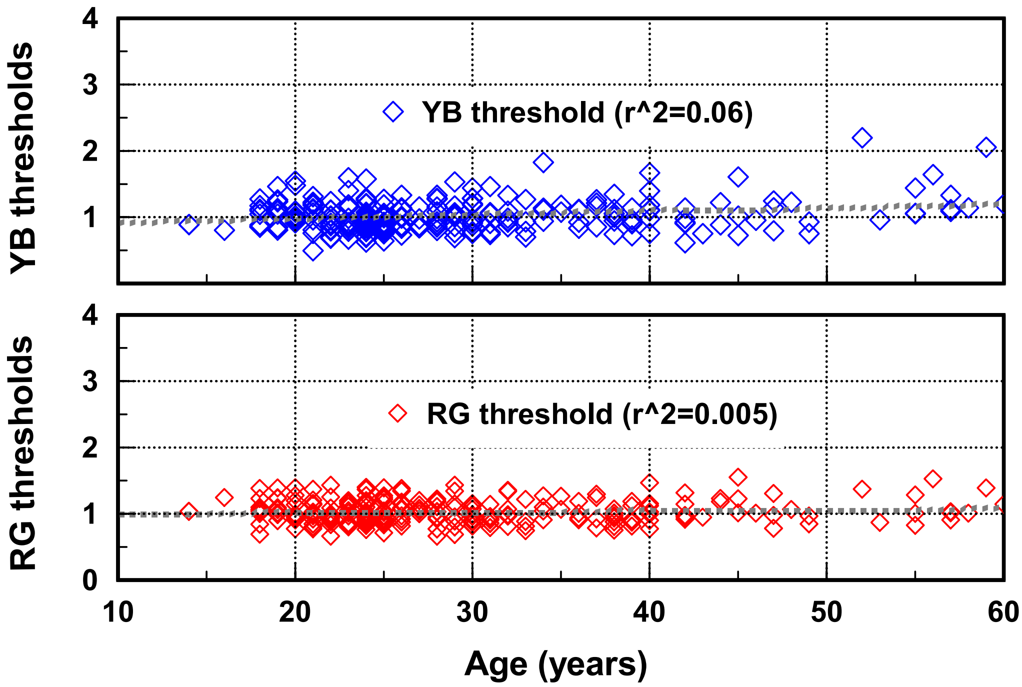

Figure 13 Effect of age on the YB and RG chromatic thresholds for normal trichromats under normal daylight conditions. The best-fit line is shown for both sets of data. The correlation coefficients (r^2) for the YB and RG thresholds are 0.06 and 0.005, respectively.

1.10 Summary of congenital colour vision deficiencies

1.10.1 Congenital colour vision deficiencies remain unchanged throughout life and are largely determined by changes in the spectral responsivity of cone photoreceptors that are determined genetically. There are a number of other factors that can affect chromatic sensitivity, such as the optical density of photoreceptors, post-receptoral amplification of cone signals or pre-receptoral filters that are spectrally selective and reduce the amount of light that reaches the cone photoreceptors in the eye (Alpern & Pugh, Jr., 1977; Alpern, 1979; Neitz & Jacobs, 1986; Barbur, 2003). These factors are all likely to contribute to the variability measured both within normal and colour deficient observers.

1.10.2 Congenital yellow/blue colour vision deficiency is very rare (with an incidence of 1 in 13000 to 65000; Sharpe et al, 1999) and usually implies the absence of S-cones. Loss of YB sensitivity with age, on the other hand, is very common and is often associated with toxicity or disease (see below).

1.11 Acquired colour vision deficiencies

Acquired deficiencies tend to affect both RG and YB colour discrimination, although frequently the YB loss is greater and more apparent. Acquired colour deficiencies are most commonly caused by systemic (e.g. diabetes, multiple sclerosis) and other diseases that are specific to the eye (e.g. glaucoma, age-related macular degeneration, optic neuritis, etc.). Acquired deficiency affects predominantly older subjects. Acquired loss can sometimes be expressed in subjects with congenital colour deficiencies. If congenital colour deficiency is present, the identification of acquired colour deficiency and the classification of the congenital component are 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). There are other differences as well. Acquired loss of colour sensitivity is generally non-uniform over the retina in the same eye and often affects one eye more severely than the other. One can also separate the congenital and the acquired loss by carrying out the CAD test in each eye both at the fovea and in the near periphery of the visual field or / and by using more than one stimulus size. The congenital component remains largely unchanged, whereas the acquired component varies with stimulus size, retinal location and eye tested. Since the yellow-blue sensitivity is most affected, the CAD is particularly suitable for investigating acquired deficiency since it tests for both red-green and yellow-blue loss.

Figure 14 below shows examples of acquired colour vision deficiencies.

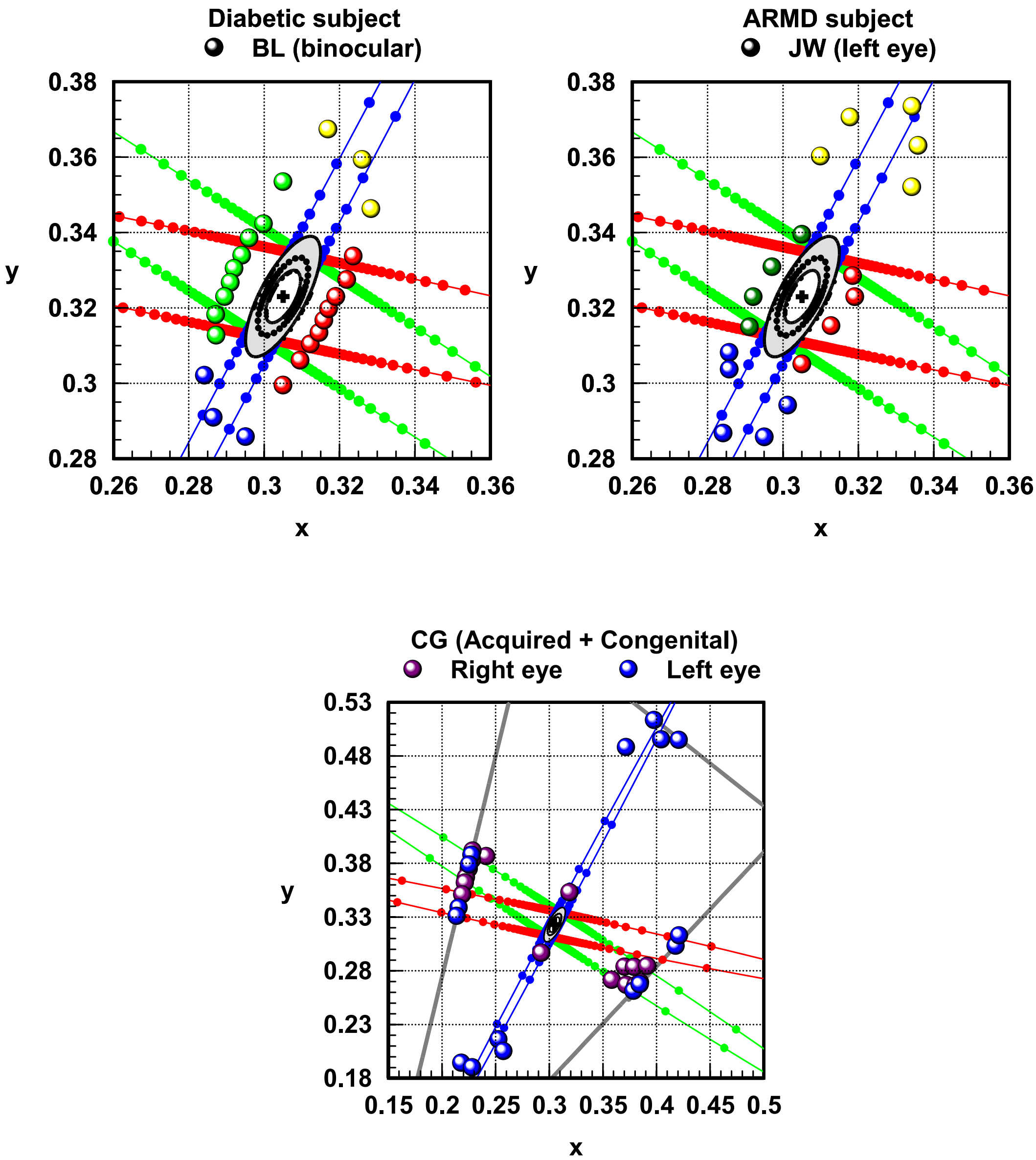

Figure 14 Examples of subjects with acquired loss of chromatic sensitivity. The data shown on the top left graph is from a subject with diabetes; top right shows data from the left eye from a subject with Age Related Macular Degeneration (ARMD); and bottom graph shows data from a subject with both congenital and acquired colour vision loss (note the difference between the two eyes).

2 Subjects and Methods

2.1 Summary of tests employed in this study

a) Ishihara plate test

b) Dvorine plate test

c) Nagel anomaloscope

d) CAD test

e) Aviation Lights Test (ALT)

f) PAPI simulator test

g) PAPI Signal Lights test (PSL)

The PAPI and PSL simulator were designed and constructed specifically for this investigation. A full assessment of colour vision using all these tests takes between 1.5 to 2 hours per subject. The order the different tests are carried out varied randomly and the testing took place in three different rooms, allowing the subject to take short breaks in between tests. We examined 182 subjects in this investigation: 65 normal trichromats and 117 subjects with deutan- and protan-like colour deficiencies. The age of the subjects ranged from 15 to 55 years (mean 30.2 years, median 27 years).

2.2 PAPI and PSL simulator

2.2.1 The PAPI system consists of four lights arranged in a horizontal line and installed at right angles to the runway with the nearest light some 15m away from the edge. The lights are approximately 30cm in diameter with an inter-light separation of 9m. The unit nearest the runway is set higher than the required approach angle at 3°30′, with progressive reductions of ~20 minutes of arc further out field: 3°10′, 2°50′ and 2°30′ (for a 3° approach). Usually each unit contains three light projectors (in case one fails). The light system has an intensity control for day and night use, with up to six luminous intensity settings: 100%, 80%, 30%, 10%, 3% and 1% (CAA, 2004).

2.2.2 The units direct a beam of light, red in the lower half and white in the upper half, towards the approach. The different elevation angles give a combination of red and white for an on-slope signal, all-red if the aircraft is too low, and all-white if it is too high (see Figure 1). The chromaticities of the lights should follow the ICAO specification for Aerodrome Ground Lighting (AGL) (see Figure 15). The light intensity of the white signal is required to be no less than twice and no more than 6.5 times as bright as the red signal. The recommended intensities for the white and red light are 85000cd and 12750cd, respectively, at the maximum of their light intensity distribution (CAA, 2004)

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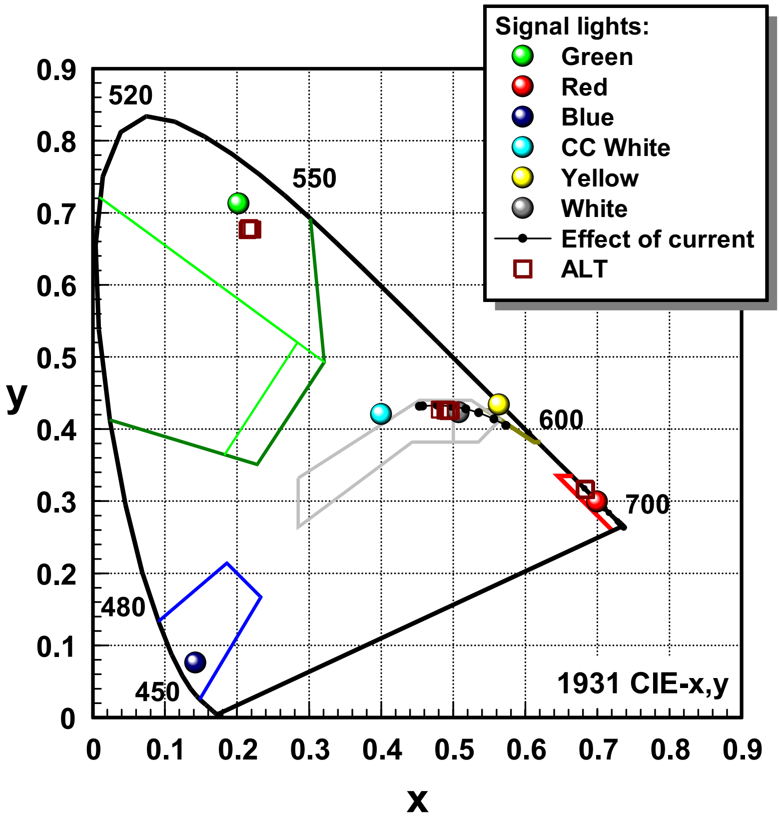

Figure 15 1931 CIE-x,y colour space diagram showing the recommended chromaticity boundaries for the colours of light signals (CIE, 2001a; CIE, 2001b). The signal colours used in the laboratory set-up are also plotted and the effect of varying the current (i.e. the output intensity of the laps) is shown for the white light.

2.2.3 A schematic of the laboratory set-up developed to simulate the PAPI and PSL tests is shown in Figure 16. A four-channel optical system was developed using an airfield halogen lamp (JF6.6A100W/PK30d) as the single light source. The light is then split up and channelled using two beam-splitters (BS) so as to generate four beams. Each beam of light passes through two motorised filter wheels; colour (CW) and neutral density (NDW) wheels. The CW has six different filters: red, modified white (~3900K), blue, green, yellow and standard white (~2400K). Each NDW has neutral density filters with the following optical density (OD) values: 0.0, 0.3, 0.6, 1.0, 1.3, and 1.6. During the calibration procedure, the luminous intensity of each beam was measured with each filter in place to account for the actual and not the nominal absorption of each filter.

2.2.4 The angular subtense of each light was 1.36′ at a viewing distance of 4m. Beyond ~ 0.8km the angular subtense of the real PAPI lights approaches the diffraction limit of the eye. The size of each light on the retina remains relatively unchanged as the approach distance is increased, but the light flux captured from each light is decreased. On approach the PAPI lights are first seen as a small continuous line until the angular separation between adjacent lights is resolved by the eye (typically less than 2′ taking into consideration pupil size and optical aberrations). In order to reproduce the geometry of the real PAPI lights in the laboratory for a viewing distance of 4m, the adjacent lights (centre to centre) were separated by ~ 6.5mm. This corresponds to an angular separation of 5.5′ which translates to an approach distance of 5.54km in the case of the real PAPI lights. This design therefore requires the pilot to locate and recognise the white and red PAPI lights from 5.54km when the size of the image of each light on the retina is determined by the point-spread-function (PSF) of the eye. A larger approach distance was not chosen in order to minimize the effects of higher order aberrations and increased scatter in the eye have on the retinal images of the lights. When the pupil size is large, the higher order aberrations in the eye can be quite large and this causes the PSF to broaden and the visual acuity to decrease. The light distribution in adjacent PAPI lights can overlap significantly and this in turn makes it more difficult for the subject to process the colour of each light. Since a larger approach distance would produce even more overlap, a distance of 5.54km that is considered to be safe was selected for the study.

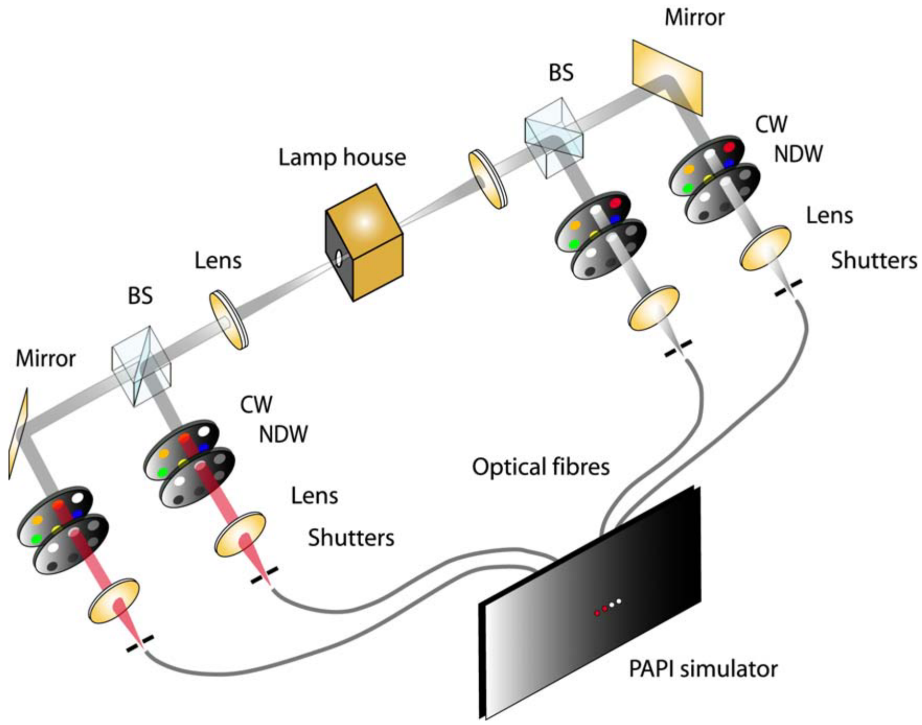

Figure 16 Schematic representation of PAPI simulator designed and constructed for this study. Light emerging from each arm of the lamp house is divided into two channels via beam splitters (BS) to produce four independent channels. Each channel has a colour wheel (CW) and a neutral density wheel (NDW) which are controlled by the computer. After passing through appropriate filters, the light from each channel is focused into an optical fibre head which are attached to the viewing panel so as to simulate the PAPI lights.

2.2.5 The optical fibre heads form a line located at the centre of a black plate which provides a dark uniform surround (see Figure 16). The whole system is encased and ventilated by two fans to prevent overheating and to reach a steady state temperature as needed for stable lamp operation. The intensities of the red and white lights were adjusted using ND filters so that the simulated PAPI lights appear as intense as the real PAPI when viewed in the dark from a distance of 5.54km. The calculations involved assumed that in the absence of significant ambient light, the pupil of the eye would in general be large (~ 6 mm). In addition, the intensities of the coloured lights also varied randomly by ±0.3 OD with respect to the nominal values to eliminate the detection of brightness cues.

2.2.6 The effect of the different intensity settings and ND filters was investigated to establish the extent to which the chromaticities of the white and red lights change with lamp current setting and / or the use of ND filters (see Figure 17). The results show that the ND filters cause only small changes in the chromaticity coordinates of the white and even less so for the red light. Changes in lamp current cause larger changes in the chromaticity of the white light, but in spite of these changes the white remains within the 'variable white' area indicated on the CIE diagram as appropriate for AGL (see Figures 15 and 17). In the case of real PAPI lights, other factors such as atmospheric absorption can also affect the chromaticity of the white, with very little effect on the red.

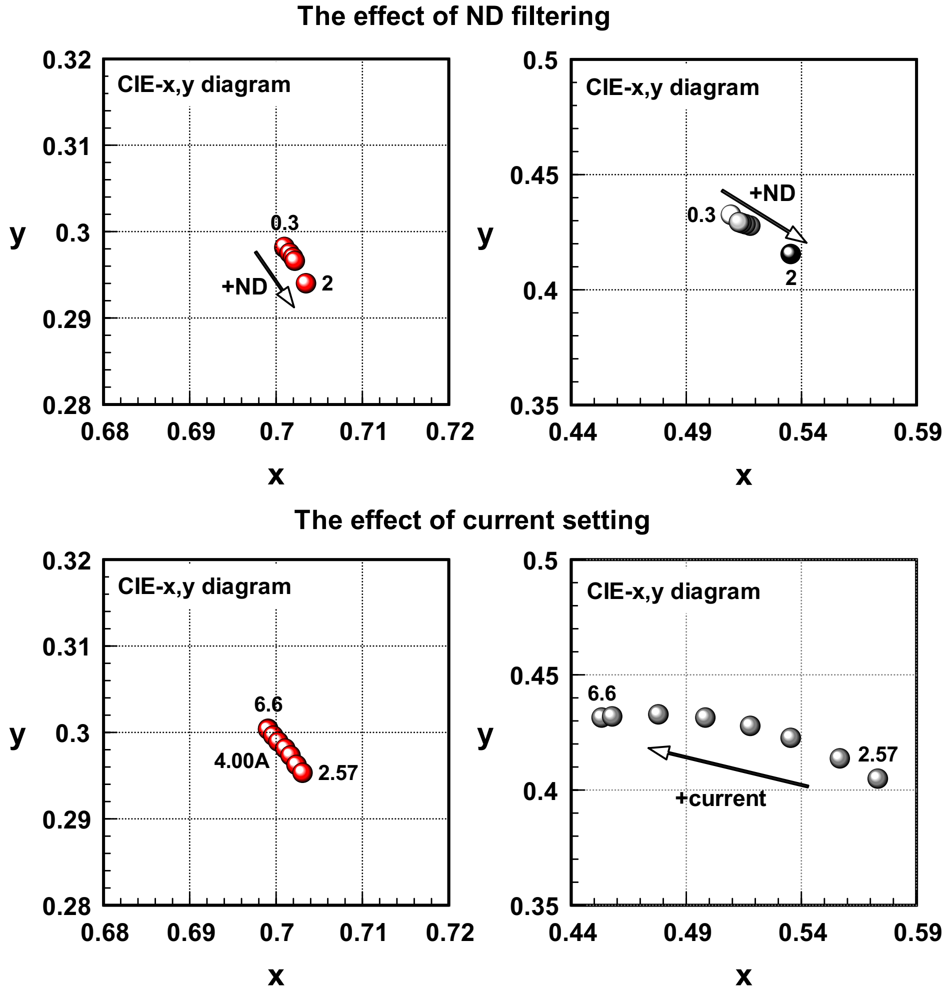

Figure 17 Graphs showing the CIE-x,y chromaticity coordinates of the Red and White lights under the effect of neutral density (ND) filtering and the effect of the current setting (intensity) on the lamp in amps (A).

2.3 Testing procedure

2.3.1 The four horizontal lights are presented for 3 seconds and the subject's task is to simply report the number of red lights in the display. There are five possible combinations of red and white lights that are presented randomly (Figure 18, left). Observers are instructed to report the number of red lights using the following names: one, two, three, four or zero (to avoid confusing 'none' with 'one') when carrying out the PAPI simulator test. Prior to the test, observers were allowed to dark adapt to the low mesopic surround and then were presented with a practice run. A low power lamp was placed behind the test equipment to provide low mesopic conditions of ambient illumination. The black, immediate surround around the PAPI lights was dark (i.e. mean luminance ~ 0.005 cd/m2). Subjects were encouraged to respond only after an auditory cue signalled the end of the 3 second viewing period. The PAPI test was carried out twice, once with the standard white (~2400K) and once with a modified white light (higher colour temperature of ~3900K).

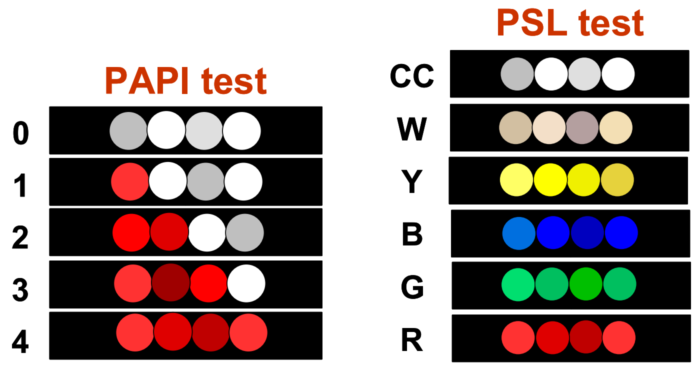

Figure 18 Schematic representation of the Precision Approach Path Indicator (PAPI) simulator test (left) and PAPI Signal Lights (PSL) test (right). The PAPI test presents 5 different conditions (as shown) twelve times giving a total of 60 presentations. The PSL presents 6 different conditions (as shown) twelve times giving a total of 72 presentations. The intensities of the lights varied randomly by ±0.3 OD with respect to the nominal values to eliminate the detection of brightness cues.

2.3.2 The PSL test uses similar parameters to the PAPI lights test. In this test six possible colours are presented (standard white, modified white, red, green, blue and yellow). The chromatic properties of the lights lie within the boundaries for the recommended signal lights for AGL (CAA, 2004) as shown in Figure 15. The PSL addresses the issue of correct colour naming when all lights have the same chromaticity as opposed to the ability to distinguish and categorise some of the four lights as red and the others as white on the bases of some perceived differences between the lights. The PSL tests whether the applicant can recognise and name reds as 'red' and whites as 'white' for the same conditions and geometry as the PAPI lights, but when all the lights are of the same colour. The conditions when all four PAPI lights have the same colour to indicate "far too low" (all reds) or "far too high" (all whites) are clearly very important. Observers were instructed to report the colour of the lights as either: red, green, yellow, blue or white.

2.3.3 There were two whites, the standard white as produced by the lamp and a modified white produced by raising the colour temperature of the standard white by 200 MIREDS. This is achieved by using a colour correction filter that modifies the spectral content of the tungsten light to make it more like daylight. Prior to the test, observers were presented with a practice run. All the colours were shown to the subject and named by the examiner during the practice run and the subject was allowed to review any of the lights and to ask the examiner to confirm their colour. The results for the PAPI and PSL are recorded as the percent correct.

3 Results

3.1 The colour vision of each subject was examined using five different colour vision tests as well as the PAPI and PSL simulator tests. Results from each of the five tests were then examined in relation to the subject's performance on the PAPI to establish which test yields the best prediction of performance in the PAPI task.

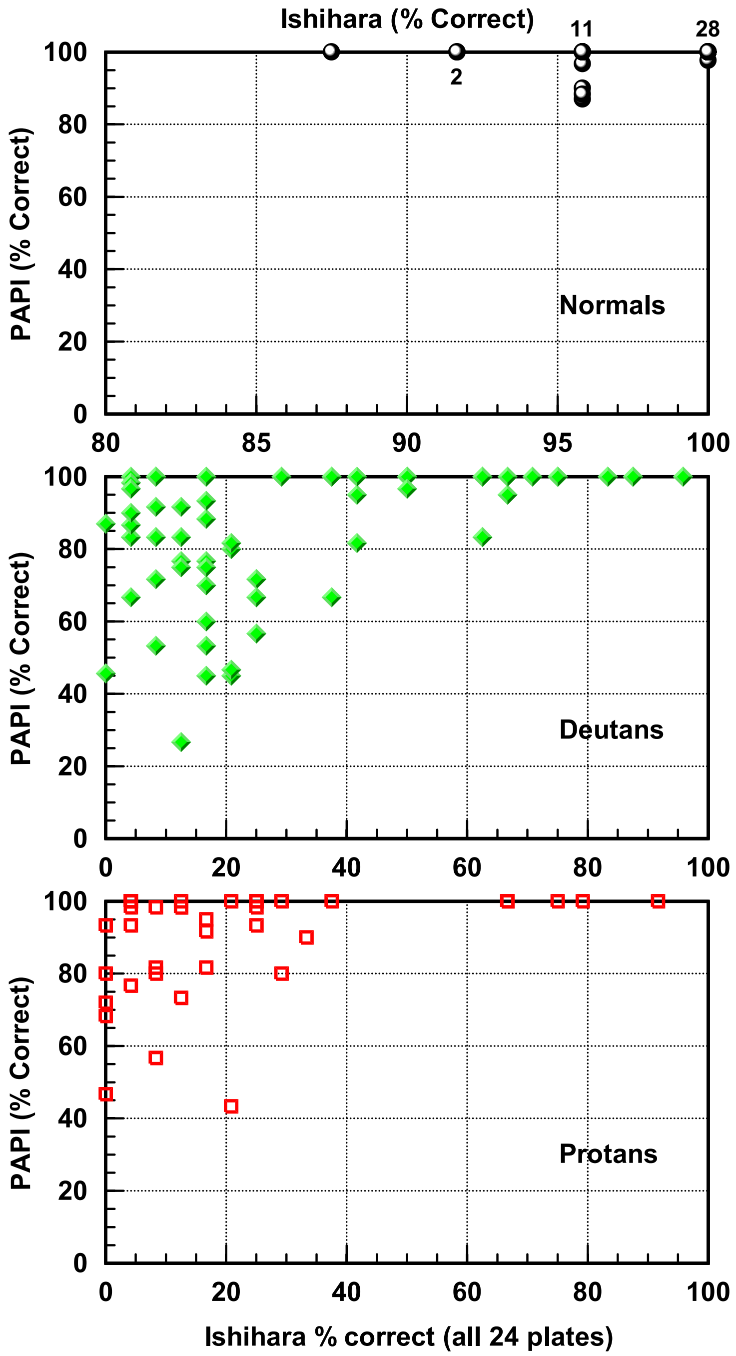

Figure 19 The number of plates read correctly expressed as a percentage on the Ishihara test (24 plates) is compared to performance on the PAPI simulator test separately for normals, deutan and protan colour vision observers. The x-axis for the top graph has been expanded to show clearer the errors made by normals.

3.2 Performance on the PAPI task is computed as number of correct reports out of a total of 60 presentations.

3.3 The results summarised in Figure 19 show that normal trichromats can also make errors, both on the PAPI and the Ishihara tests (i.e. five subjects produce one error, one subject produces two errors and one other subject produces three errors on the PAPI). The rest of the normal subjects score 100% correct on the PAPI test. Results for deutan colour deficient observers reveal that all subjects with scores > 70% (i.e. 16 or more correct plates out of 24 on the Ishihara 24-plate test) pass the PAPI with a score of 100% correct. Results for protan observers show that four subjects with scores greater than 40% pass the PAPI test. Overall the results reveal very poor correlation between the subjects' performance on the Ishihara and the PAPI test scores. Many of the subjects that pass the PAPI task can score anything from 0 to 95% correct on the Ishihara test.

3.4 Comparisons of data from the Dvorine plate test with the PAPI simulator show similar results to those obtained with the Ishihara test (Figure 20). Three normals obtain less than 100% on the Dvorine test (but pass the PAPI with no errors). Deutan and protan colour deficient subjects need more than 65 and 50%, respectively, on the Dvorine plate test to achieve 100% on PAPI. Since the prediction of the class of deficiency (protan or deutan) involved is poor with both Ishihara and Dvorine tests, it is difficult to know which of the two limits one should apply to any colour deficient subject.

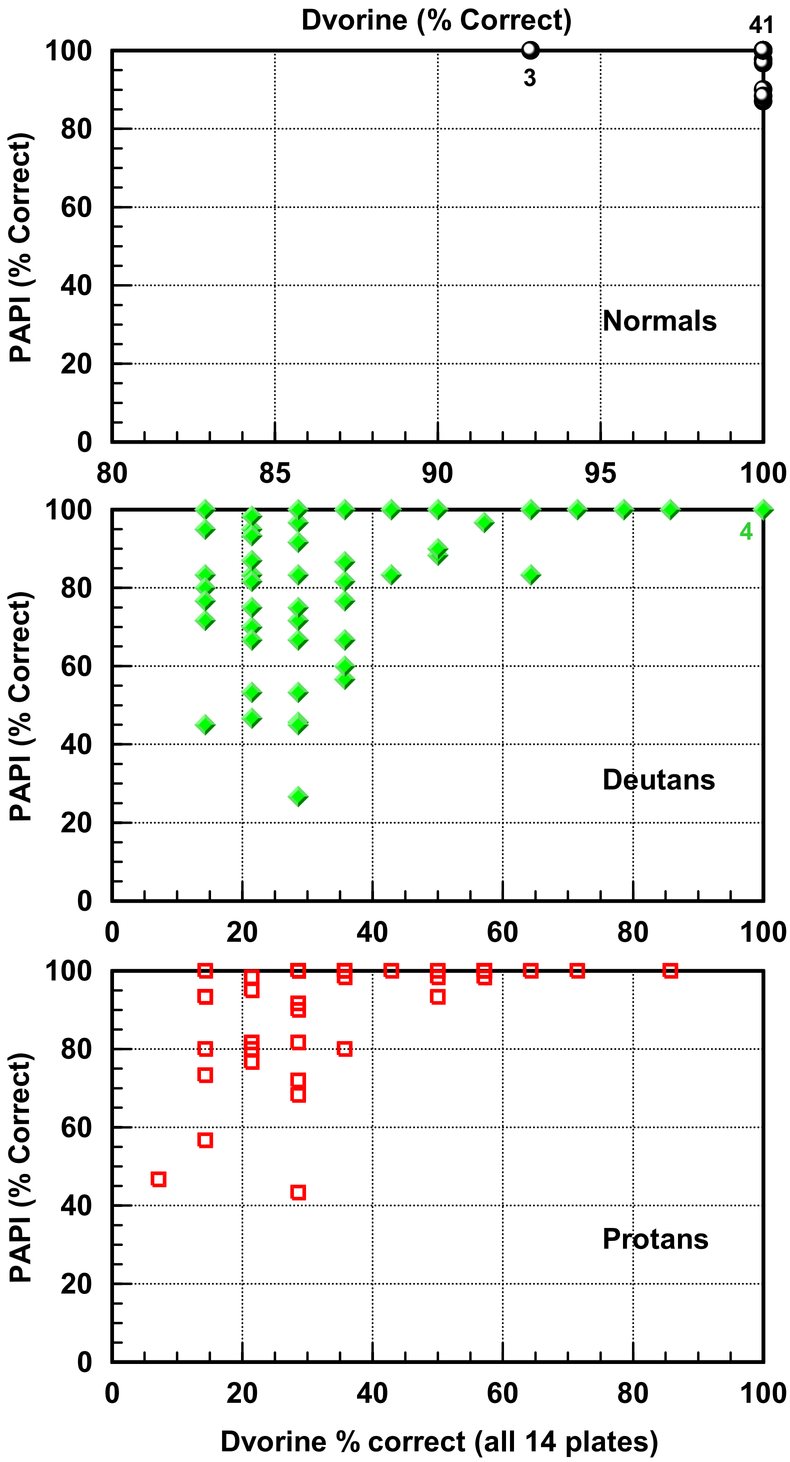

Figure 20 PAPI percentage correct scores plotted as a function of the number of plates read correctly on the Dvorine test (expressed as a percentage) for normals, deutan and protan observers.

3.5 Figure 21 plots the PAPI scores against the subjects' performance on the ALT test. All normals secure 100% score on the ALT, but not on the PAPI test. Results for deutan observers show that out of 77 subjects tested, only 18 pass the ALT (with a pass criterion of one or no errors). Fourteen of the 18 subjects that pass the ALT also pass the PAPI. Results for protans show that all 40 subjects tested failed the ALT test and that only one subject achieved a score higher than 80%, although just over 50% of protans passed the PAPI.

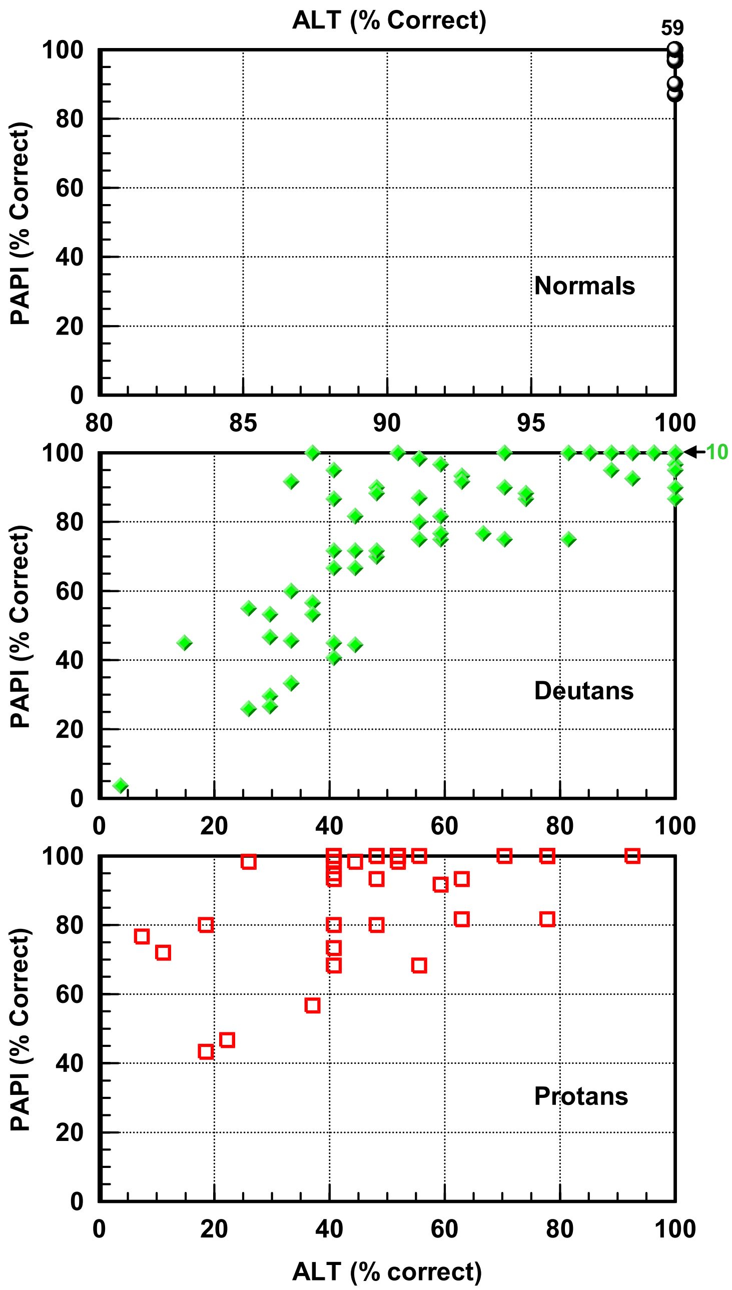

Figure 21 The number of presentations identified correctly on the Aviation Light Test (ALT) from a total of 27 presentations is compared to performance on the PAPI simulator test separately for normals, deutan and protan colour vision observers.

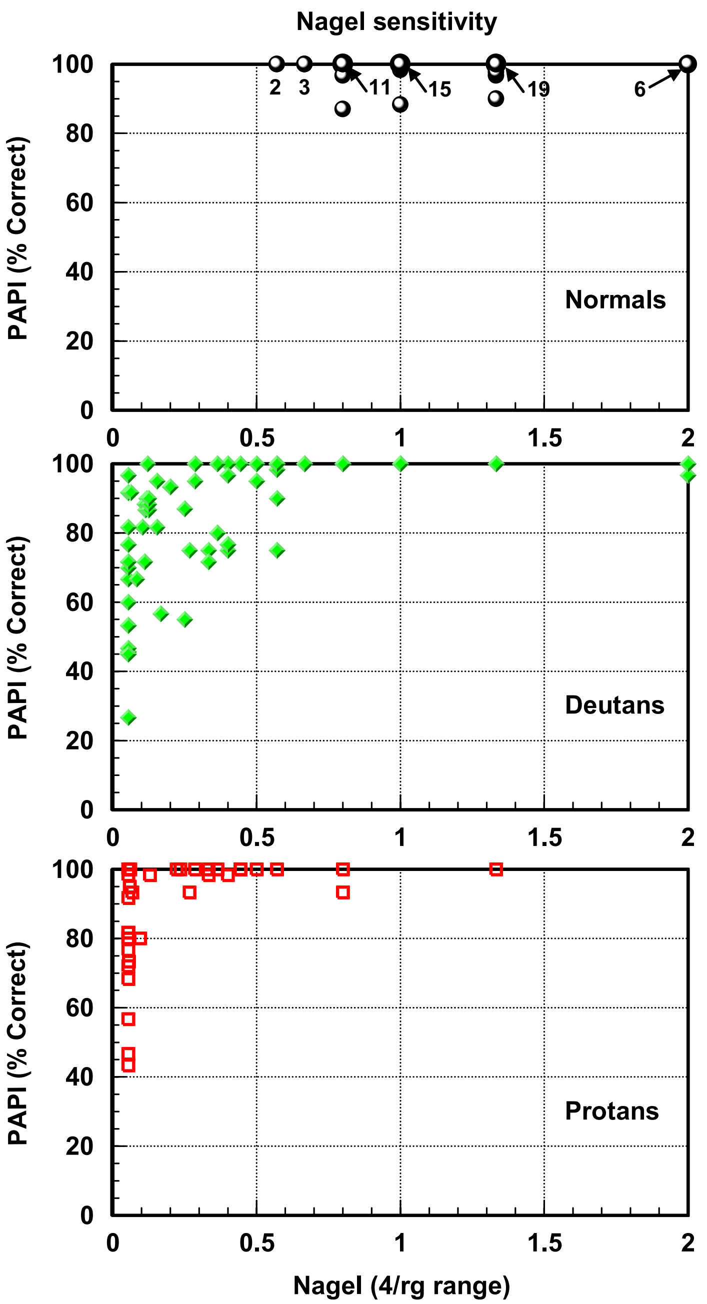

Figure 22 PAPI test scores plotted against an index of red-green chromatic sensitivity based on the Nagel anomaloscope range. Results are again shown separately for normals, deutan and protan observers. Numbers next to some symbols indicate number of subjects with overlapping data points.

3.6 Figure 22 compares PAPI scores with a measure of RG sensitivity based on the Nagel anomaloscope range. Only a few deutan and protan observers pass the PAPI with Nagel sensitivity > 0.6 (deutan) and > 0.4 (protan). The Nagel anomaloscope test is excellent at distinguishing between deutan and protan like deficiencies, but fails to quantify reliably the severity of colour vision loss and does not test for yellow/blue deficiency.

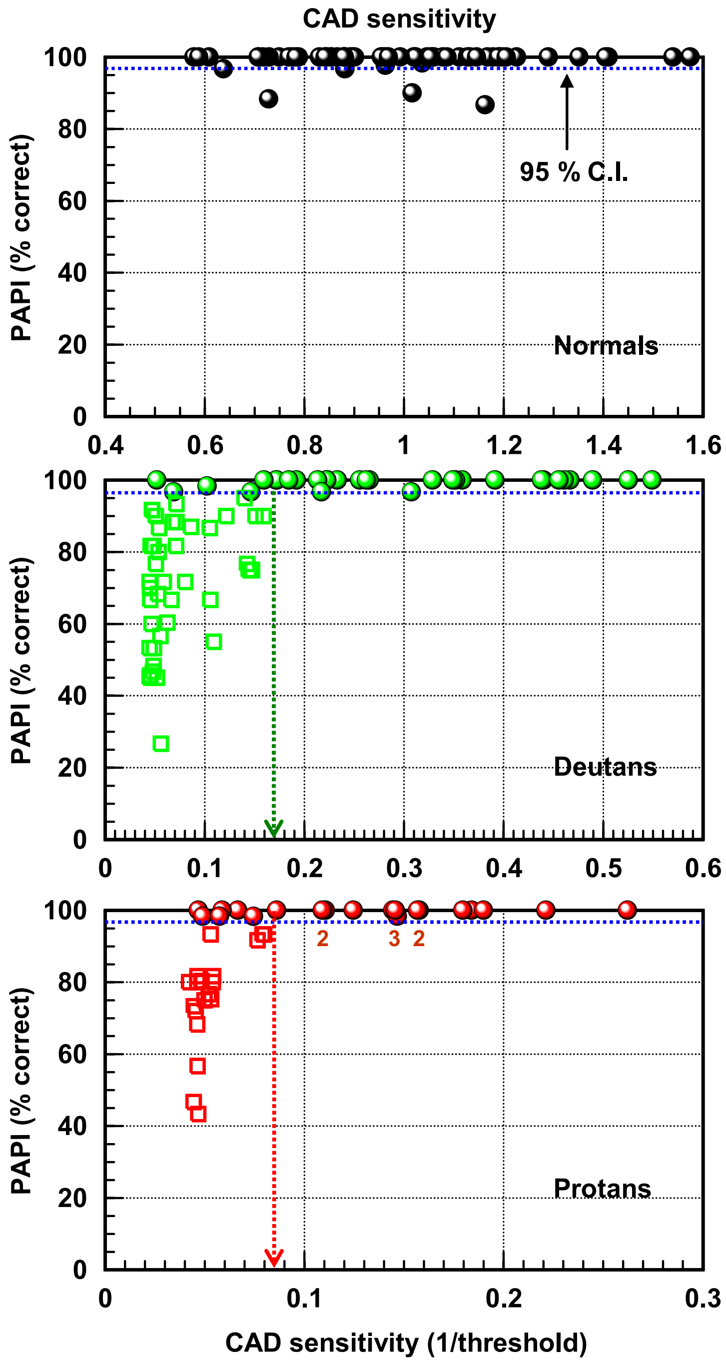

Figure 23 Graphs showing performance of normal, deutans and protan observers on the PAPI (standard white) versus CAD test sensitivity (1/threshold). Note the scale of the x-axis is different for the three graphs for clarity of presentation.

3.7 PAPI test scores are shown in Figure 23 plotted against the corresponding CAD based measure of RG sensitivity. The top section shows the performance in normal trichromats. Most normal trichromats perform 100% correct in the identification of the red and white lights. However, 7 out of the 65 normal subjects made some errors. This could be due to lack of attention and / or reduced visual acuity at low light levels caused by increased higher order aberrations when the pupil size is large. The errors were found to be distributed with equal probability amongst the five conditions. The blue dotted line in Figure 23 shows the 95% confidence interval. The lower sections compare the performance on the PAPI test with the corresponding CAD measure of RG sensitivity for subjects with deutan- and protan-like deficiencies. The sensitivity limits beyond which deutans and protans perform the PAPI test as well as normal trichromats are 0.17 (RG threshold ~ 6 SN units) and 0.085 (RG threshold ~ 12 SN units), respectively. These limits are indicated by dotted vertical lines in Figure 23.

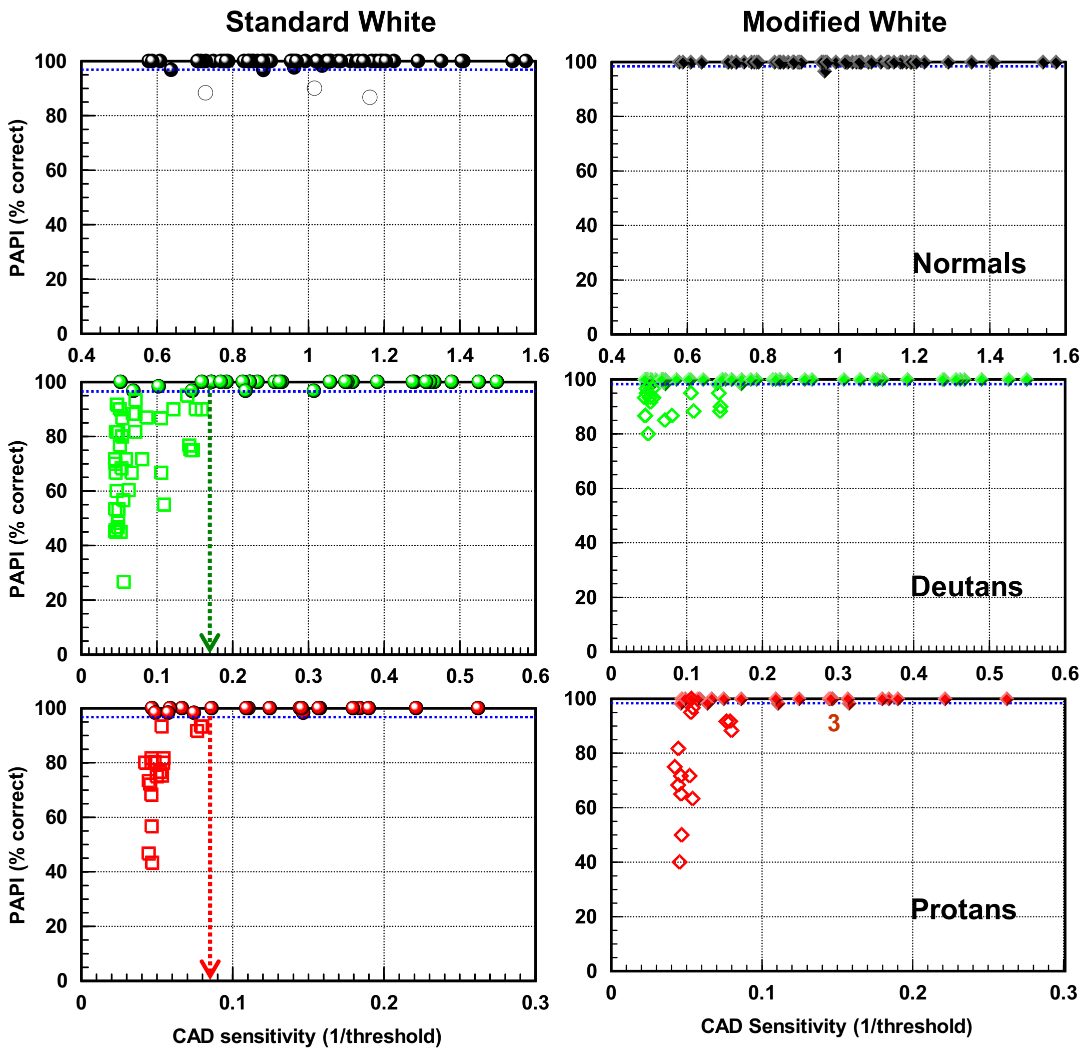

Figure 24 Graphs showing comparisons between standard and modified white (colour-corrected white) versus the CAD test sensitivity values.

3.8 Figure 24 shows the benefit of replacing the standard white light in the PAPI test with the colour-corrected (CC) white. Higher PAPI performance scores were obtained with the CC white in all subject groups. All, but one normal trichromat, scored 100% correct on the PAPI test when using the CC white. Figure 24 shows the overall improvement observed in the deutan group. All deutans obtain 80% correct or higher and many score 100% correct with the CC white. The improvement is, however, very small among protanomalous observers, particularly among subjects with severe deficiency (i.e. those with RG sensitivity less than 0.05 units). The improvements were statistically significant in normal trichromats (p=0.019) and deutans (p=0.000). Protans also showed slightly higher PAPI performance scores with the CC white, but the improvement failed to reach statistical significance (p=0.224).

3.9 The PSL test was introduced to examine the condition when all four PAPI lights have the same colour. In this condition the subjects can no longer make use of perceived differences between two adjacent colours presented simultaneously without being able to name the correct colour. The results in Figure 25 show that subjects do not often confuse reds with whites or whites with reds. Four protan subjects with severe loss of chromatic sensitivity (i.e. CAD RG sensitivity less than 0.05 units) make W=R and R=W errors and six deutan subjects with CAD RG sensitivity less than 0.15 units make errors on W=R.

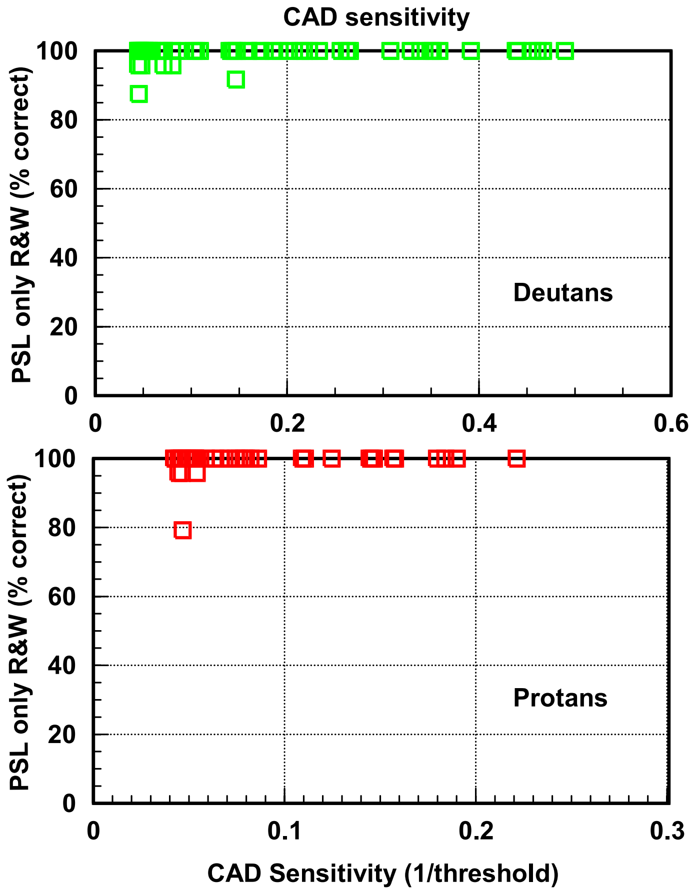

Figure 25 Graphs showing R=W and W=R errors only made on the PSL versus the RG CAD sensitivity.

3.10 Computing an index of overall chromatic sensitivity

3.10.1 The threshold signal needed to just see the coloured stimulus is expressed by direct comparison with the median threshold for normal trichromats. This approach has the advantage that a threshold <1 indicates colour discrimination better than the standard normal trichromat whereas values >1 indicate precisely the increase in threshold signal with respect to the normal observer. Sensitivity is usually defined as the reciprocal of the signal strength needed to just see the stimulus. The normalised CAD threshold falls within the range ~ 0.7 (i.e. better than normal sensitivity) to a maximum of 23.7 (a value limited by the phosphor limits of the display). It is therefore reasonable to use the reciprocal of the CAD threshold as a measure of chromatic sensitivity which ranges from just above 1, for subjects with better than normal sensitivity, to ~ 0.04 for subjects with very slight or absent chromatic sensitivity. In the case of the most common occupational colour vision tests, loss of chromatic sensitivity is more difficult to quantify because the tests do not measure the smallest colour signal strength needed to detect the stimulus. Instead, most occupational tests yield scores of correct responses that are indicative of the subject's overall chromatic sensitivity. In spite of these limitations, it is of great interest to derive an index of mean chromatic sensitivity based on the subject's performance in several colour vision tests. With this aim in mind, we used the parameters of each test to derive the best measure of average chromatic sensitivity which ranges from around 1, for normal trichromats, to close to zero, for subjects with very limited or complete absence of colour discrimination:

Ishihara: Fraction of plates named correctly

Dvorine: Fraction of plates named correctly

ALT: Fraction of stimulus pairs named correctly

Nagel: See definition of RGI (i.e. red-green discrimination index)

CAD: Reciprocal of threshold signal when measured in standard normal CAD units

3.10.2 Using this approach we were able to quantify the subject's average chromatic sensitivity as derived from the above tests which we take as the best available measure of the subject's overall ability to cope with a variety of colour vision tasks. This measure of average chromatic sensitivity has been used to further justify the selection of minimum colour vision requirements that can be classed as safe within the aviation environment and the exclusion of the very few subjects with poor overall RG chromatic sensitivity that pass the PAPI test.

3.10.3 Figure 26 shows that the very few subjects that pass the PAPI with CAD sensitivities less than 0.2 (deutan) and 0.1 (protan) have poor overall chromatic sensitivity. The results also show that the pass / fail limits proposed on the basis of the CAD test ensure that the colour deficient subjects that pass have an overall chromatic sensitivity greater than ~ 0.7 (deutans) and greater than ~ 0.5 (protans)

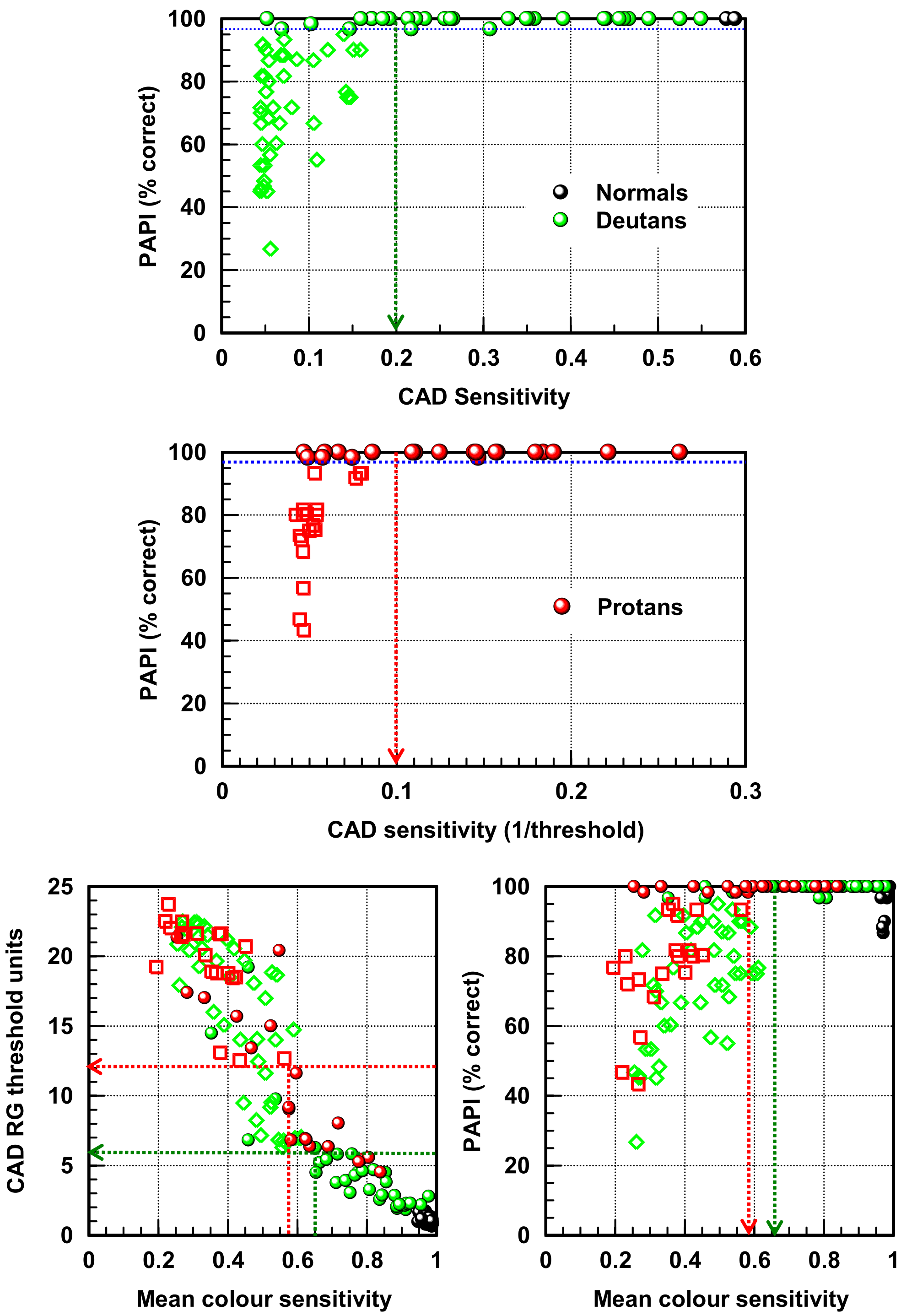

Figure 26 Justification for limits chosen. The top two diagrams compare PAPI (% correct) versus CAD test (sensitivity units=1/RG CAD threshold); colour deficient subjects to the right of the dotted line perform the PAPI test as well as normal trichromats do. CAD sensitivity of 0.2 and 0.1 corresponds to 6 and 12 CAD threshold units, respectively, for deutans and protans. Note the change of horizontal scale units for protan observers. The bottom two diagrams compare: left, CAD RG threshold units and right, PAPI performance, versus the "mean" or overall colour sensitivity as computed by averaging the subject's performance on the Ishihara, Dvorine, ALT and Nagel anomaloscope tests.

4 Discussion

4.1 Colour vision concerns in aviation

4.1.1 Colour enhances object conspicuity and can also be used to code information. In overcrowded displays or complex visual scenarios, colour allows segmentation and grouping operations which enhance and speed up the acquisition and processing of visual information (Firth, 2001). The primary signal colours in aviation are red, green and white with blue and yellow as supplementary colours (CAA, 2006b). ICAO requires member nations to maintain a colour standard to ensure pilots can recognise the colours of signal lights used in aviation (ICAO, 2006). Further, it acknowledges that the requirements are open to interpretation and at present there is no clearly defined line that specifies the class and severity of colour deficiency beyond which the applicant is no longer safe to fly (for a full review see CAA, 2006a). This is partly due to the varied task requirements and the technological advances in the use of colour in the aviation industry.

4.1.2 There are a number of currently approved JAA and FAA colour vision tests that applicants have to pass in order to be licensed to fly. In this investigation we assessed 182 subjects using several colour vision tests and the results reveal both inter-subject variability and poor consistency amongst the various tests. Comparison of the outcome from Ishihara and the Dvorine tests show that significant variability remains even when, at least in principle, the tests are very similar. These findings expose the facts that colour deficient subjects can produce very different scores on the two tests and that normal trichromats can make more errors on one test, but not on the other. Further, the pseudoisochromatic tests designed for screening are not suitable to either diagnose accurately the class of deficiency, or to quantify the severity of colour vision loss (Belcher et al, 1958; Birch, 1997).

4.1.3 The measures of chromatic discrimination on the CAD and Nagel anomaloscope reveal very poor correlation. Some colour deficient observers that require a lot of red or green in the match can only accept a narrow, red-green range that is a characteristic of normal red/green colour vision. Figure 22 confirms well-known observations (Wright, 1946) in that the measure of chromatic sensitivity based on the Nagel range overestimates the subject's ability to discriminate red-green colour differences under more natural conditions of illumination. Subjects with severe loss of chromatic sensitivity, as measured on the CAD test, can have RGI (Nagel) values that are similar to those measured in normal trichromats. The JAR pass criterion of 4 scale units (RGI=0.95) suggests that some normals are likely to fail, and more worryingly, that some severe colour deficient subjects are likely to pass.

4.1.4 Figure 21 shows comparisons between the ALT and the PAPI simulator tests. The results suggest that the ALT is a more challenging test, i.e. the average percent correct scores are lower on the ALT than on the PAPI test. However, normals were found to make no errors on the ALT. The fact that colour deficient subjects perform worse on the ALT than on the PAPI could be due to the increased number of colours presented on the ALT (three instead of two) and the very dark immediate surround in which the apertures of the lights presented are encased in the ALT.

4.1.5 These discrepancies among the various screening tests can be attributed partly to the differences in the methods of assessing colour vision. These include differences in stimulus configuration, background lighting conditions and also the different instructions given to subjects. The results from this study justify the recent concerns expressed by ICAO (1999) and CAA (2006a) in relation to some aspects of colour assessment in aviation. The results confirm earlier findings from a study that examined three lantern types accepted by the JAA and found that the same individual can pass some of the tests and fail others (Squire et al, 2005). The study also showed that some normal trichromats that fail the initial screening may also fail the secondary test and that the outcome of regulatory assessment depends on which secondary colour vision test is used, which varies between countries. The observed inconsistency in results between the currently approved colour vision tests is therefore unsatisfactory, both in terms of flight safety issues, as well as being potentially unfair to some pilot applicants.

4.2 Advances in assessment of colour vision

Red-green chromatic sensitivity varies from 'normal' performance to total 'colour-blindness', with an almost continuum of colour impairment between these two extremes. Amongst congenital colour deficient observers, the loss of RG colour sensitivity varies along a continuous scale (see Figure 12). This is the most common type of colour vision deficiency, affecting 8% of the male population (< 1% females) (see Table in Section 4.4). Yellow-blue deficiencies affecting the S-cone are very rare (1 in ~20000) and are most often related to acquired colour vision defects, as a result of eye disease, or as a side effect of toxicity or medication (see Section 1.11 in this report). Acquired deficiencies tend to be age-dependent and, when unnoticed, may compromise safety within certain occupations. Follow up colour vision tests are carried out for some revalidation/renewal examinations for Class 1 medical certification (JAR-FCL 3, 2006). Current civil aviation tests are not designed to detect or measure YB sensitivity so any anomalies due to YB loss or disease are likely to remain undetected. Yellow-blue discrimination has also become more important because of the extensive use of different colours in the modern aviation environment.

4.3 Safe colour vision limits in aviation

4.3.1 The PAPI system built for this investigation reproduces the red and white lights under conditions simulating the spectral composition, the angular subtense and the retinal illuminance of real PAPI lights viewed from 5.54km. Comparisons between the performance on the PAPI and CAD tests reveal the minimum level of chromatic discrimination below which subjects with red/green colour deficiency no longer perform the PAPI task with the same accuracy as normal trichromats. Figure 23 shows that deutans and protans with a RG threshold of less than 6 and 12 CAD units, respectively, perform the PAPI simulator test in a similar way to normal trichromats. The PSL test addresses the question as to whether subjects can also name correctly the colour of the PAPI lights when all lights are of the same colour, either red or white. Figure 25 shows how the ability to name correctly the white and red lights on the PSL test relates to the subject's RG discrimination sensitivity on the CAD test. Colour deficient subjects do not have difficulty with this condition and no subject with RG threshold units less than 6 and 12, for deutans and protans, respectively, confuse R=W or W=R when all four lights are the same colour. The PAPI and PSL tests also include a CC white to investigate whether the use of a more 'bluish' white can improved performance. The results show that this is indeed the case for both PAPI and PSL tests in all subject groups.

4.3.2 Using the proposed pass and fail limits of 6 and 12 RG CAD threshold units, for deutans and protans, respectively, 29 out of 77 deutans and 13 out of 40 protans would pass the PAPI simulator test using the standard white (Figure 27). However, 5 deutans and 7 protans (Figure 28) with RG thresholds larger than the proposed safe limits also pass the PAPI. An important question is whether these subjects are disadvantaged unfairly if the new pass / fail limits were to be adopted. There is little doubt that these subjects have severely reduced RG colour discrimination (as revealed in all the colour vision tests employed in this investigation). The overall loss of chromatic sensitivity becomes increasingly more severe as the subject's thresholds increase beyond the recommended limits. These subjects are therefore likely to be disadvantaged in other, less safety-critical, visual tasks that involve colour discrimination. By computing an average chromatic discrimination performance on a battery of colour vision tests we are able to examine whether these subjects have poor overall colour discrimination performance. Figure 26 shows that the very few subjects that pass the PAPI with CAD threshold limits greater than 6 (deutan) and 12 (protan) units have poor overall chromatic sensitivity. The results also show that the pass / fail limits proposed on the basis of the CAD test ensure that the colour deficient subjects that pass have an overall RG chromatic sensitivity greater than ~ 0.7 (deutans) and greater than ~ 0.5 (protans).

4.3.3 The use of the colour-corrected white condition increases quite significantly the number of subjects that pass the PAPI test. For deutans (Figure 27), with thresholds higher than 6 units, 28 subjects pass instead of only 5 with the standard white condition. Similarly, for protans (Figure 28), 10 pass in the modified condition, instead of 7 for the standard white condition. Overall, the CC white condition improves performance of the PAPI test for all subject groups. This improvement is, however, more significant for deutan than protan colour deficient observers.

4.3.4 The analysis shown graphically in Figures. 27 & 28 reveal that 37.6% of subjects with deutan-like deficiency and 32.5% of subjects with protan-like deficiency would be classified as safe to fly under the new research-based pass/fail limits. When using the current PAPI systems (i.e. PAPI with the standard white light), 44% of deutan subjects pass the PAPI test and according to the proposed pass/fail limit of 6 SN CAD units 85% of these subjects (i.e. the deutans that passed the PAPI) would be classified as safe to fly. Similarly, 50% of subjects with protan-like deficiency pass the PAPI test and according to the pass / fail limit of 12 SN CAD units 65% of these subjects would be classed as safe to fly.

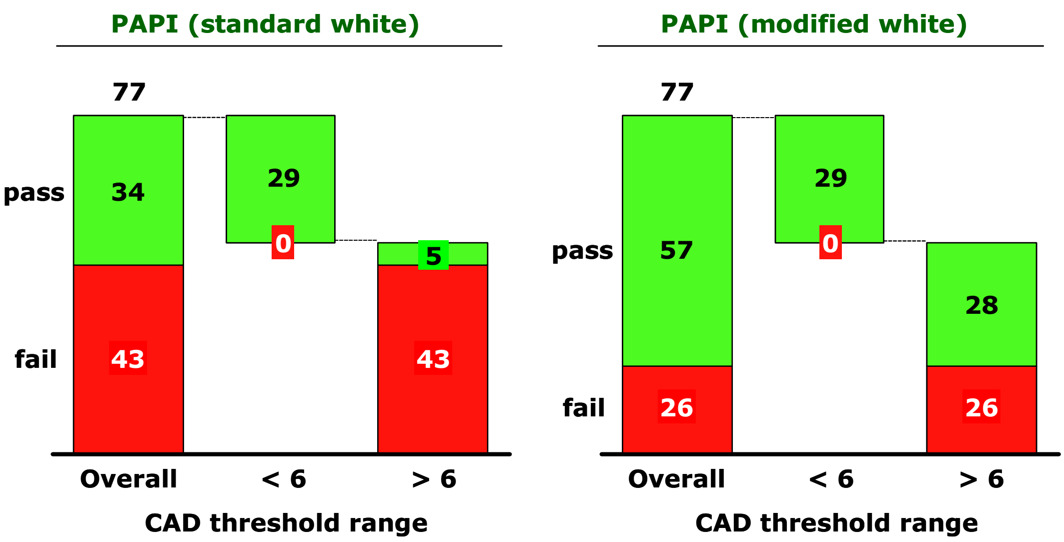

Figure 27 Summary of deutan subjects' results if the proposed pass/fail criterion of 6 RG CAD threshold units is accepted.

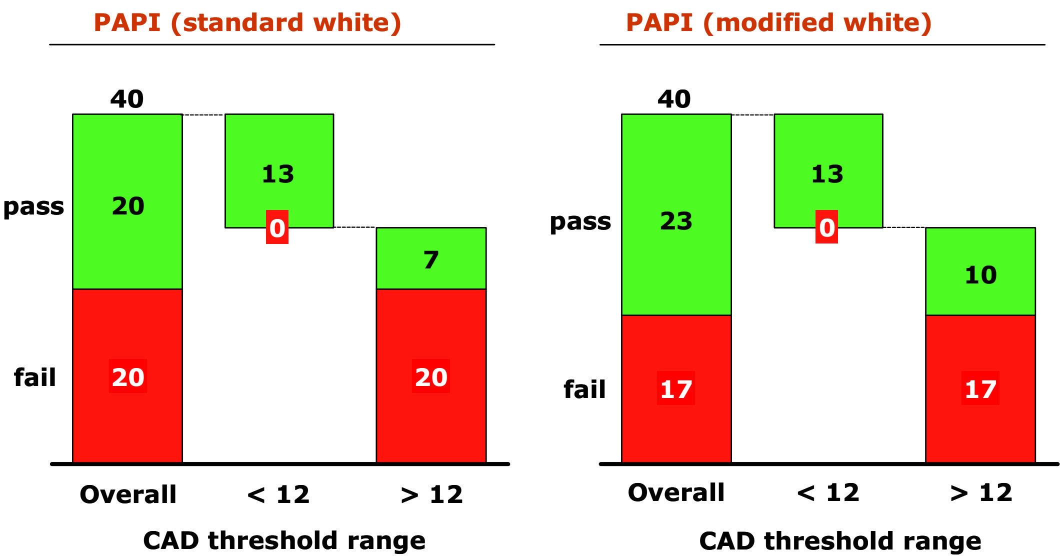

Figure 28 Summary of protan subjects' results if the proposed pass/fail criterion of 12 RG CAD threshold units is accepted.

4.3.5 So far 386 colour deficient observers have been examined on the CAD test as part of this as well as other ongoing studies. Two hundred and fifty-five (255) of these subjects had deutan and the remaining 131 had protan deficiencies. If the proposed limits of 6 and 12 SN CAD units for deutan and protan subjects, respectively, were applied to this larger group, **36.1**% of deutans and **29.8**% of protans would pass these limits. These findings suggest that 35% of the total number of colour deficient subjects investigated should be certified as safe to fly. The percentages shown above are very close to those estimated from the smaller number of colour deficient subjects (n = 117) that participated in the PAPI study.

4.3.6 The proposed pass / fail limits relate accurate measurements of chromatic sensitivity to the subjects' performance on the most critical colour vision task in aviation. The limits ensure that the subjects that pass can also perform the PAPI task with the same accuracy as normal trichromats. In addition, the proposed limits ensure that all subjects that fail according to these limits have poor, overall chromatic discrimination sensitivity.

4.4 Benefit analysis of using the new approach

4.4.1 Analysis based on CAA / JAA pass criteria and guidelines

The following table shows the different classes and relative distribution of colour deficient subjects that make up ~ 8% of the male population (Sharpe et al., 1999).

Accepted Prevalence of Colour Vision Deficiencies†						
Protanope	Deuteranope	Tritanope	P-nomalous	D-nomalous	T-nomalous	Total
1	1.1	0.002	1	4.9	0	8.002
†Gegenfurtener, K.R. & Sharpe, L.T. "Color Vision, from Genes to Perception" : Cambridge University Press.						

Other facts based on normal trichromats and colour deficient subjects studies at AVRC	
Percentage of normal trichromats that fail the Ishihara test*	15.8
Percentage of protan-like subjects that fail the Ishihara test	100
Percentage of deutan-like subjects that fail the Ishihara test	99
Percentage of normal trichromats that fail the Holmes-Wright lantern test	0
Percentage of protan-like subjects that fail the Holmes-Wright lantern test	100
Percentage of deutan-like subjects that fail the Holmes-Wright lantern test	90

*Results based on 202 normal trichromats when employing the strict CAA/JAA pass criteria (i.e., no errors, no misreadings in the first 15 plates of the 24-plate version).

Table 1 Percentage of colour deficient observers that fail Ishihara and HW tests.

4.4.1.1 The data in Table 2 are based on the strict CAA/JAA pass criteria for Ishihara test. A similar analysis using the FAA pass/fail criteria for Dvorine, Ishihara and ALT tests will be shown separately. Interestingly, only 7% of the colour deficients pass the Holmes-Wright (HW) lantern, and there is no clear evidence to suggest that all of these subjects are safe to fly.

4.4.1.2 One hundred and sixty-three (163) colour deficients (i.e. 110 deutan and 53 protan subjects) have been investigated using the HW lantern in all of our studies. All protans failed, but only 99 of 110 deutan subjects failed the HW lantern. These findings make it possible to predict the number of colour deficient subjects that are classified as safe to fly using current assessment procedures:

Predicted outcome per 1000 applicants using current assessment methods				
Applicants	***1000***	***No. that fail Ishihara***	***No. that fail HW***	***No. classed as safe to fly***
Normals	920	145	0	920
Deutans	60	59	53	6
Protans	20	20	20	0
Total	**1000**	**225**	**73**	**926**
Percentage of applicants that undergo secondary tests =				**22**
Percentage of deutan subjects that pass secondary tests =				**10**
Percentage of protan subjects that pass secondary tests =				**0**
Percentage of total colour deficient subjects that pass =				**7**

Table 2 Predicted outcome per thousand applicants using current CAA/JAR guidelines.

4.4.1.3 Table 3 shows the predicted outcome when the same 1000 applicants are examined on the CAD test and the pass / fail criteria employed are based on the findings from this study. The current procedures that employ a secondary test whenever the applicant fails the primary test results in 22% of the applicants having to take the secondary test. The new procedure based on the CAD pass / fail limits does not require any secondary test. The analysis in Table 3 shows that 36% of deutan and 30% of protan subjects meet the pass/fail criteria established experimentally and can therefore be classed as safe to fly. Given the higher prevalence of deutan subjects within the male population, these findings suggest that 35% of all colour deficient subjects pass the new guidelines and are therefore safe to fly.

4.4.1.4 If the HW secondary test is replaced by the Nagel anomaloscope test (using the current JAA pass/fail limits for midpoint and range), the percentage of colour deficient subjects that are classified as safe to fly decreases to less than 2%. If the HW lantern test is replaced with other, less demanding secondary tests, the percentage of colour deficient subjects that pass can increase to more than 10%. There is, however, no guarantee that the colour deficient subjects that pass these secondary tests can carry out the most safety-critical, colour-related tasks.

Predicted outcome per 1000 applicants using CAD pass / fail criteria**				
Applicants	***1000***	***No. that pass CAD as normals***	***No.that fail set CAD limits***	***No. classed as safe to fly***
Normals	920	920	0	920
Deutans	60	0	38	22
Protans	20	0	14	6
Total	**1000**	**920**	**52**	**948**
Percentage of applicants that undergo secondary tests =				**0**
Percentage of of deutan colour deficients that pass =				**36**
Percentage of protan colour deficients that pass =				**30**
Percentage of total colour deficient subjects that pass =				**35**

** % deutan subjects that pass CAD (pass < 6 SNU) = 36.1
** % protan subjects that pass CAD (pass < 12 SNU) = 29.8

Table 3 Predicted outcome per thousand applicants using the new, CAD based pass / fail limits.

4.4.2 Analysis based on FAA pass / fail criteria and guidelines

4.4.2.1 The FAA pass/fail criteria are more liberal and were selected deliberately to be fair to those colour deficient applicants that may well be able to carry out safety-critical, colour-related tasks with the same accuracy as normal trichromats. The criteria are not, however, based on the PAPI task and employ a large number of recommended tests that fail to correlate well when used to quantify the severity of colour vision loss. This means that some of the applicants fail some tests and pass others. In this investigation we have included two of FAA's most popular tests, the Ishihara and the Dvorine pseudoisochromatic plates. The ALT (i.e. a Farnsworth lantern (FALANT) with modified filters designed to produce lights with chromaticities specified for aviation signal lights (Milburn & Mertens, 2004)) was included in the study. Normal trichromats pass both the FALANT and the ALT lanterns, but no data are available to describe how the deutan and protan subjects examined in this study perform on the FALANT test. The following analysis is, however, of great interest since it provides a useful comparison of expected outcomes when FAA guidelines are followed.

4.4.2.2 Table 4 lists the percentage of normals, deutan and protan subjects that fail each of the three tests: Ishihara, Dvorine and ALT, according to the FAA criteria. The first observation of interest is that the Dvorine test passes the largest number of deutan and protan subjects. The Ishihara is more demanding for both deutan and protan subjects, and all protan subjects fail the ALT test. In the following sections we examine the correlation between the outcome of each of these tests and the corresponding PAPI pass / fail scores for the 182 subjects investigated.

Other percentages based on the FAA pass / fail guidelines*	
Percentage of normal trichromats that fail the Ishihara test	0
Percentage of protans that fail the Ishihara test	90
Percentage of deutans that fail the Ishihara test	81.8
Percentage of normal trichromats that fail the Dvorine plates	0
Percentage of protans that fail the Dvorine test	82.5
Percentage of deutans that fail the Dvorine test	75.3
Percentage of normal trichromats that fail the ALT	0
Percentage of protans that fail the ALT	100
Percentage of deutans that fail the ALT	77.9

*The results listed in the table are based on the FAA pass limits for Ishihara / Dvorine tests (fail equals 7 or more errors). Percentages based on 65 normal trichromats and 117 colour deficients (i.e., 77 deutan and 40 protan subjects). All protans failed the ALT test, but only 60 out of 77 deutans failed the same test (pass classification on the ALT requires no more than one error on 27 trials).

Table 4 Percentage of colour deficient observers that fail Ishihara, Dvorine and ALT tests (using FAA pass / fail criteria for the Dvorine and the 24-plate Ishihara test).

4.4.2.3 The contingency tables below (i.e. Table 5) show that only one deutan subject (i.e. less than 1%) passes the Ishihara according to the FAA criterion and fails the PAPI. Not unexpectedly, the same subject also passes the Dvorine test and fails the PAPI. Of equal interest is the observation that 31% of colour deficients (deutan and protan) fail the Ishihara, but pass the PAPI. The results also show that only 24% of the colour deficients that fail the Dvorine test pass the PAPI. It is also of interest to investigate the outcome if the ALT were used as a secondary test for those deutan and protan pilot applicants that fail either Ishihara or Dvorine tests using the FAA pass / fail criteria.

Number of subjects that pass/fail each test (i.e., a pass requires less than 7 errors on Ishihara; less than 7 errors on Dvorine; one or no errors on ALT)

Normals (65)		PAPI Pass	PAPI Fail	Protans (40)		PAPI P	PAPI F	Deutans (77)		PAPI P	PAPI F
Ishihara	Pass	62	3	Ishihara	P	4	0	Ishihara	P	13	1
	Fail	0	0		F	16	20		F	20	43

Normals (65)		PAPI P	PAPI F	Protans (40)		PAPI P	PAPI F	Deutans (77)		PAPI P	PAPI F
Dvorine	P	62	3	Dvorine	P	7	0	Dvorine	P	18	1
	F	0	0		F	13	20		F	15	43

Normals (65)		PAPI P	PAPI F	Protans (40)		PAPI P	PAPI F	Deutans (77)		PAPI P	PAPI F
ALT	P	62	3	ALT	P	0	0	ALT	P	17	0
	F	0	0		F	20	20		F	16	44

Table 5 Contingency tables showing results of Ishihara, Dvorine and ALT tests and the corresponding pass/fail PAPI scores.

4.4.2.4 This analysis should strictly be carried out using the applicant's performance data on the FALANT test, but in the absence of such data, the ALT test provides the nearest, useful substitute. Findings from a recent study (Cole and Maddocks, 2008) suggest that some subjects that pass the FALANT lantern test can confuse red and white signals and may not therefore perform the PAPI task as well as normal trichromats. Table 6 compares the subjects pass/fail results on Ishihara and Dvorine against the corresponding pass/fail results on the ALT. The results show that it is possible to pass Ishihara or Dvorine and then to fail the ALT. In the case of Dvorine, six deutan and seven protan subjects pass the test only to fail the ALT. Interestingly, the reverse to this also happens. Four deutans that fail the Dvorine pass the ALT and six deutans that fail the Ishihara also pass the ALT.

Number of subjects that pass/fail each test (i.e., a pass requires less than 7 errors on Ishihara; less than 7 errors on Dvorine; one or no errors on ALT)

Normals (65)		ALT		Protans (40)		ALT		Deutans (77)		ALT	
		Pass	Fail			P	F			P	F
Ishihara	Pass	65	0	Ishihara	P	0	4	Ishihara	P	11	3
	Fail	0	0		F	0	36		F	6	57

Normals (65)		ALT		Protans (40)		ALT		Deutans (77)		ALT	
		P	F			P	F			P	F
Dvorine	P	62	0	Dvorine	P	0	7	Dvorine	P	13	6
	F	0	0		F	0	33		F	4	54

Table 6 Pass/fail scores on Ishihara and Dvorine compared against the ALT.

4.4.2.5 These findings reveal clearly the lack of agreement that exists when using different occupational colour screening tests and the difficulties involved if one wished to use such data to predict performance in other tasks such as the PAPI.

Predicted outcome per 1000 applicants using the FAA criteria

Applicants	*1000*	*No. that fail Ishihara*	*No. that fail Dvorine*	*No. that fail ALT*	*Safe to fly Ishihara*	*Safe to fly Dvorine*	*Safe to fly ALT*
Normals	920	0	0	0	920	920	920
Deutans	60	49	45	47	11	15	13
Protans	20	18	17	20	2	3	0
Total	**1000**	**67**	**62**	**67**	**933**	**938**	**933**

Percentage of deutan subjects classed safe to fly according to each test	18.3	25.0	21.7
Percentage of protan subjects that are classed safe to fly	10.0	15.0	0.0
Percentage of all colour deficient subjects classed safe to fly	**16.3**	**22.5**	**16.3**

Table 7 Predicted outcome per thousand applicants when using Ishihara, Dvorine and ALT tests.

4.4.2.6 Table 7 shows the predicted outcome per thousand applicants when using Ishihara, Dvorine and ALT tests. Although the FALANT is an accepted FAA alternative test, the ALT test (used by FAA for assessing air traffic controllers) was employed in this study. The ALT fails all protan subjects and passes only 16% of deutan applicants. The results are of interest since they show clearly that an applicant is most likely to pass the Dvorine test, followed by ALT and Ishihara when only deutan subjects are considered. In the case of protan deficiency, an applicant is again most likely to pass the Dvorine followed by Ishihara, but all protans fail the ALT test.

5 Conclusions

5.1 The aim of this project was to develop new methods for accurate assessment of colour vision and to provide evidence-based guidelines for minimum colour vision requirements for flight crew. The current diversity in colour vision testing methods and standards demonstrates the need to adopt more objective assessment techniques internationally and to set minimum colour vision requirements that are both safe and fair to the applicants.

5.2 The CAA/JAA[3] guidelines are strict and consequently only 10% of deutan applicants are classified as safe to fly (see Table 2). The applicants that pass are likely to perform the PAPI task as well as normal trichromats. The current CAA / JAA procedures have some disadvantages. A large percentage of applicants fail the primary tests and have to take lengthy secondary tests that vary in various member states. This introduces some variability in that the same subjects can pass some secondary tests and fail others. Some of these subjects may not necessarily be able to carry out the PAPI tasks as normal trichromats. Equally important, a large percentage of colour deficients that can carry out the safety-critical, colour-related tasks fail the tests and are therefore unfairly disadvantaged.

5.3 The FAA guidelines are more liberal and, as a result, more colour deficient applicants pass. In the case of Dvorine and Ishihara tests, less than 1% of the applicants that pass these tests fail the PAPI. All colour deficient applicants that pass the ALT test also pass the PAPI (see Table 5). The current FAA guidelines also have some disadvantages. The colour vision tests employed provide only an approximate measure of the severity of colour vision loss and the pass / fail limits have not been validated against the PAPI. The FAA accepts 14 different tests (FAA guide for Aviation Medical Examiners, 2008). The use of so many tests that may not correlate well with each other (when used to assess the severity of colour vision loss) increases variability and gives rise to odd outcomes when an applicant passes one test and fails another. Although the number of colour deficient applicants that pass can increase significantly, this increase is test specific and often dependent on the use of the Signal Light Gun test that has not been validated against the PAPI task.

5.4 The results also show that one cannot treat as equivalent subjects with deutan- and protan-like deficiencies. Therefore, minimum colour vision requirements must be set separately for each class of deficiency.

5.5 The principal findings of this study can be summarised as follows:

- Subjects with red/green congenital colour deficiency can exhibit an almost continuous loss of chromatic sensitivity
- The loss of red/green chromatic sensitivity is greater in subjects with protan congenital colour deficiency when compared to the deutan class. Unlike many conventional colour vision tests, the CAD test cannot be learned and hence the outcome depends entirely on the subject’s chromatic sensitivity. The test provides the means to classify protan and deutan subjects and also quantifies the severity of colour vision loss.
- 94% of all applicants are likely to complete the CAD test in less than 20 seconds (using the fast-CAD option) which is based on screening for minimum colour sensitivity in the deutan category. The remaining applicants are expected to fail fast-CAD. The definitive-CAD test takes 12 to 15 minutes to complete and provides

3. JAR requirements on this subject are still applicable under EASA, transition of the relevant text to an EASA document is anticipated by 2012.

the information needed to establish whether the subjects that fail (i.e. ~ 4% of all applicants) have protan colour deficiency and have residual chromatic sensitivity within the established pass limit for protan subjects.

- Below 60 years of age, normal ageing does not affect significantly either RG or YB thresholds, provided adequate levels of ambient illumination are employed.
- Use of a modified "white" light results in significant, overall improvements in PAPI performance, particularly within normal trichromats and deuteranomalous observers.
- A comparison between the PAPI and CAD tests shows that deutan subjects with CAD thresholds < 6 SN units and protan subjects with CAD thresholds < 12 SN units can perform the PAPI test as well as normal trichromats.
- A small number of deutan and protan observers with thresholds higher than 6 and 12 SN units, respectively, passed the PAPI test, but these subjects exhibit poor overall chromatic sensitivity and are therefore likely to be affected unfavourably in other visual performance tasks that involve colour discrimination.
- If these findings were adopted as pass / fail limits for pilots ~ 35% of colour deficient applicants would be certified as safe to fly.

6 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 organization 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 organization, 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.

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:

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.

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, $V(\lambda)$, $V'(\lambda)$: Weighting functions used to derive photometric measures from radiometric measures in photometry. Normally the $V(\lambda)$ function is used, but, if the conditions are such that the vision is scotopic, the $V'(\lambda)$ 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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