Minimum colour vision requirements for London Underground train operators

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Executive summary

Minimum colour vision requirements for train operators have been produced by assessing the level of colour vision loss beyond which subjects with colour deficiency no longer perform the most safety-critical, colour-related tasks within the London Underground (LU) environment with the same accuracy as normal trichromats. The tasks involve the correct naming of red, green and yellow / green signal lights within the tunnel. Other colour-related tasks are less demanding and also less safety-critical. The driver of the train has to recognise the correct colour of the lights from the minimum breaking distance needed to stop the train safely. This distance depends on the speed of the train and in some locations on the geometry of the tunnel. For completion, both 110m and 220m have been investigated in this study and minimum colour vision requirements produced for each distance.

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 sensitivity falls within the normal range and the severity and class of colour vision loss in subjects with colour deficiency. The results of the CAD test also indicate whether the applicant has sufficient chromatic sensitivity to carry out the colour-related, safety-critical tasks with the same accuracy as normal trichromats. If the new, experiment-based, pass / fail colour limits were adopted as minimum requirements for the LU tube network and an approach distance of 110m was considered appropriate, 46% of deutan subjects and 22% of protan subjects would be classed as safe to operate trains. Given the higher prevalence of deutan deficiencies, these findings suggest that 40% of colour deficient applicants would be classed as safe to work as underground train drivers. For the larger approach distance of 220m, only 11% of colour deficient applicants pass. This estimate is based on 9% deutan and 18% protan subjects who perform the critical tasks with the same accuracy as normal trichromats.

Background

The use of colour in the railway industry for coding of signals and information is important, hence the need to set adequate colour vision requirements to ensure that railway personnel are able to discriminate and recognise different colours, both in the cabin and externally. Concern has, however, been expressed during the past few years that the current colour vision standards are not appropriate since most tests and pass limits only screen for normal trichromacy. Subjects with minimal colour deficiencies often fail normal trichromacy tests and the great majority are therefore stopped from joining the railway as, for example, train operators, although many of these subjects may well be able to perform colour-related, safety-critical tasks, as well as normal trichromats, when presented with the same, suprathreshold colour signals. In principle, these subjects should be allowed to work as train drivers. 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 ever pass the Ishihara colour screening test 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, 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 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 Railway Group Standards (RGS) employ the Ishihara screening test to identify applicants with red/green deficiency; '*colour vision shall be normal, as assessed by the Ishihara Plates Test*' (see Appendix A; RGS, 2002). The number of errors allowed is not specified. Most colour deficient observers (both deutan and protan) fail the Ishihara test except for a very small number of minimum deuteranomalous that pass. In addition, ~15% of normal trichromats (an estimate based on 205 normal trichromats examined at AVRC) also fail the Ishihara, when one employs the strict pass / fail criteria of allowing for no errors. Further colour vision tests such as the Farnsworth D15 or the City University tests pass many colour deficient subjects; ~48% (115 out of 239 subjects) and ~38% (87 out of 227 subjects) pass the D15 and the City University tests, respectively. Although many colour deficient observers (and in particular deuteranomalous subjects) pass these tests, the severity of their colour vision loss remains unknown. The current occupational colour vision standards are not therefore satisfactory for at least two reasons. First, there is no guarantee that the deutan subjects that pass these 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 fail the standard colour vision tests and will not therefore be allowed to work in the LU transport environment. There are also other problems. The variability of conventional, primary 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 LU environment. Another important, practical aspect of regulatory testing of colour vision is that aspiring applicants 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 has been reported that, in order to pass the Ishihara test, or similar pseudoisochromatic tests, colour deficient applicants have been known to have learnt the correct responses, so as to maximize their chances of passing the test. When used in a recommended clinical setting, the most 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 place to place, even when the same tests are employed.

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 Transport for London (TfL) to sponsor a study to establish minimum colour vision requirements for LU train operators. As a result of the progress made at the Applied Vision Research Centre (AVRC) 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 at the AVRC 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 Fig. 12).

- A study that compared results from the most common, occupational colour vision tests, in both normal trichromats and in a large number of colour deficient observers, provided useful information that helps us understand the limitations of current tests. 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.
- 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 Fig. 12). In addition, similar measurements in over 300 colour deficient observers that participated in a number of projects related to colour vision provide the data needed to describe the differences in the severity of colour vision loss within deuteranomalous and protanomalous observers (see Fig. 15).
- Identification of the most important, safety-critical, colour-related tasks for train drivers and faithful reproduction of such tasks in the laboratory made it possible to establish experimentally limits of colour vision loss that can be classed as safe. The visual task analysis carried out as part of this study identified the coloured signal lights within the tunnel as the most important, safety-critical task that relies largely on colour vision. Also within the LU environment, colour signals are used from the control tower to signal to train drivers in poor visibility. 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 and more favourable conditions of light adaptation and other cues make the colour coding less critical. In the case of the signal lights, it is essential that the train operator names correctly the colour of each light. The signal 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 Fig. 20) when colour discrimination sensitivity is known to be poor.
- Colour discrimination limits (based on the CAD test) that can be classed as safe for train operators in the LU environment have been established. This was achieved by measuring and relating performance in the task of identifying the colours used within the tunnel and the subject's colour discrimination sensitivity,

as assessed on CAD and a number of other colour vision tests (see description below). This investigation was carried out in 28 protanomalous, 38 deuteranomalous and 40 normal trichromats. There are other visual tasks that can be classed as important and colour-related, 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 Bardic lamp and the coloured flags) or, in some cases, the tasks benefit from the use of colour signals as redundant information (such as the lights within the cabin). The tasks that involve these additional lights have not been simulated in the laboratory, but as discussed in the main report, these tasks 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 TL test scores and CAD sensitivity thresholds are shown in Fig. 27-30 for 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 (Fig. 15).
- 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 Fig. 16).
- Analysis of the results from the TL test using an approach distance of 110m shows that the deuteranomalous subjects investigated in this study with thresholds < 7 SN CAD units and the protanomalous subjects with thresholds < 10 SN units perform the TL test as well as normal trichromats.
- 18 out of the 38 deuteranomalous subjects failed the TL test. 16 out of the remaining 20 subjects that passed the TL test had CAD thresholds < 7 SN units.
- 18 out of the 28 protanomalous subjects failed the TL test. 7 out of the remaining 10 subjects that passed the TL test had CAD thresholds < 10 SN units.
- A small number of deuteranomalous (4) and protanomalous (3) observers with thresholds higher than 7 and 10 SN units, respectively, passed the TL test. All these subjects do, however, exhibit poor overall, RG chromatic sensitivity (as assessed by combining results from all other colour tests employed in the study) and are therefore likely to be disadvantaged in other visual performance tasks that involve colour discrimination.

- The results suggest that subjects with minimum colour deficiency that do not exceed 7 SN units for deuteranomalous observers and 10 SN units for protanomalous observers perform the TL test as well as normal trichromats. If these findings were adopted as pass / fail limits for pilots ~40% of colour deficient applicants would be classed as safe to operate trains. If the larger approach distance is accepted as appropriate, only 11% of colour deficient applicants can be classified as safe. The current practice for colour vision assessment is based on the Railway Group Standards (RGS) and employs the Ishihara screening test to identify applicants with red/green deficiency. The number of errors allowed is not specified. Since a large percentage of normal trichromats (~15%) can make at least one or two errors on the Ishihara test, in practice the pass / fail limit must allow for three or less errors to ensure that normal trichromats pass this test. Analysis of data obtained from several studies at AVRC show that 21 out of 282 deutans and 3 out of 156 protan subjects pass the Ishihara test with three or less errors. If we account for the larger number of deutan subjects within the population (see Table 2), these findings show that 6.1% of colour deficient applicants may pass current requirements (practice) and are therefore classed as "normal trichromats". The actual percentage of deutan subjects that pass depends on the number of errors allowed, but three errors or less ensures that all normal trichromats pass the Ishihara test. The new pass / fail limits proposed in this report would therefore increase significantly the number of colour deficient applicants that pass and at the same time would also ensure that those that pass are able to carry out the signal lights discrimination task required within the tunnel with the same accuracy as normal trichromats.
- The administration of the CAD test eliminates the need to use any other test. 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 7 SN limit established for deutan subjects. Deutans represent ~ 6% of colour deficients and 46% of deutan subjects pass the recommended CAD limit (see Table 3). This means that ~ 95% of all applicants will pass the fast-CAD screening test and be classed as safe to work as train operators. This process is very efficient since the fast-CAD test is simple to carry out and takes less than 40 seconds to complete. The definitive test (which takes between 6 and 9 minutes) 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 subject can also be examined to establish whether the YB chromatic discrimination sensitivity falls within the normal range (~ 40 secs) and / or to assess accurately the loss of YB chromatic sensitivity by comparison with the standard normal observer (~ 6 to 9 mins). Confirmation of normal YB chromatic sensitivity may be important and relevant to railway safety in the future given the increased use of colour in the railway environment. Findings from other ongoing studies so far suggest that loss of YB chromatic sensitivity is also indicative of early stage systemic or ocular diseases such as glaucoma, diabetes and age-related macular degeneration and that the loss of chromatic sensitivity precedes any structural changes that can be detected in fundus imaging.

Contents

List of Figures & Tables

Abbreviations

RG	Red-Green
YB	Yellow-Blue
BS	British Standard
CS	Chromatic Sensitivity
AVRC	Applied Vision Research Centre (City University)
CAD	Colour Assessment and Diagnosis test
CIE	Commission Internationale de l'Eclairage
LC	Luminance Contrast
L-cones	Long-wavelength sensitive cones
LU	London Underground
M-cones	Medium-wavelength sensitive cones
RGS	Railway Group Standards
RSSB	Railways Safety and Standards Board
S-cones	Short-wavelength sensitive cones
SI	Système International d'Unités (International System of Units)
SN	Standard Normal
SPAD	Signal Passed at Danger
TfL	Transport for London
TLT	Train Lights Test
UK	United Kingdom

Nomenclature

°	degrees
cd m^{-2}	candelas per square metre
λ	wavelength (lambda), nm
λ_{max}	maximum (peak) wavelength of $V(\lambda)$
%	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)
nm	nanometres (1 nm=10^{-9} of a metre)
s	second (time)
μ	micro=x10^{-6}
$V(\lambda)$	Standard photopic luminous efficiency (for high ambient illumination) (CIE, 1924)
$V'(\lambda)$	Standard scotopic luminous efficiency (when very low light levels are involved) (CIE, 1951)

Minimum colour vision requirements for LU Train Operators

1. Introduction

The need for colour vision standards in the railway transport industry was first recognised as early as 1855. These standards reflected both the needs and the methods available for colour vision assessment at the time. Concern has been expressed by TfL during the last few years that the current colour vision standards are often too stringent and also variable and do not relate directly to the tasks train operators encounter in today's LU environment. Fitness standards for many groups within the railway such as train drivers, conductors, signallers, track workers and other groups require normal colour vision as determined by the Ishihara pseudoisochromatic plates. When an alternative colour assessment is needed other 'validated equivalent' tests such as the City University Test (2nd Edition) may be employed (RSSB, 2007). An examination of current standards and techniques employed to assess colour vision requirements suggests the need to develop a suitable common method of testing that provides an accurate measure of colour vision loss. The subject's chromatic sensitivity assessed in this way should then be related directly to the subject's ability to carry out the most safety-critical, colour-related tasks within the specific railway environment.

1.1.1. The use of colour in the railway environment

The use of colour in the railway 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 1 in section 4.4).

Railway accidents have high social and economic costs, especially if the accident involves a busy line. Rigorous safety standards have been established over decades to decrease the probability of accidents. An important strategy in achieving high levels of safety is to build redundancy in equipment and the interpretation of signals and other information by train drivers and other personnel. Colour is used extensively to code information in the railway environment and train operators 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 (Favre, 1873; Nettleship, 1913). There is also some evidence to suggest that the likelihood of accidents is increased in colour deficient subjects (Vingrys & Cole, 1986). Other studies have shown that subjects with colour vision deficiencies make more errors and are slower in recognising light signals and colour coded instrument displays (Vingrys & Cole, 1986; Cole & Maddocks, 1995; Squire et al., 2005). There are also a small number of tasks when there is no redundancy and the correct interpretation of colour signals therefore becomes very important.

1.1.2. Current colour vision requirements and assessment methods in the railway

The Rail Safety and Standards Board (RSSB) provides guidance on colour vision requirements for rail workers to ensure the correct recognition of the colours of signal lights used in the railway. Medical fitness requirements in relation to colour vision state that *'train driving is not permitted by persons who have defective colour vision'* and *'colour vision shall be normal, as assessed by the Ishihara Plates Test.'* (Appendix A; RGS, 2002).

The Ishihara test (section 1.3.1 of this report) is easy and relatively quick to administer. Clinical trials suggest that this test is the most efficient pseudoisochromatic screening method for red-green colour vision deficiency (Birch, 2001). Some debate remains as to the number of errors that should be allowed on the Ishihara test to ensure appropriate separation between normal and colour defective vision (see section 4.4). Further, the results have been shown to lack reproducibility and as a result applicants may pass the Ishihara test on one occasion and fail at a later date when re-certified for medical fitness. Another problem with the

Ishihara test and also other tests that employ a relatively small number of plates is the possibility of learning the correct responses.

Re-certification of medical fitness is carried out every five years below the age of 56, every two years between the age of 56 and 62 and every year above 62 years (Appendix A; RGS, 2002). 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 1.6 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.

1.1.3. 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 LU (TfL) to sponsor a project to establish minimum colour vision requirements for LU train operators. As part of the TfL funded study, the current accepted colour vision requirements for train drivers 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 operationally "safe" within the LU environment. Additionally the study also involved a visual task analysis identifying the use of colour in the LU rail network.

1.1.4. 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 "*normal*" 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 1.4 of this report).

1.2. Identification of the most safety-critical and demanding colour vision tasks

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 LU rail transport environment.

Figure 1: (a) Open air track-red signal light. The red signal lights are always positioned on the bottom of the two aspect signal house to correspond to the driver's line of sight. (b) St. John Wood station: Co-acting signal, i.e. a signal on both sides of the tunnel. It has been reported that the installation of the co-acting signal has reduced the number of SPADs at this station.

The approach adopted in this investigation was to relate the accurate assessment of colour vision loss to the subject's ability to carry out 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 to identify and characterise the most important safety-critical, colour-related tasks for LU personnel, in particular train operators. This investigation identified the signal lights to be the most safety-critical, colour related task when no redundant information is available to carry out the task. The signal lights (similar to traffic lights) provide the train operator with critical information about the status of the section of the track ahead. Different colours mean different things and can be used in combination to increase the amount of information that can be indicated:

- Green: Proceed at line speed. Expect to find next signal green or yellow
- Yellow: Prepare for next signal to be at red
- Red: Stop
- White is used occasionally, mainly as a router which provides information about which route / track the train is heading (Fig. 2). Also can mean proceed whilst the section ahead to the next signal is clear (Victoria and Central line)

The number of aspects a signal can have varies in the UK railways. When the signal is a four-aspect signal (used mainly for higher speed trains) the lights occupy a certain position in the semaphore, arranged from top to bottom: yellow, green, yellow, red. When mounted on the ground (see Fig. 1a), the order is reversed so that the red is nearest the driver's normal line of sight. However, not all railway lines use full four-aspect signalling. Some use a three or two aspect variant. The three-aspect version uses three colour lights, omitting the top yellow light, to give a red, yellow and green aspect choice. The two-aspect version has only the red and green aspects, with repeaters or distant signals (that can show only green or yellow) used to give advance warning of a red (Fig. 2).

Signal engineers calculate the size of the sections or blocks of the track and hence the spacing between the signals, which depends on:

- Line speed (the maximum speed the train is allowed to travel)
- Gradient (to compensate for the assistance or otherwise afforded to deceleration)
- Braking characteristics of the train(s) that travel on that line
- Sighting (the ability of the driver to see the signal)
- Reaction time (of the driver)

The track at either end of the block is electrically insulated, and within the block a small electrical current passes through the track. When a train passes and enters a block, the metal wheels and axle of the train short-circuit the current, which causes a relay associated with the track circuit to itself become de-energized. When the relay is de-energized, the signal which the train has just passed automatically turns from green (or yellow) to red, the signal behind that one automatically turns yellow, and the signals behind that one can show green. If any train is following behind, the yellow signal will warn it to slow down in order to stop at the next signal. If, however, the train in front has passed into the next block, the following train will come across another yellow signal. If the train in front is travelling faster than the following train and clears two blocks, the following train will come across a green signal.

The track is comprised of three sections; within tunnel (see Fig. 1b), sub-surface track and open air track (see Fig. 1a) and the signal lights for each section have different physical properties due to the different viewing conditions. Most of LU employs a two aspect signal approach, i.e. two lamps are housed together and vertically separated (see Fig. 2). The signal boxes span over 50 years and hence the properties will to a certain extent vary. We have taken measurements of the photometric and radiometric characteristics of each individual lamp in the signal school at Stratford.

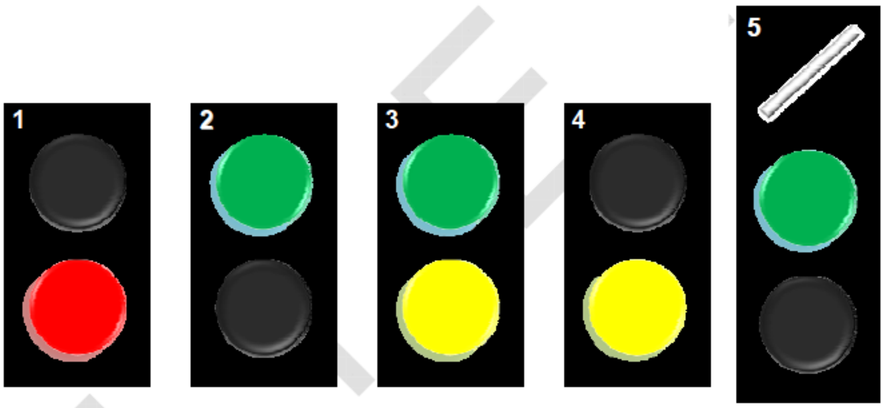


Figure 2: Sketch of the various colour combinations used on the London Underground. (1) Red = stop; (2) Green = safe to go at recommended speed; (3) Green and Yellow = proceed with caution as next signal is Red; (4) Yellow = repeater signal, slow down as next signal is Red; (5) Signal found at a tunnel junction with White route indicator.

The within tunnel lamps are short distance viewing lamps and comprise of two 100V 6W tungsten filament lamps, one placed behind each other. The signal lights are viewed against a dark background (within the tunnel) and the lenses are single stepped coloured glass and are ~9cm wide. Sub-surface signals are similar to within tunnel aspects but are single twin 100V 33W tungsten filament lamps and are approximately 15cm in diameter. A higher luminance is required so that the signals are still visible against a brighter background. Open-air track signals are known as long range signals and are viewed under high ambient light levels. The lamp comprises of a small 12V 35W tungsten filament lamp which has a complex lens arrangement to provide a more collimated beam. To facilitate close viewing, a deflector is also inserted in the lens. The lenses are larger; approximately 20cm in diameter and the interspacing of adjacent lamps is larger due to increased speed.

The viewing distance of the signals in the three different track sections also varies. The normal viewing distance for within tunnel aspects is dependent on the curvature of the tunnels. A slight curvature results in the practical visibility being reduced to less than 250m and with many sharp curves visibility can be down to less than 100m. The normal viewing distance for sub-surface signal is similar to within tunnel signals and critical viewing distances can be also less then 100m for the same reasons. The normal viewing distance for open air track aspects are longer at around 400m (up to 850m on long stretches of track) due to the greater speeds achieved compared to within tunnels, with many signals requiring repeating signals. The corresponding visual angle can be computed for the different signals, resulting in angles varying from ~2.6 to 1.53 minutes of arc. The most critical viewing angle corresponds to within tunnel signals and the least critical to sub-surface signals.

The comparison between the three signal types reveals that the within tunnel signals represent the most unfavourably viewing conditions. Within tunnel signals have the smallest, most critical viewing angle and are viewed against a dark background, when the ambient lighting level in tube tunnels is almost negligible under normal conditions. Sub-surface signals have a higher luminance due to the numerous long bridges with periods of sunlight increasing the overall background luminance. Thus, within tunnel signal lights were deemed to be the most colour-critical, visually unfavourable viewing condition that a train operator is likely to encounter. The laboratory simulation and all analysis of the results were done for the within tunnel condition.

1.2.1 Other uses of signal lights within London Underground environment

There are many other colour signals that are used in the LU transport environment to enhance conspicuity, code information and group objects of interest together. These situations are, however, 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, symbols or audible signals). The signal lights, on the other hand, offer no redundancy – there is no other unique cue in addition to colour discrimination to help the train operator recognise the red, green and yellow signal lights reliably.

a. Bardic Lamp

The Bardic lamp is a hand held light source, equipped with a rotating filter wheel which changes the emitting light colour from white, to red, green or yellow. It is used mainly by the control tower personnel to signal to train drivers in poor visibility conditions and at night.

b. Flags

The coloured flags are either green or red and approximately 70 by 50cm. The coloured flags are used to signal to train drivers in bright, favourable viewing conditions. However, both the Bardic lamp and flags are only utilised when there is a signal or communication failure which is a rare occurrence.

Figure 3: Photographs of the Bardic lamp (left) and the coloured flags (right) taken on a visit to Upminster Depot.

Both the Bardic lamp and the coloured flags represent a colour-related, safety-critical task simply because no other redundant cues are available. However, in the case of the Bardic lamp, the lights are bright, the colour difference between the lights is large and the lights subtend a large visual angle at the eye. The flags are also much larger and are viewed under higher ambient illumination. Consequently, these colour discrimination tasks are less demanding and it is therefore expected that observers with minimum colour vision deficiency that pass the signal lights test will be able to carry out these tasks with the same accuracy as normal trichromats. Neither the Bardic lamp nor the coloured flags were investigated in this study.

c. Cabin lights

The lighting found in the cabin of LU trains provides the driver with information about the status of the train, i.e. whether doors are open or closed, whether an alarm has been set off by a passenger, speed of the train, information display, tripcock test, audio on or off, and others. These lights have redundant cues to signal the particular piece of information. The lights signal information by being either off or on, and have a written text over or below the light and a specific geometry (being located in a specific location). These lights provide essential information but are less critical to safety because they have built in redundancy in addition to the colour information. Therefore they are less demanding than the signal lights. In addition these lights are viewed at a very close distance, thus the discrimination of colour differences is less demanding.

Figure 4: Examples of the use of key visual tasks that involve colour within the cabin. Information to the train driver is provided by means of displays and other controls that differ in size, shape, position, colour and luminance. Intermittent lights and audible signals are also used.

It has therefore been assumed that if the applicants can discriminate the red, green and yellow signal lights from the distance within the tunnel, they should also be able to discriminate with no difficulty the lights in the train cabin which subtend a much larger visual angle and are viewed in photopic (cone mediated) vision. The discrimination by the train operator of the cabin lights is not an essential requirement to carry out the task safely, but the use of appropriate colours aids learning and may well emphasise the function of the lights. There is therefore little doubt that an acceptable level of colour discrimination is needed and can enhance conspicuity even when the colour is used redundantly and the tasks are less demanding or safety critical.

1.2.2 Analysis of the signal lights task

The signal lights task is a simple, efficient, three colour code using red, green and yellow (these lights stimulate both red-green and yellow-blue colour channels 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 differ somewhat between deutan and protan subjects. The signal lights 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 ~ 75m (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 TL signal lights task with no errors, but these subjects will be disadvantaged in many other colour related tasks. A system for simulation of signal lights must ensure that the use of less reliable brightness difference cues is minimised. On the other hand, the recognition of the red, green and yellow lights when small point-like sources are involved is not an easy task even for normal trichromats due to the poor chromatic sensitivity of the eye under these viewing conditions. When two adjacent lights are involved, other problems concerning the spatial resolution of the eye can arise due to large higher order aberrations and increased light scatter under dark background conditions when the pupil size is large. Visual acuity at low light levels in the mesopic range is not normally assessed in most occupational tasks. These additional factors explain why the signal lights task is considered to be more critical than other colour based tasks.

1.2.3 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 essential occupational tasks that involve colour vision with the accuracy and efficiency expected of normal trichromats. In view of these arguments, we have developed a train lights (TL) simulator test that can be used under controlled laboratory conditions. The simulator reproduces both the photometric and the angular subtense of the real lights under demanding viewing conditions when the lights are viewed against a dark background (i.e. inside a tunnel). 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 LU environment. 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 signal lights task.

1.3. Brief description of the most common occupational colour vision tests

There are many manuals and references describing colour vision tests employed to assess occupational fitness (for a complete review, see Birch, 2001). 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 American Optical (Hardy, Rand and Rittler) pseudoisochromatic plate tests, Farnsworth D15 and City University hue discrimination tests and the Nagel Anomaloscope. Measures of colour discrimination performance computed from each of these tests will be examined and compared with the subject's scores on the Train Lights simulator test.

1.3.1 Ishihara plate test

The Ishihara pseudoisochromatic plate test consists of a series of numbers outlined by different coloured dots as shown in Fig. 5. 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, 1997b). 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 38-plate test standard version consists of the following: plate 1 for demonstration of visual task, plates 2-21 for screening, plates 22-25 for protan/deutan classification, and the remaining plates for unlettered persons. The Ishihara test employs a range of designs, such as transformation, vanishing or hidden digit. In the vanishing type plate (Fig. 5, 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 (Fig. 5, 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 (Fig. 5, right), protans only see the number on the right side of each plate and deutans only see the number on the left.

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

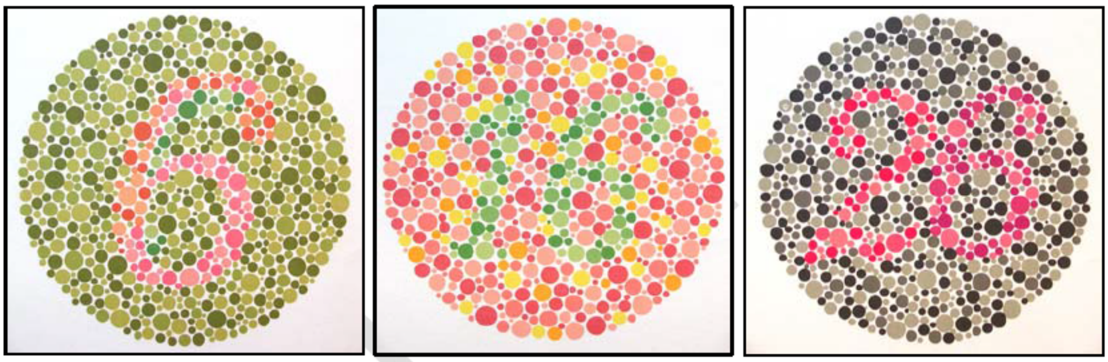


Figure 5: Ishihara pseudoisochromatic plates; left, transformation design; middle, vanishing design; right, protan/deutan classification plate. Please note that these may not be reproduced accurately as the printed colour and the viewing illuminant will be different.

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 are used of the 38-plate test version. 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 as 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.

1.3.2 American Optical – Hardy, Rand and Rittler test

The American Optical - Hardy, Rand and Rittler pseudoisochromatic plates (AO-HRR) (HARDY et al., 1954) is still one of the most popular plate tests despite being now out of print. It has both screening and diagnostic plates for tritan defects, and diagnostic and grading plates for protan and deutan defects. There are four introductory plates used to describe the test, then four protan/deutan and two tritan screening plates, and these are followed by diagnostic and grading plates for protan, deutan and tritan defects. 24 plates are used in total. The plates have vanishing designs containing geometric shapes (circle, cross and triangle) that are printed in neutral colours on a background matrix of grey dots (Fig. 6). The saturation of the neutral colours increases in successive plates to produce designs with progressively larger colour difference steps (HARDY et al., 1954) so identifying different levels of deficiency. This test is often used complementary to the Ishihara plates. The AO-HRR plates are given in reverse order, after showing the introductory plates, so giving the advantage that the test moves from an easy to a more difficult level. The value of the AO-HRR is in classifying protan and deutan defects, grading the severity of red/green colour deficiency and identifying moderate tritans. The classification of protan/deutan defects is not 'straight-forward' as it is based on the number of protan/deutan designs failed and, due to the relatively small numbers of plates, people often fail an equal number of both designs. The test should be conducted using a MacBeth easel lamp for illumination.

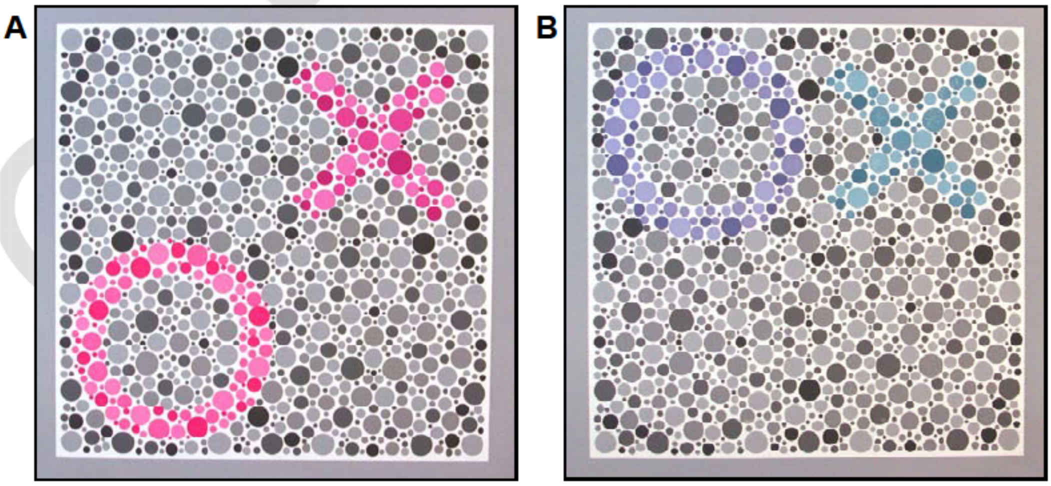


Figure 6: The American - Optical Hardy, Rand, Rittler pseudosichromatic plate test. (A) The intended design of this plate was to identify severe protan and deutan deficiency depending on which geometrical shape is seen. (B) Example of a plate intended to identify tritan deficiency. Again note that these may not be reproduced accurately as the printed colour can be different.

1.3.3 Farnsworth-Munsell D-15

In hue discrimination tests, the observer is required to identify colour differences or arrange colour samples according to hue, lightness, and saturation. The Farnsworth-Munsell D-15 (D15) was originally designed for vocational guidance to select recruits with adequate discrimination for work in the electronics industry (Farnsworth, 1947). The aim of the test is to separate (dichotomise) those people with moderate and severe chromatic discrimination loss, who fail the test, from people with normal colour vision and minimal colour deficiency, who pass the test. In addition, the test indicates yellow/blue discrimination loss, detects achromatopsia, and is useful in the evaluation of acquired colour vision defects (Verriest, 1963). The D15 panel contains 15 movable colour samples. One reference colour sample subtends a visual angle of 1.5º at 0.5m when shown at a distance comfortable for manipulation. The samples are chosen to represent approximately equal hue steps for the "natural" colour circle. The test contains colours selected from an incomplete Munsell hue circle. Isochromatic colour confusions are demonstrated when colours from opposite sides of the hue circle are arranged side by side in the subject's arrangement. All the colour caps, except for the reference colours, are removed from the box and mingled on the table. The subject is instructed to place the caps back into the box arranging them "in a natural order according to colour" (caps are numbered on the reverse). The test is performed under appropriate illumination, i.e. MacBeth easel lamp. The majority of individuals with normal colour vision can complete the box in one minute. Usually, as much time as necessary is allowed to complete the task. The order of the caps is transferred to the results diagram that shows the correct cap positions forming a circle starting with the reference cap (Fig. 7).

A

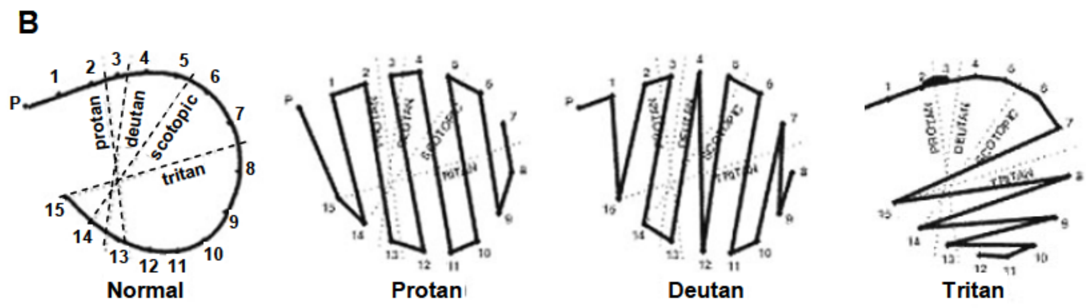


Figure 7: (A) Farnsworth D15 test showing a typical sequence ordered by a protanomalous observer. (B) Results plotted on the results form showing typical results for a normal, protan, deutan and tritan observers.

Major errors give rise to lines crossing the circle, e.g. cap 3 and 12 are placed next to each other. These types of errors fall consistently on certain axes that correspond to protan, deutan or tritan defects. The axes are indicated in Fig. 7B.

1.3.4 City University Test

The City University test (CU) (Fletcher, 1972) consists of a series of ten plates. On each plate five circles mounted on black matt background are displayed: a central and four peripheral colours of equal size. Subjects are asked to select which of the four peripheral colours is most similar to the central colour. The colours employed are all selected from the Munsell series. Three peripheral colours are selected from the opposite side of the hue circle used in the D15 panel sequence and represent typical isochromatic confusions with the central colour, for each type of defect. The fourth colour is an adjacent colour in the D15 sequence and is designated as the normal choice (Fig. 8). Since it is based on the D15 panel, the CU test is not designed for screening; approximately 20% of colour defectives pass the test (Birch, 1997a) and the protan/deutan classification is not always clear. Most moderate and severe defects are diagnosed correctly and the number of errors is related to the severity of colour deficiency.

The CU test is useful for identifying significant colour deficiency when a format other than the D15 is required.

Figure 8: Photograph of the City University test illuminated with the MacBeth easel lamp.

1.3.5 Nagel Anomaloscope

The Nagel anomaloscope (Fig. 9) 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 brightness of the yellow lower field (see Fig. 9). 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 minimise 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.

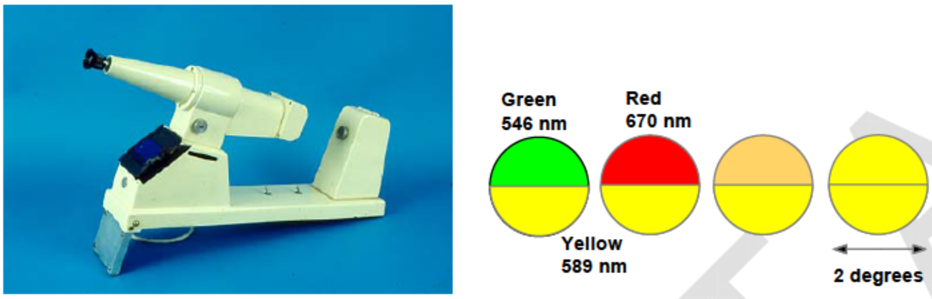


Figure 9: Photograph of the Nagel anomaloscope (Model I, Schmidt and Haensch, Germany) and illustration of the Nagel anomaloscope split field. The percentage mixture of red to green in the top half and the luminance of the yellow bottom field can be changed until a match of the two fields can be perceived.

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 one cone class) or anomalous trichromat (anomalous cone pigments). 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 to provide 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.
A more appropriate measure of red/green sensitivity based on the Nagel is proportional to the reciprocal of the matching range. This 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:

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

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 Fig. 10). 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 Fig. 10). 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).

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. Some colour deficient subjects can, however, produce "normal" anomaloscope matches both in terms of midpoint and range, but the number of such subjects is likely to be small (Barbur *et al.*, 2008)

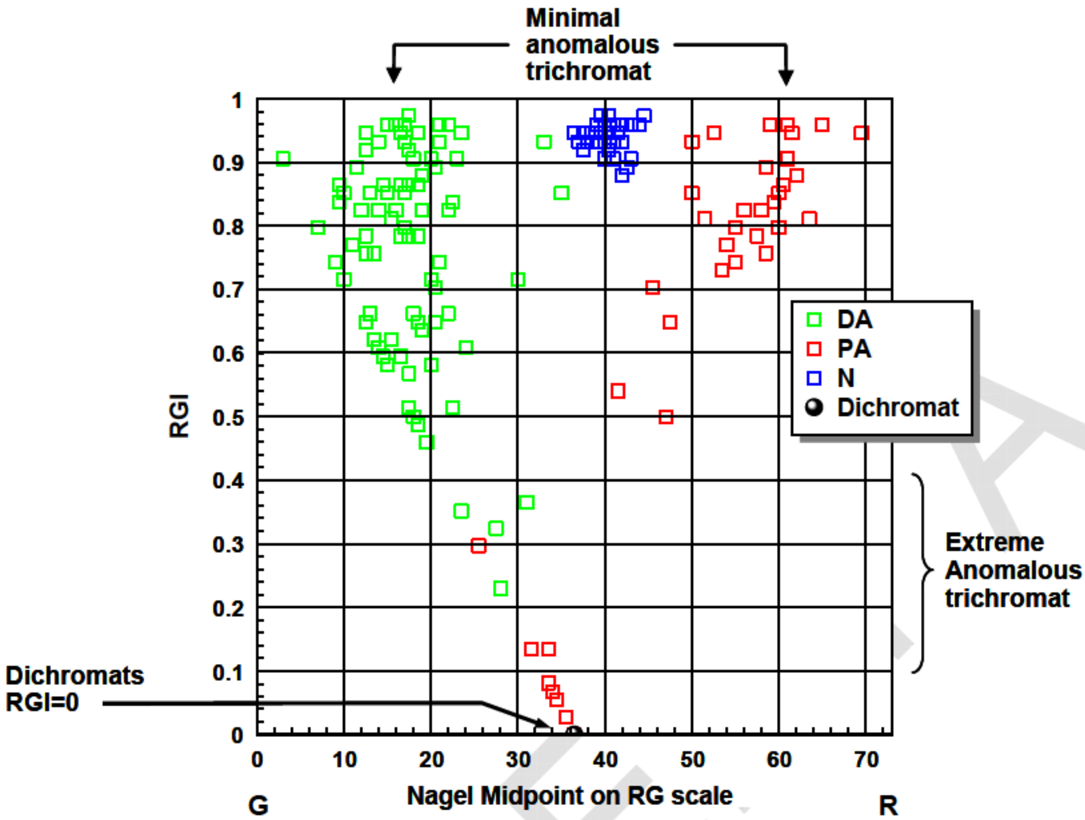


Figure 10: Scatter plot of matching midpoints versus RGI for 231 observers; 70 subjects formed a cluster that is separated from all other subjects by having a midpoint around 40 and a high RGI. The abbreviations in the legend refer to deuteranomalous (DA), protanomalous (PA), and normal trichromat (N) 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.

1.4. The CAD test

The Colour Assessment and Diagnosis (CAD) test requires the use of 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 colour thresholds in each direction of interest so as to establish reliable estimates of red-green and yellow-blue chromatic sensitivity. 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:

- **Isolation of colour signals**

When examining chromatic sensitivity it is essential 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 the relative numbers of L and M cones 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 averaged luminance of the foreground remains unchanged, both in space and time, and equal to that of the surrounding background field. The technique isolates the use of colour signals and ensures that the subject cannot make use of any subject specific, residual LC signals in the moving coloured stimulus. 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).

- **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 randomly 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.

- **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 deficient observers (Fig. 15). Fig.

11 shows the distribution of YB and RG chromatic thresholds obtained in the 250 normal trichromats. Fig. 12 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 needed by the average standard CAD observer. Fig. 12 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.

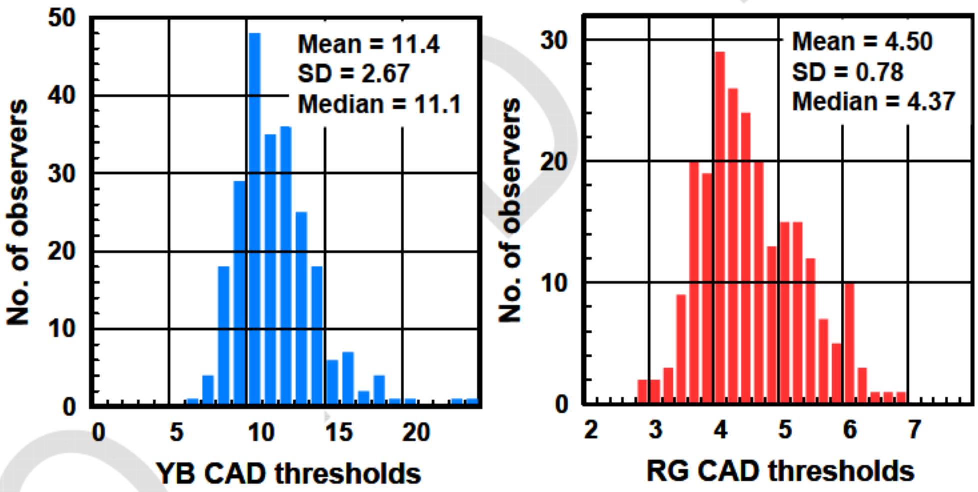


Figure 11: Frequency distributions of the YB and RG chromatic thresholds obtained in 250 observers with 'normal' trichromatic vision. The mean, standard deviation (SD) and median are shown.

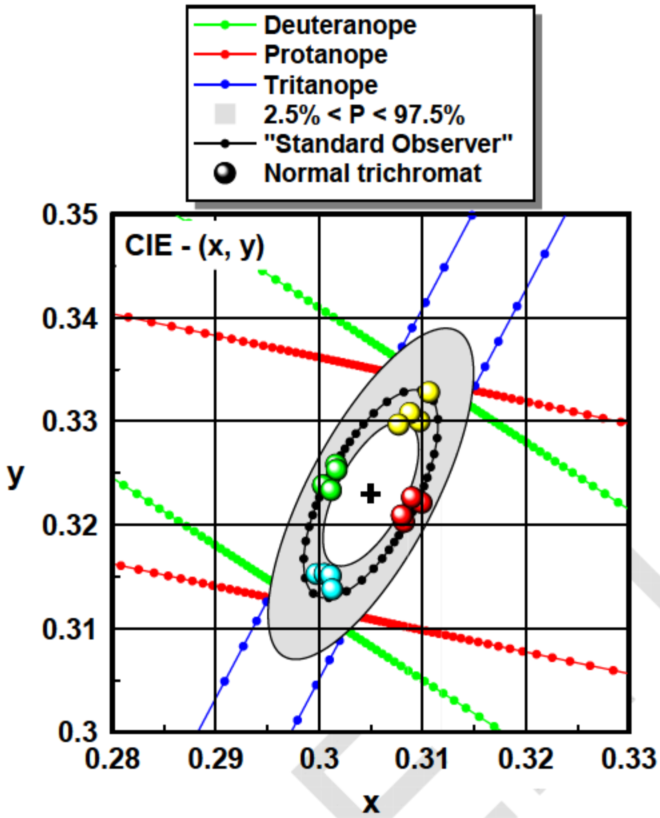


Figure 12: Data showing the 97.5 and 2.5% statistical limits that define the "standard" normal CAD test observer. The dotted, black ellipse is based on the median RG and YB thresholds measured in 250 observers. Only 2.5% of normal trichromats are expected to have thresholds just outside the grey shaded area. The deuteranopic, protanopic and tritanopic colour confusion bands are displayed in green, red and blue, respectively and are based on averaged CAD thresholds measured in dichromats. The background (x,y) chromaticity is indicated by the black cross and corresponds to 0.305, 0.323. The coloured symbols show data measured for a typical normal trichromat.

- **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, Fig. 13 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, whilst 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 red/green matching range that is smaller than the average normal trichromat). The second subject is classified as normal on the Nagel, but potentially red/green deficient on the Ishihara.

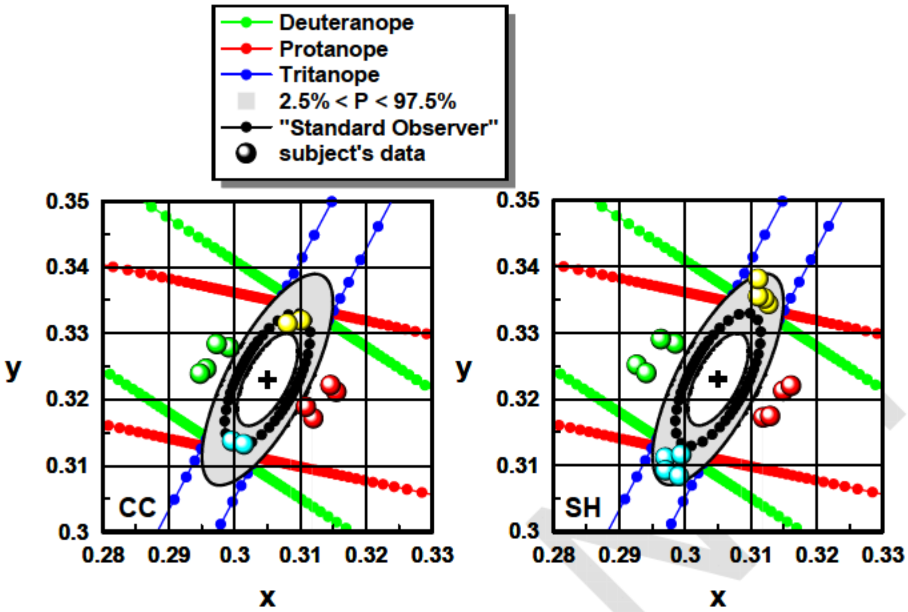


Figure 13: CAD thresholds for two colour deficient observers (both with minimal colour vision deficiency). The dotted, black ellipse show data for the average normal trichromat.

- **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 (Fig. 14, left) or protanopic (Fig. 14, right) confusion bands. In the case of absolute minimum deuteranomalous deficiencies the distribution of the thresholds is as shown in Fig. 13. In the case of minimum protanomalous deficiencies the thresholds are much larger and extend sufficiently in the protanopic direction to be able to diagnose minimum protanomaly with no ambiguity. The agreement with the Nagel for screening for and classification of the class of congenital red/green deficiency is ~99%.

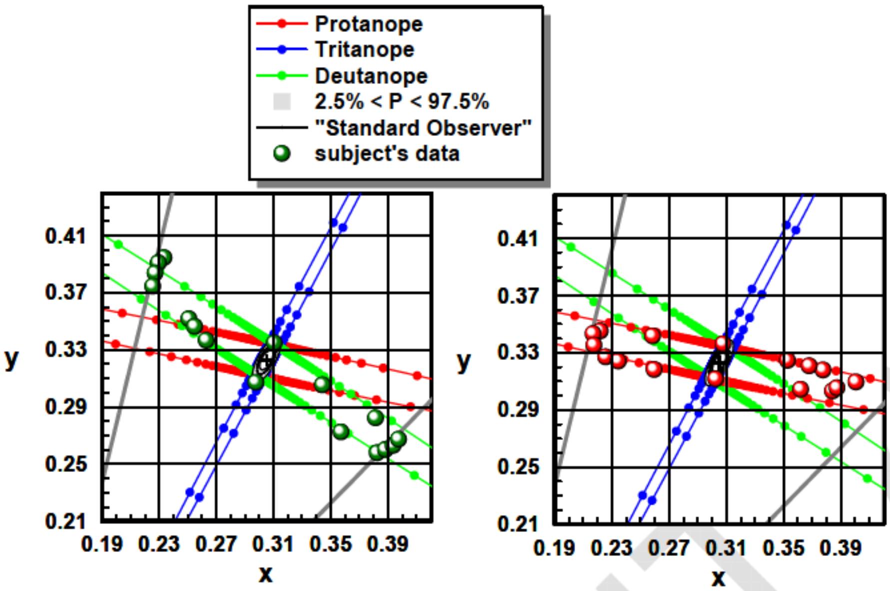


Figure 14: Chromatic thresholds for two colour vision deficient observers with severe colour vision deficiency. The largest chromatic displacements away from background chromaticity, as set by the isoluminant condition and the limits imposed by the phosphors of the display, are shown as grey lines. The extent of colour vision loss relates to the elongation of the thresholds along the corresponding colour confusion bands. Chromatic sensitivity (as derived from the CAD test) is defined as the reciprocal of the corresponding RG threshold.

- **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 Fig. 14 show more severe loss (i.e., higher thresholds or lower chromatic sensitivity) than the subjects shown in Fig. 13. The severity of colour vision loss can be quantified with respect to the standard normal observer (Fig. 11 and 12). 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. Fig. 15 shows RG thresholds in SN CAD units along the abscissa, plotted against the YB threshold along the ordinate for 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 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 (SN) CAD units is greater in protanomalous than deuteranomalous observers (Fig. 15).

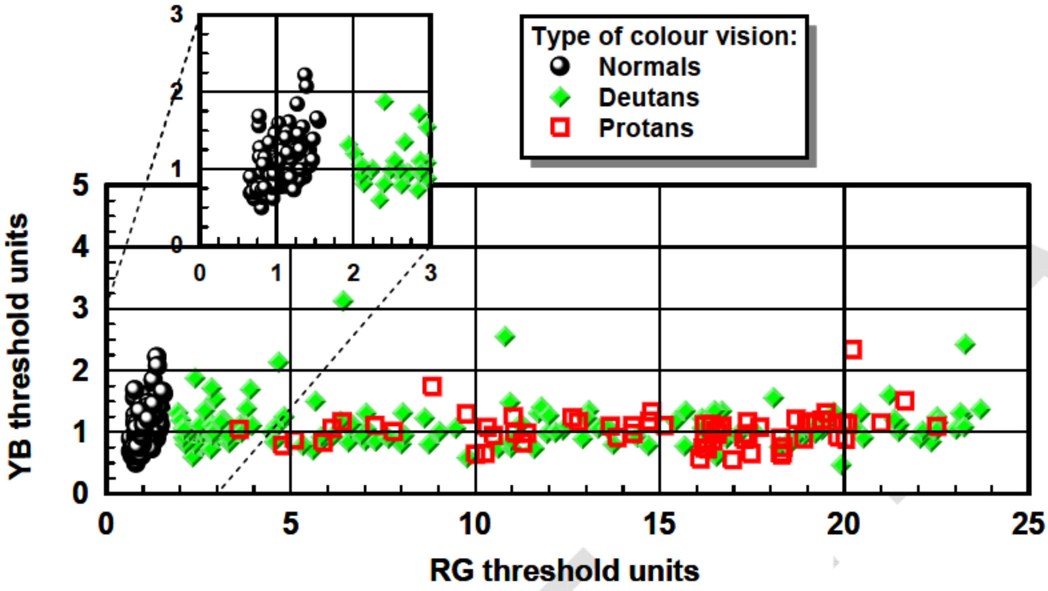


Figure 15: Graph showing Red-Green (RG) and Yellow-Blue (YB) thresholds expressed in SN CAD units. The spread in RG thresholds along the abscissa illustrates the almost continuous variation in RG chromatic sensitivity which exists in subjects with deutan- and protan-like deficiencies.

- **Effects of light level and stimulus size**

Both the background 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 pronounced 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.

- **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 Fig. 16. 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. Colour vision is usually assessed in demanding occupational environments. The upper limit of the age range examined (Fig. 16) is typical of pilots in the aviation environment. 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.

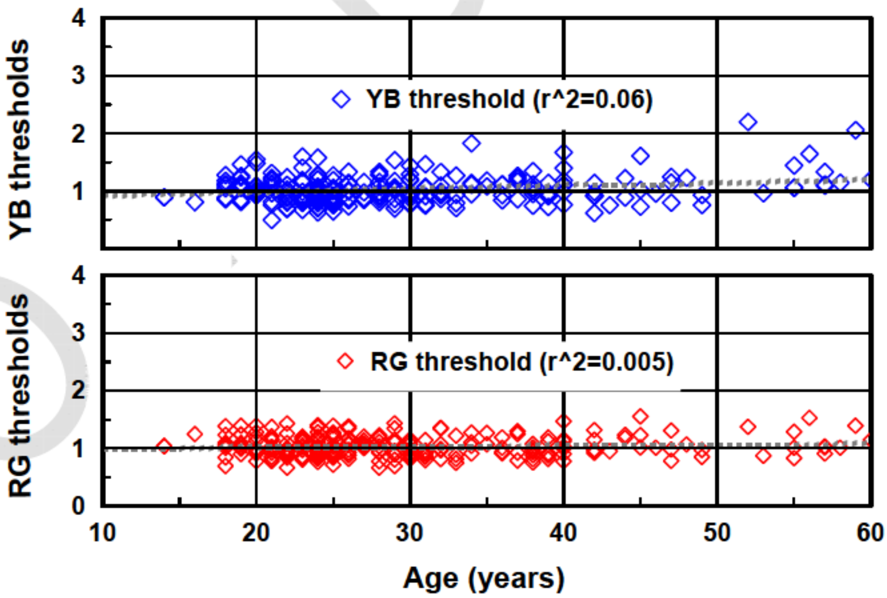


Figure 16: Effect of age on YB and RG chromatic thresholds for normal trichromats under normal daylight conditions. The best-fit line is shown for each set of data. The correlation coefficients (r^2) for the YB and RG thresholds are 0.06 and 0.005, respectively.

1.5. Summary of congenital colour vision deficiencies

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; Barbur et al., 2008). These factors are all likely to contribute to the variability measured both within normal and colour deficient observers.

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).

1.6. Acquired colour vision deficiencies

Acquired deficiencies tend to affect both RG and YB colour discrimination, although in some diseases the YB loss is greater and more apparent. Acquired colour deficiencies are commonly caused by systemic (e.g., diabetes, multiple sclerosis) and other diseases that are more specific to the eye (e.g., glaucoma, age-related macular degeneration, optic neuritis, etc). Acquired deficiency affects predominantly older subjects. Acquired loss can sometimes also 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, whilst the acquired component varies with stimulus size, retinal location and eye tested. Since yellow-blue sensitivity is most affected, the CAD is particularly suitable for investigating acquired deficiency since it also tests for yellow-blue loss. Fig. 17 below shows examples of acquired colour vision deficiencies.

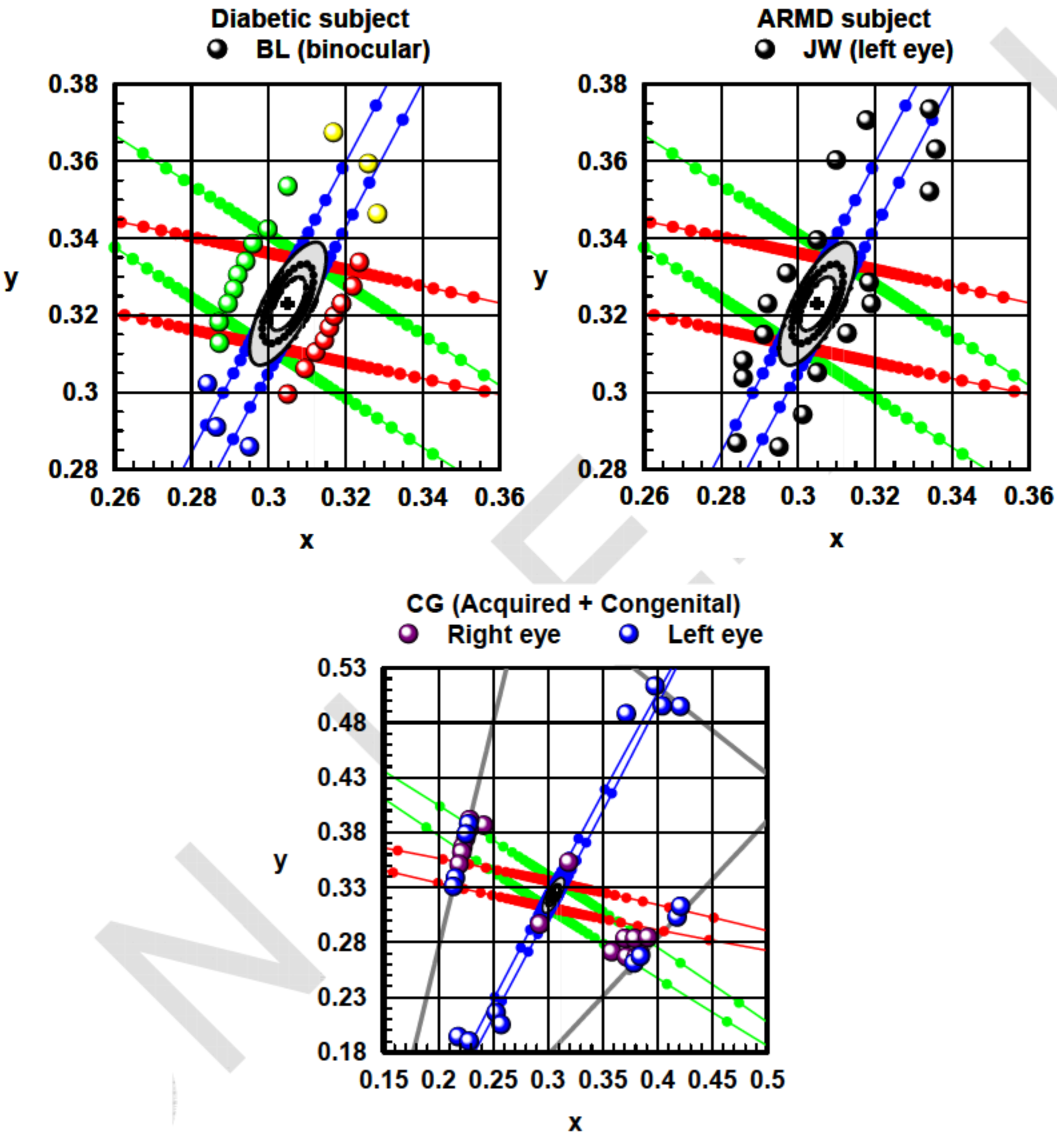


Figure 17: Examples of subjects with acquired loss of chromatic sensitivity. The data shown on the top left graph is from a subject with diabetes; top right shows data from the left eye from a subject with Age Related Macular Degeneration (ARMD); and bottom graph shows data from a subject with both congenital and acquired colour vision loss (note the difference between the two eyes).

2. Subjects and methods

Summary of tests employed in this study:

1. Ishihara plate test
2. American Optical - Hardy, Rand and Rittler plates (AO-HRR)
3. Nagel anomaloscope
4. City University test (3rd Edition) (CU)
5. Farnsworth D15 (D15)
6. CAD test
7. Train Lights (TL) test

The TL simulator test was 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 were carried out varied randomly and the testing took place in two different rooms, allowing the subject to take short breaks in between tests. 106 subjects were examined in this investigation: 40 normal trichromats and 66 subjects with deutan- and protan-like deficiencies. The age of the subjects ranged from 15 to 55 years (mean 30.1 years, median 27 years).

Train Lights simulator test

The colour signalling system used in the London Underground network involves the mainly three signal lights; red, green and yellow, although white and blue colours are also used in some tasks. The chromaticities of the lights should fall within the British Standard specification for colours of light signals (see Fig. 18). The chromaticity of signal green is restricted to the area within the outer green boundary shown in Fig. 18, whilst signal green used for the railway industry must be within the smaller area labelled as 'railway' (Fig. 18). The chromaticity for signal red is restricted to *y* not greater than 0.295 for high intensity red signals (daylight conditions) and the chromaticity of the white is also restricted to between x=0.330 and 0.420 for daylight coloured lights (BS 1376, 1974).

The chromaticities of the colours used in the TL simulator test are within the specified requirements for signal colours in the railway industry and are plotted in Fig. 18.

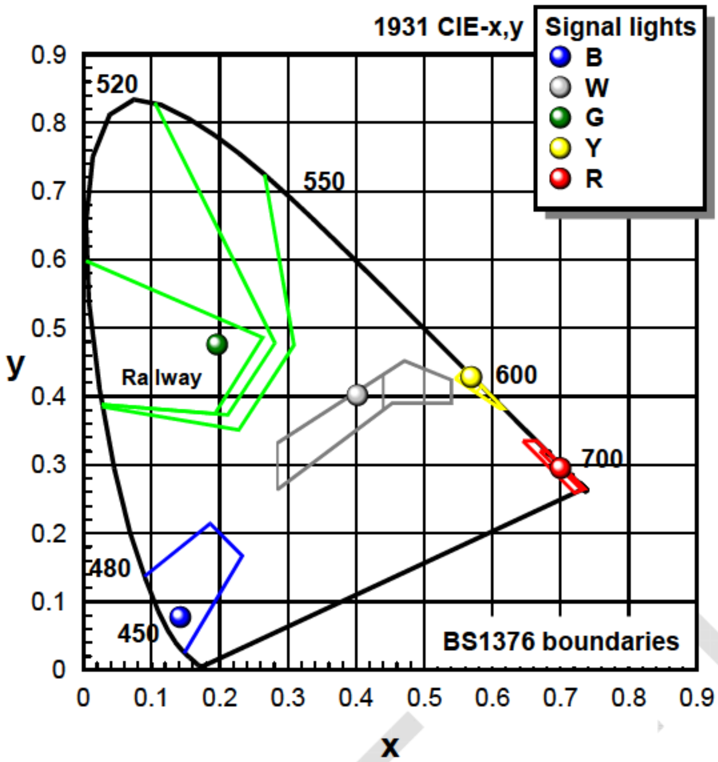


Figure 18: 1931 CIE-x,y colour space diagram showing the recommended chromaticity boundaries for the colours of light signals (BS 1376, 1974; CIE, 2001). The coloured discs plot the signal colours reproduced in the laboratory.

A schematic diagram of the laboratory set-up developed to simulate the LU train lights signal system is shown in Fig. 19. A four-channel optical system was developed using a 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 five different filters: red, white (of correlated colour temperature ~3900K), blue, green, and yellow. 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 so as to calibrate for the actual and not the nominal absorption of each filter.

‘Within tunnel’ signal lights were identified as the most demanding, safety-critical task for a LU train driver (see section 1.2). This is because colour discrimination is more difficult in the dark when point-like sources of light are involved. The lights have a diameter of 8.9cm and can be seen from ~250m, giving a viewing angle subtending less than 1.5 minutes of arc. Beyond ~75m the angular subtense of the real signal lights approaches the diffraction limit of the eye. The size of the light on the retina remains relatively unchanged as the approach distance is increased, but the light flux captured by the eye is decreased. The geometry of the real LU train lights was reproduced in the laboratory from a viewing distance of 4m. This corresponds to an angular separation of ~ 1.4' which translates to an approach distance of 220m (in the case of the real signal lights within the tunnel). This design therefore requires the train driver to see and recognise the yellow, green and red signal lights from 220m when the size of the image of each light on the retina is not larger than the point-spread-function (PSF) of the eye. We have, however, also examined a smaller approach distance of 110m which may also be considered adequate. The shorter distance causes the lights to appear brighter and also results in better separation of adjacent lights when two lights are used simultaneously. This is simply because 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. Although an approach distance of 110m may well be a safe stopping distance, the lights can be seen clearly under most conditions from larger distances, depending on the length of straight part of the tunnel without bends. Although the three important signal colours within the tunnel are red, green and yellow, the TL simulator also employed white and blue signal lights.

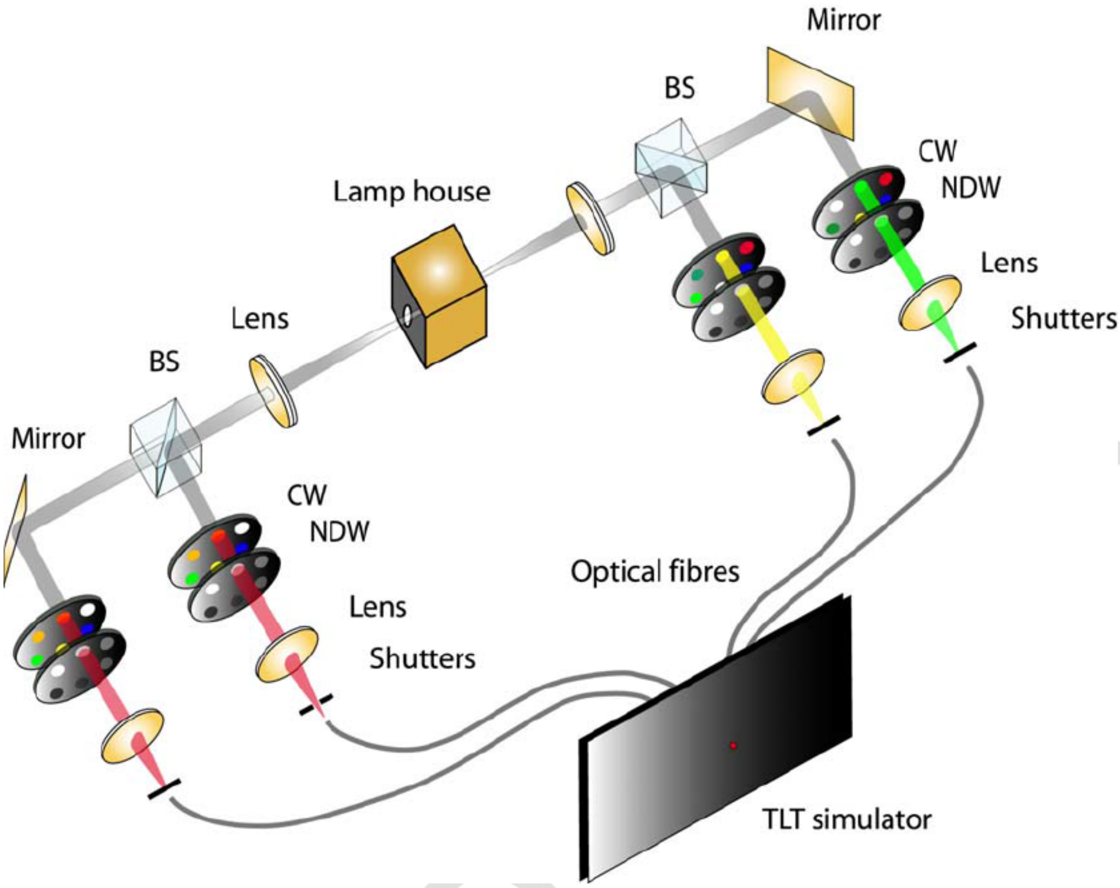


Figure 19: Optical set-up developed in the laboratory to reproduce the characteristics of the signal lights employed within the tunnel. Light emerging from each arm of the lamp house is divided into two channels via beam splitters (BS) to produce four independent beams. Each beam has a colour wheel (CW) 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 signal colour lights seen within the tunnel.

The optical fibre heads form a line located at the centre of a black plate which provides a dark uniform surround (see Fig. 19). The whole system is encased and ventilated by two fans to stop overheating and to reach a steady state temperature as needed for stable lamp operation. The intensities of the coloured lights were adjusted using ND filters so as to reproduce the light flux captured by the eye when the real signal lights are viewed in the dark tunnel from the corresponding approach distance. The calculations involved assumed that in the absence of significant ambient light, the pupil of the eye would in general be large (~6mm). In addition, the intensities of the LU coloured lights are variable due to settled dust within the housing of the lamps. This variation rarely exceeds 0.3 log units since the drivers have to report the presence of "dim" lights that is often caused by the failure of one of the two lamps. To simulate this variability and to eliminate the detection of brightness cues, the signal colours varied randomly by ±0.3 OD with respect to the nominal values.

Testing procedure

A single light is presented for 3 seconds and the subject's task is to simply report the colour of the light seen. There are five possible colours which are presented randomly (Fig. 20). Prior to the test, observers were dark adapted to the low mesopic surround and then were given 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.

A low power desk lamp was placed behind the subject so as to provide low mesopic conditions of ambient illumination similar to those found in the cabin. The black, immediate surround around the signal light was dark (i.e., mean luminance ~ 0.005 cd/m^2). Subjects were encouraged to respond only after an auditory cue signalled the end of the 3 second viewing period. The TL test was carried out twice, once at 2m (i.e. 110m) and once at 4m (i.e. 220m) viewing distance. The results for the TL test are recorded as percentage correct response.

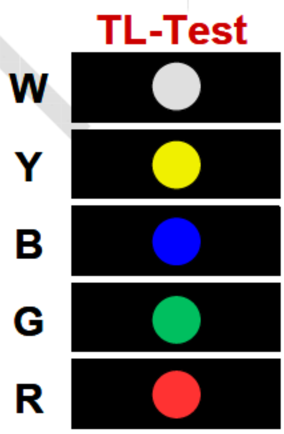


Figure 20: Schematic representation of the Train Lights (TL) simulator test. The TL-test presents 5 different conditions (as shown) twelve times giving a total of 60 presentations.

3. Results

Each subject's colour vision performance was assessed using six different tests. Results from each test were then examined in relation to the subject's correct colour naming scores on the TL task performance test.

Ishihara 24 plate test

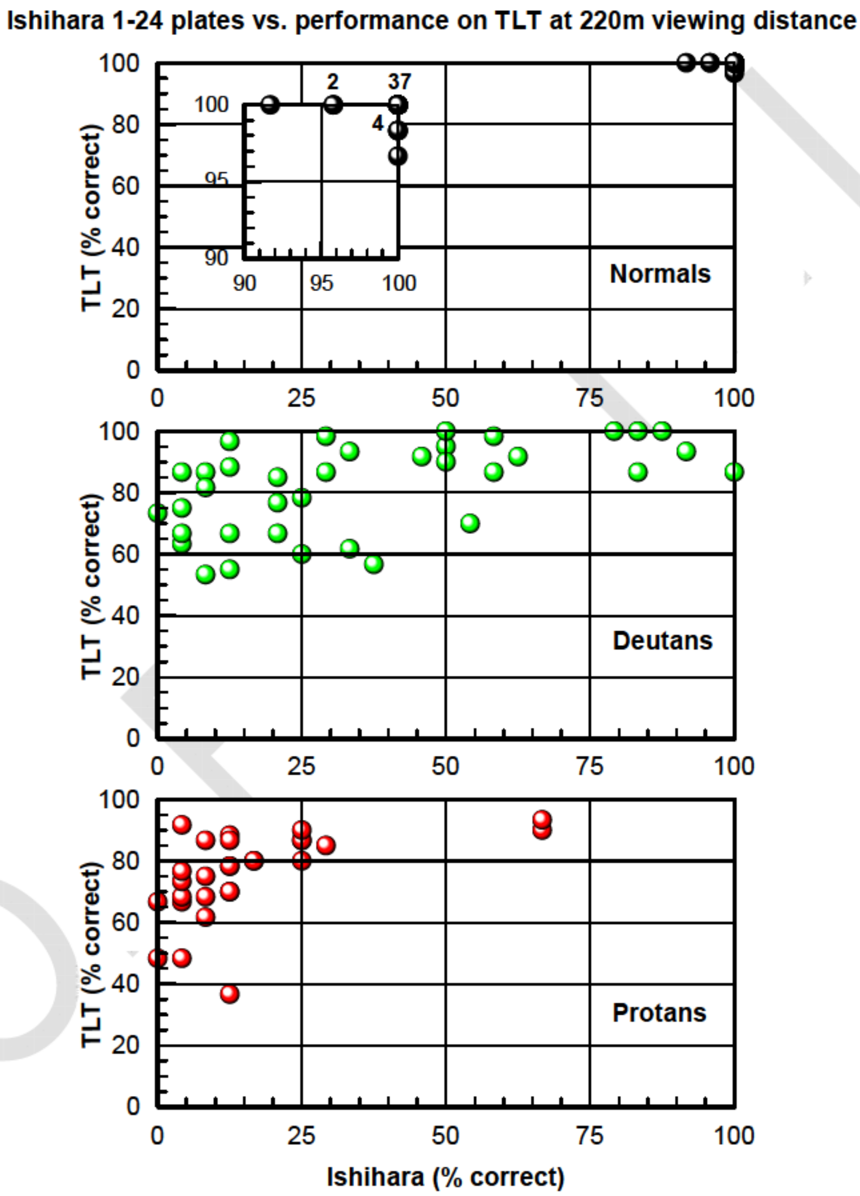


Figure 21: The number of plates read correctly expressed as a percentage of the Ishihara test (24 plates) plotted against performance scores on the TL test from a simulated approach distance of 220m. Data are shown separately for normal, deutan and protan colour vision observers.

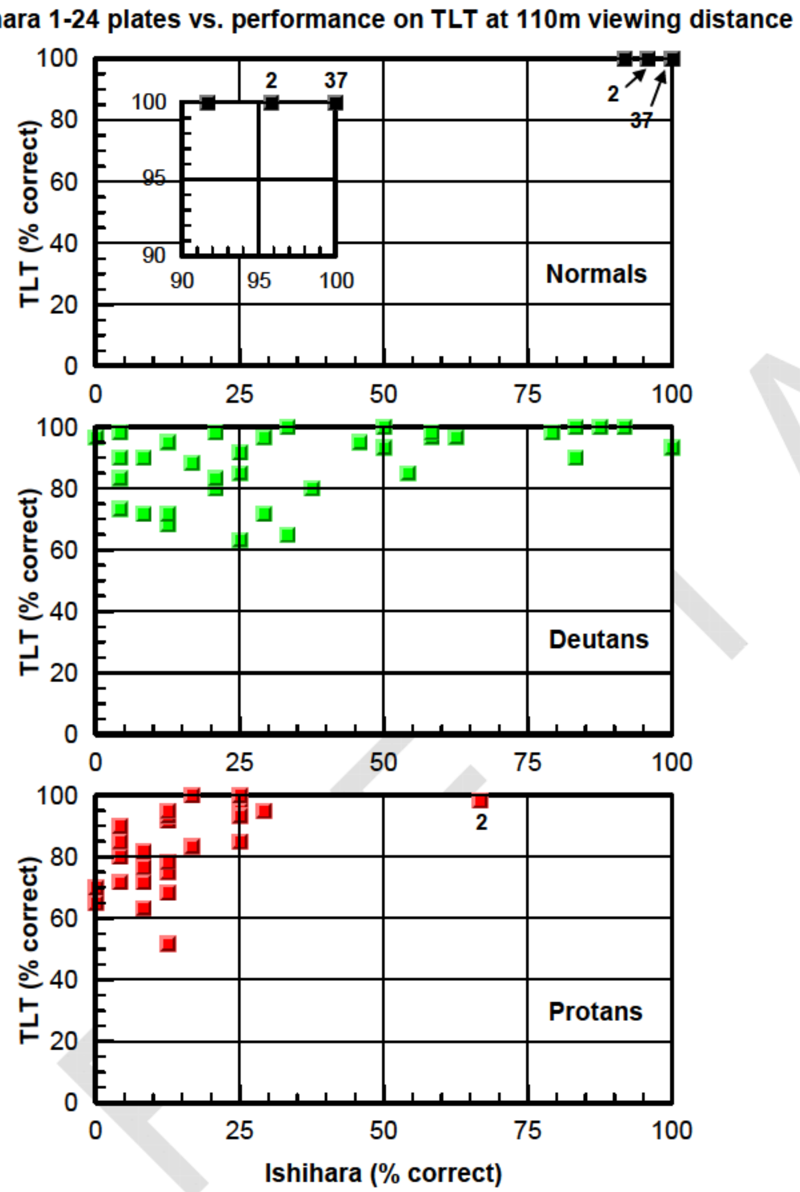


Figure 22: Ishihara percentage correct scores plotted against performance on the TL test from a simulated approach distance of 110m.

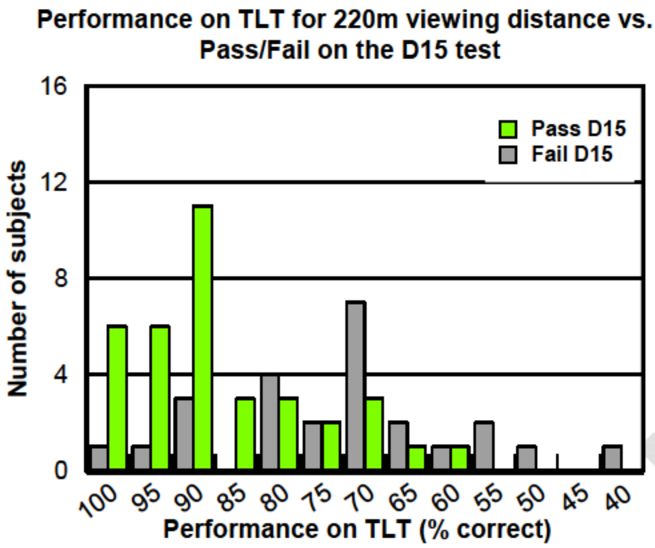
The subject's performance on the TL task is expressed as the percentage correct response (i.e., the number of colours named correctly out of a total of 60 presentations).

The results summarised in Fig. 21 show that normal trichromats can also make errors, both on the TL and the Ishihara tests (i.e., four subjects produce one error and one subject produces two errors on the TL test from 220m. The remaining normal trichromats score 100% correct on this test and all normal trichromats score 100% when the simulated approach distance is reduced to 110m (Fig. 22). Three normal trichromats from a sample of 40 subjects made errors on the Ishihara test; two subjects produce one error and one subject produces two errors. Results for deutan colour deficient observers reveal that one subject reads all the Ishihara plates, however, the same subject scores only 86.7% and 93.3% correct on the TL test from 220m and 110 m, respectively. Results for protan observers show that four subjects score 100% on the TL test, but make more than 16 errors on the Ishihara test. Overall the results reveal very poor correlation between the Ishihara based measure of chromatic sensitivity loss and the TL test scores. Many of the subjects that pass the TL test can score anything from 20% to 90% correct on the Ishihara test.

Farnsworth D15 and CU tests

Results from the Farnsworth D15 test were found to correlate poorly with the percentage correct scores achieved on the TL test. Fig. 23 shows the percentage correct TL test scores separately for subjects with mild colour vision deficiency (i.e., those that pass the D15 test), and for those subjects that fail the D15 (and are therefore classified as having moderate to severe deficiency). The results show that subjects that pass the D15 can produce TL error scores in the range 55 to 100%. The data show clearly that the results of the D15 test cannot be used to predict the signal lights discrimination test. It has also been shown that protans make fewer errors than deutans on the D15 test and that the overall pass / fail outcome is very dependent on the choice of sample population of subjects (Birch, 2008). In this study, 79% of deutans (30 out of 38) compared to 29% of protans (8 out of 28) passed the D15 test.

The results obtained on the CU test were very similar. There is a lack of correlation between subject's pass / fail score on the CU test and the corresponding performance on the TL test. Fig. 24 shows that subjects can pass and fail the CU test and achieve a score of 100% on the 110m TL test. In total, 32 colour deficient observers pass the CU test (allowing for no errors): 25 deutans (out of 38) and 7 protans (out of 28). These results confirm previous findings in that a larger percentage of deutans than protans pass the CU test. Since prediction of the class of deficiency involved is poor with Ishihara, D15 and CU tests, it is difficult to use these tests to set pass / fail limits that reflect the differences in performance on the TL test between protan and deutan subjects.



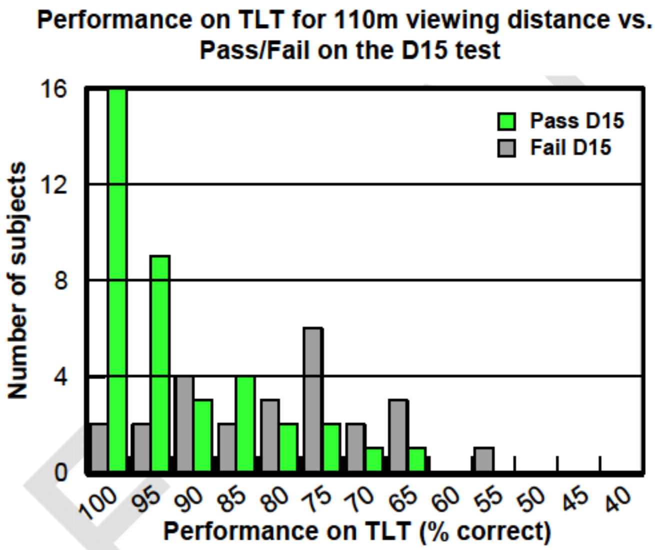
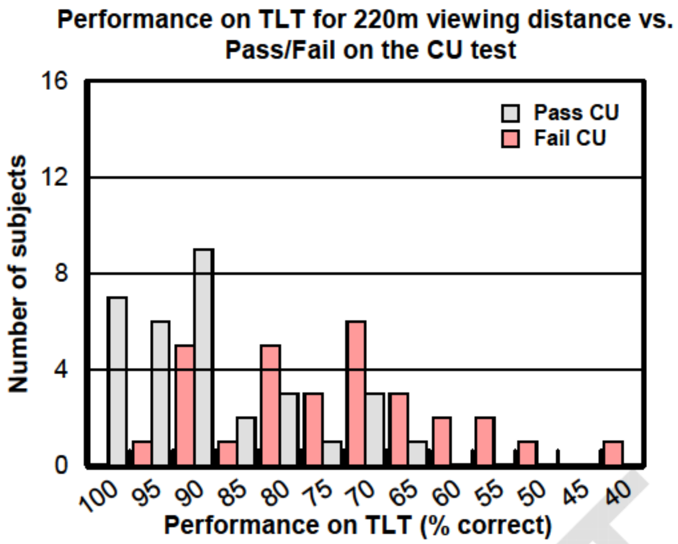


Figure 23: Distribution of percentage correct scores on the TL test plotted separately for subjects that pass and for subjects that fail the Farnsworth D15 test. A pass on the D15 test implies mild colour vision deficiency and a fail classifies the subject's colour vision loss as moderate to severe.



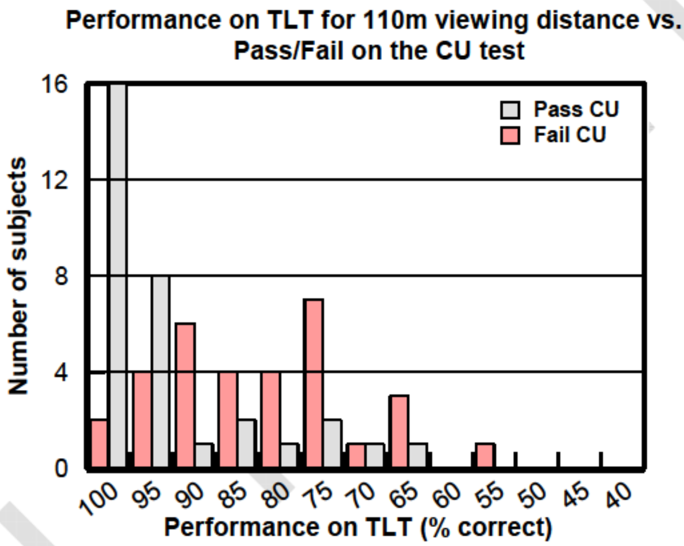


Figure 24: Distribution of percentage correct scores on the TL test plotted separately for subjects that pass and for subjects that fail the City University test. Scores produced by subjects with mild colour vision deficiency (i.e., those that pass the CU test) and subjects classified as having moderate to severe colour deficiency (i.e., those that fail the CU test) are shown separately.

Nagel anomaloscope test

Fig. 25 compares TL test scores from a simulated approach distance of 220 m with a measure of chromatic sensitivity based on the Nagel anomaloscope range.

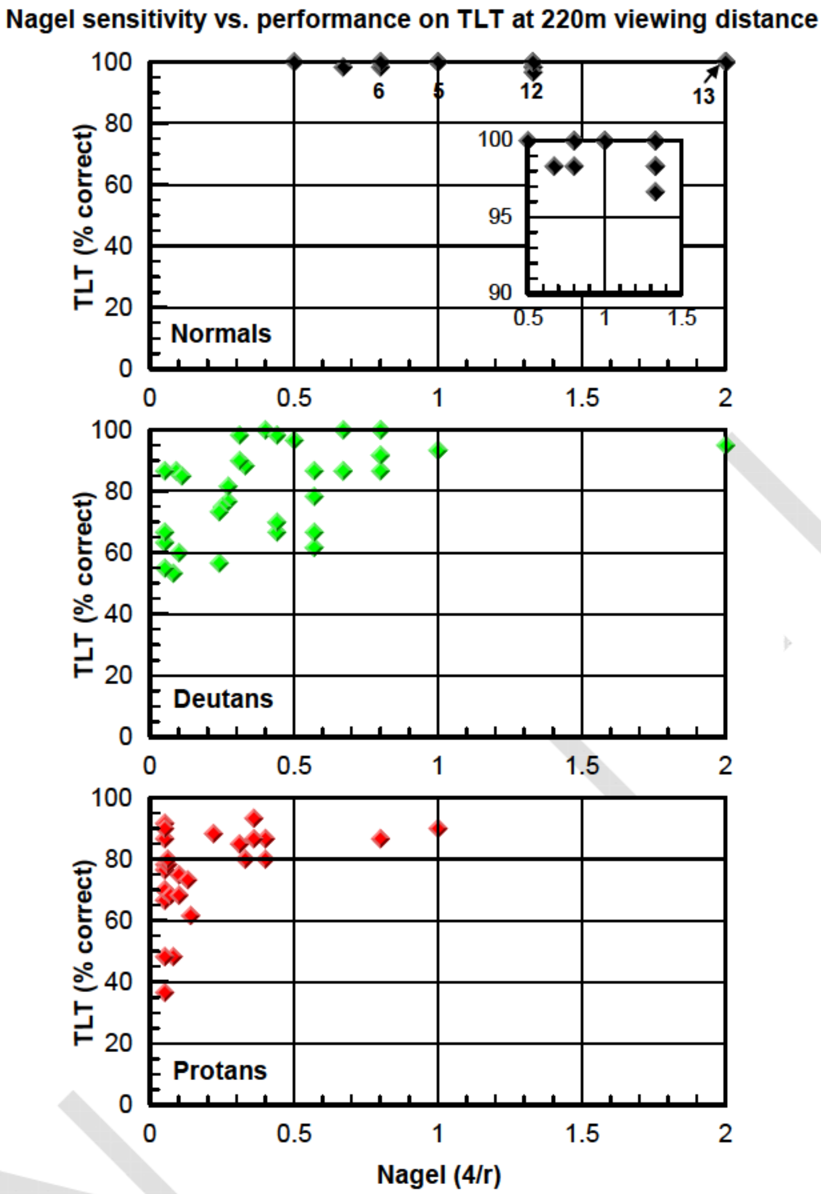


Figure 25: TL test scores for 220 m approach distance plotted against an index of red-green chromatic sensitivity based on the Nagel anomaloscope range. Results are shown separately for normal, deutan and protan observers. Numbers next to some symbols indicate number of subjects with overlapping data points.

Fig. 26 shows how TL test scores (for 110 m) vary with the subject's RG sensitivity derived from the Nagel anomaloscope range. Only a few deutan and protan observers pass the TL test with Nagel sensitivity > 0.3 (deutan) and > 0.1 (protan) (Fig. 26). 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.

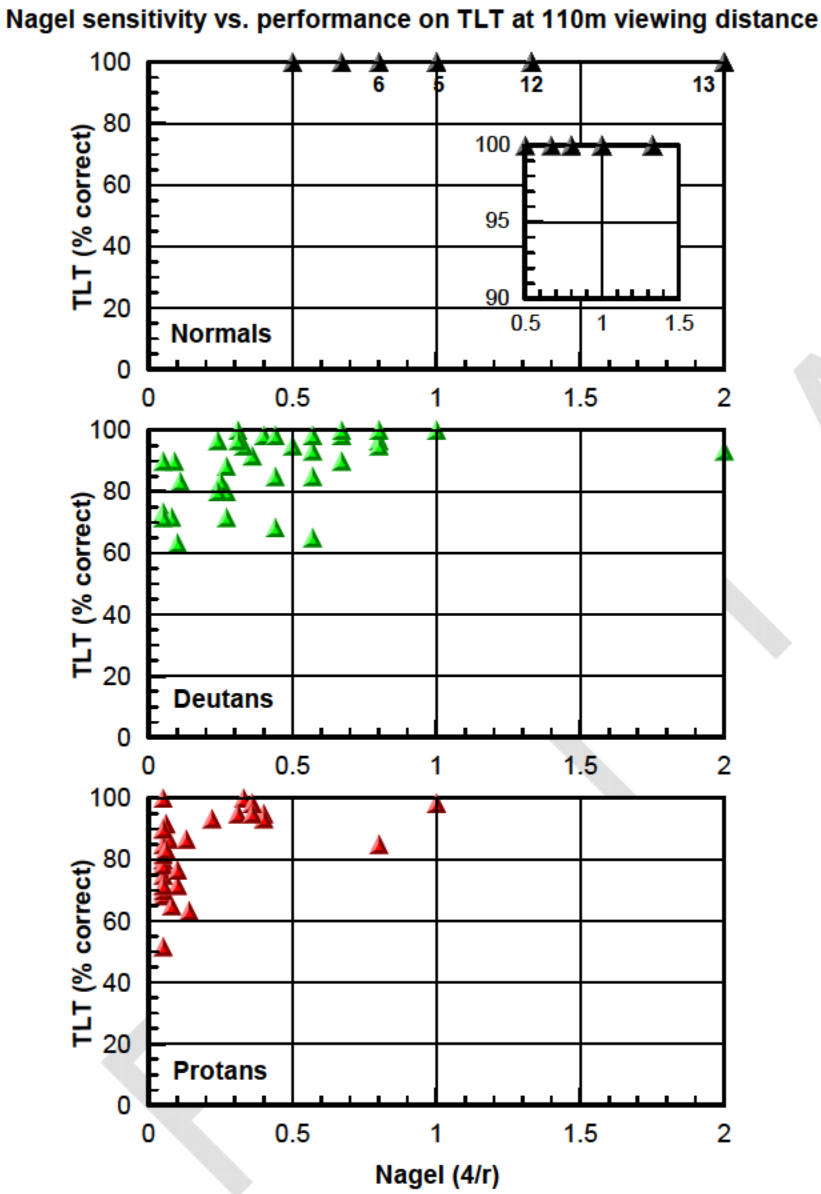


Figure 26: TL test scores for 110m approach distance plotted against an index of red-green chromatic sensitivity based on the Nagel anomaloscope range. Results are shown separately for normal, deutan and protan observers. Numbers shown next to some symbols indicate number of subjects with overlapping data points.

The results show that normal subjects also make some errors on the full TL test from a simulated approach distance of 220m, but no errors from 110m (see Figs. 21, 22, 25, 26). The small number of errors made from the larger approach distance can probably be attributed to the reduced colour signal strength expected with the smaller lights. In fact, the types of errors normal trichromats make on the TL test are not considered critical to safety within the tunnel. Analysis of results reveals only G=B and W=Y errors (see Fig. 34 in Appendix). The critical colours train drivers must name correctly within the tunnel are R, G and Y (see section 1.2). Based on these colours that have to be recognised correctly from a large distance within a tunnel with little or no ambient illumination we can establish minimum colour vision requirements to ensure that colour deficient subjects perform this safety-critical, colour-related task with the same accuracy as normal trichromats.

Colour Assessment and Diagnosis (CAD) thresholds

Although the correct naming of all signal colours may be required in some tasks, the very demanding viewing conditions within the tunnel involve only R, G and Y lights. TL test scores for these colours are shown in Figs. 27-31 plotted against the subject's CAD threshold in standard normal units. The top section shows the performance in deutans / protans when only R=G and G=R errors are considered. The middle section shows Y=R and R=Y errors and the bottom section plots the percentage errors resulting from Y=G and G=Y confusions.

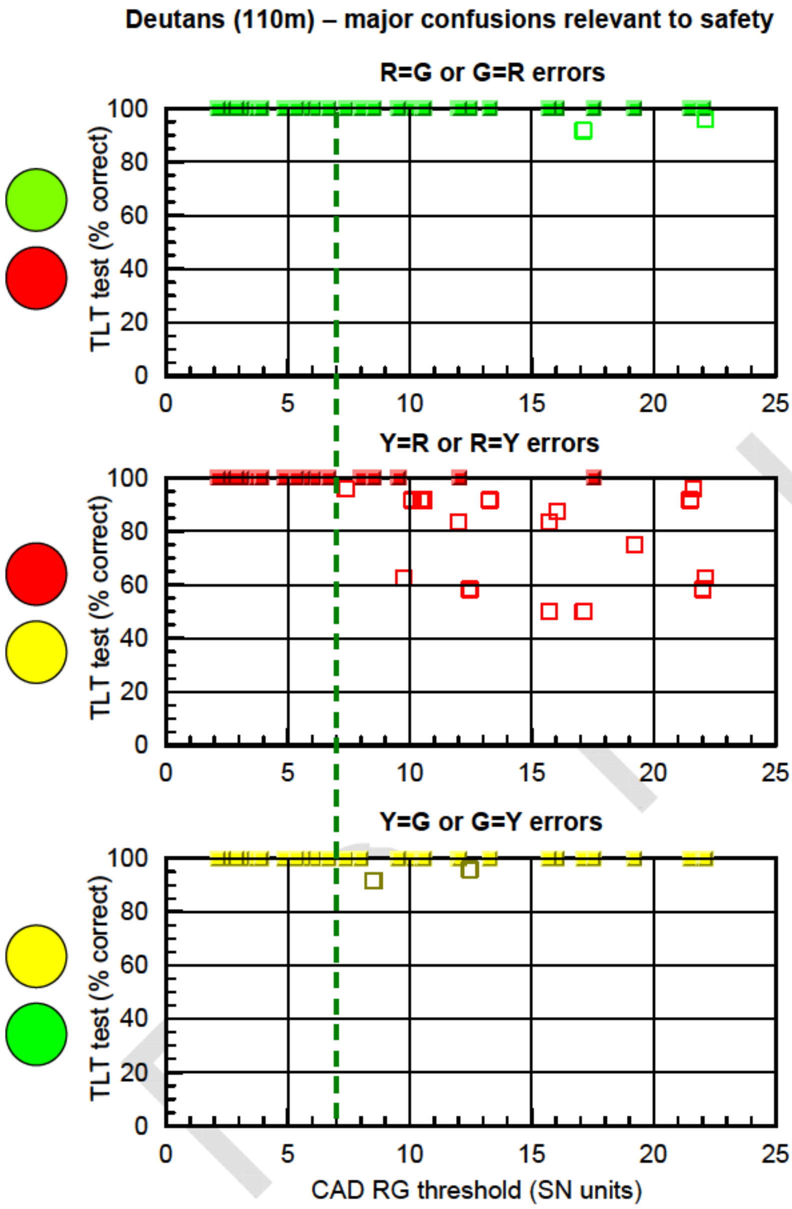


Figure 27: Graphs showing performance of deutans, when simulating an approach distance of 110m on the TL test, plotted against CAD test thresholds in standard normal (SN) units (Note: the median, normal threshold corresponds to one SN CAD unit)

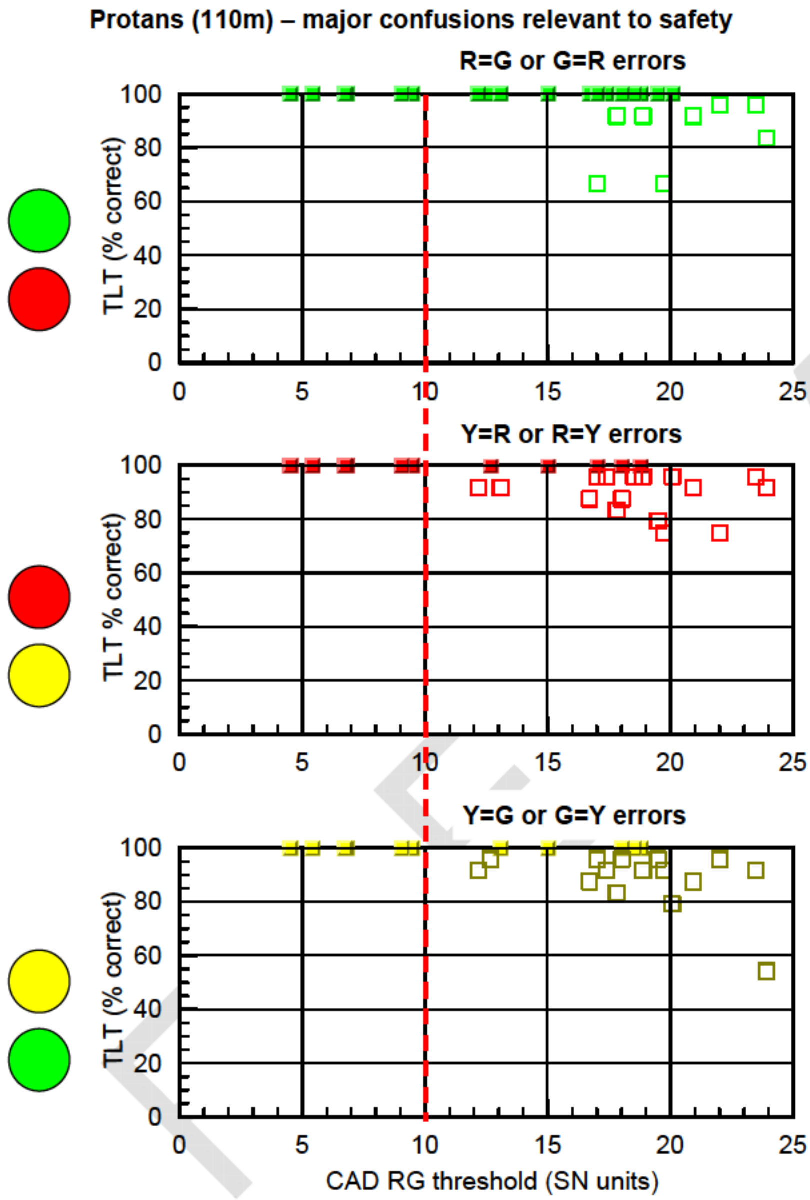


Figure 28: Graphs showing the TL test performance of protans for an approach distance of 110 m, plotted against the corresponding CAD thresholds in SN units.

The RG threshold limits beyond which deutans and protans perform the 110m TL test as well as normal trichromats are ~ 7 and 10 SN units, respectively. These limits are indicated by dotted vertical lines in Figs. 27 and 38.

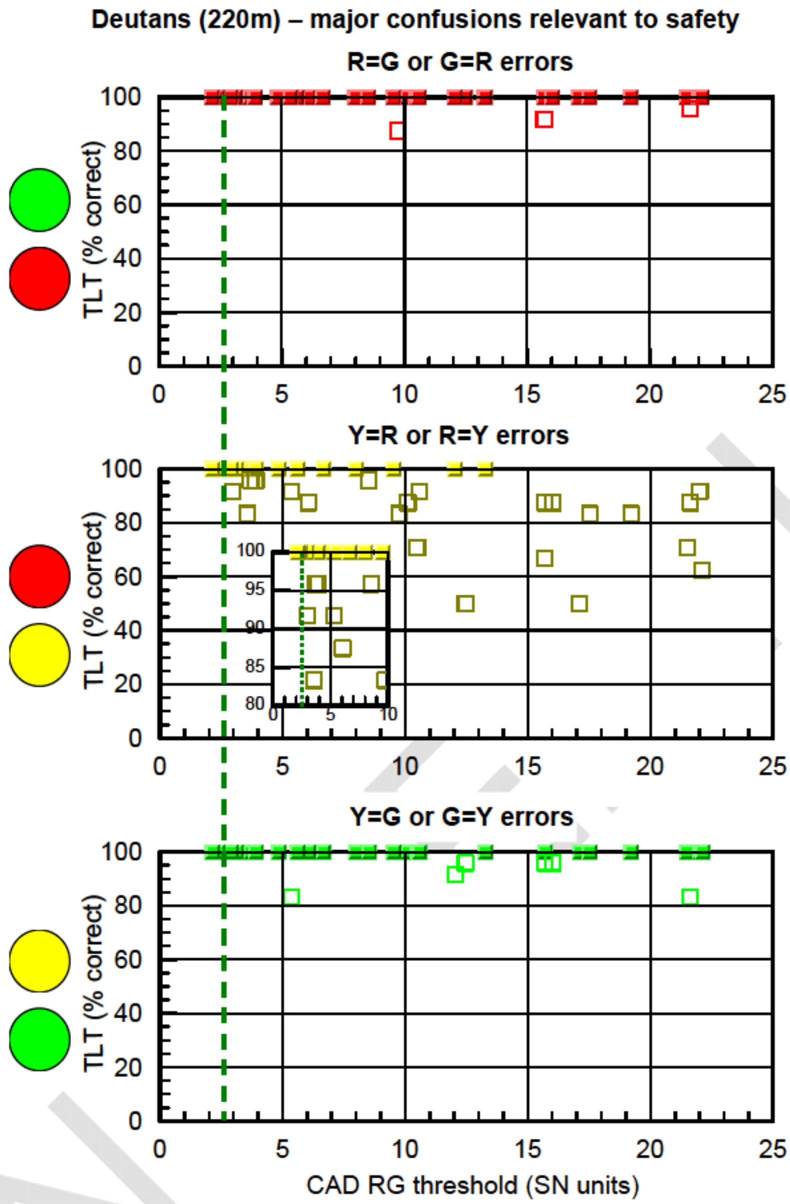


Figure 29: Graphs showing performance scores of deutan subjects for a simulated approach distance of 220m on the TL test, plotted against CAD test thresholds (in SN units).

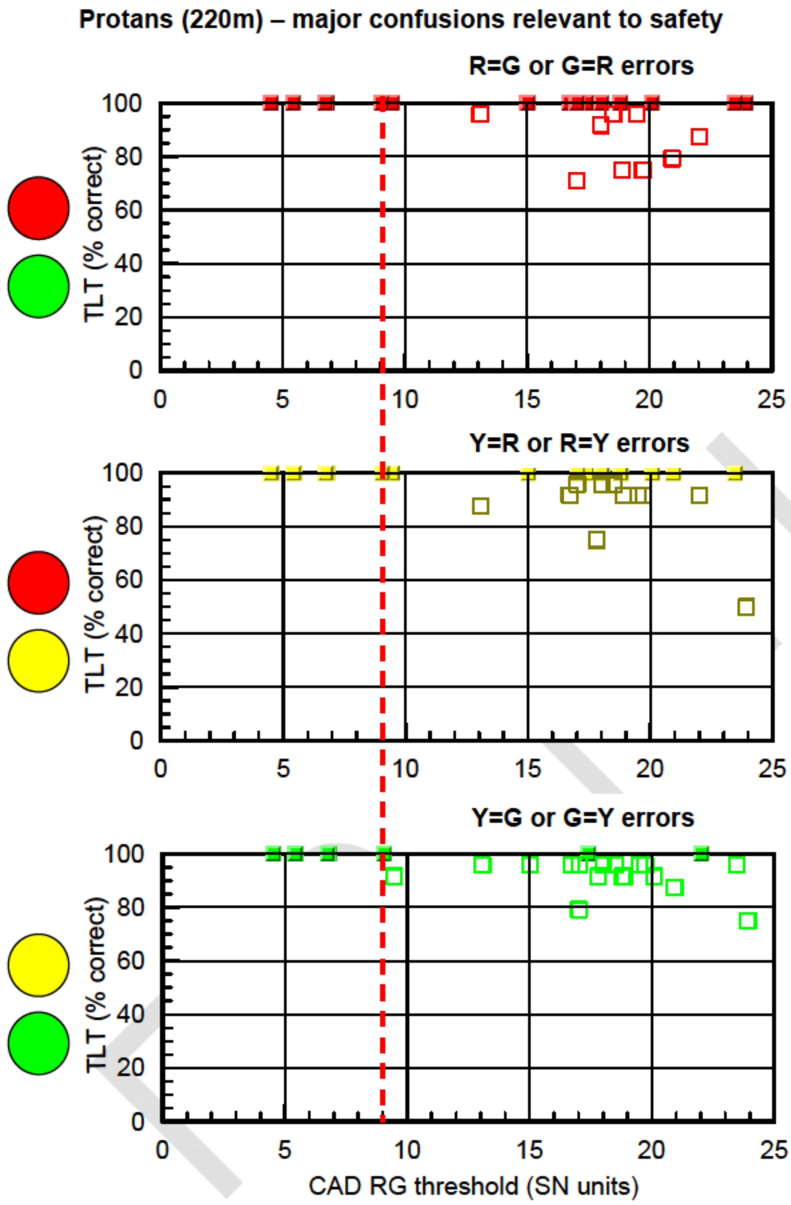


Figure 30: Graphs showing performance of protan subjects for a simulated approach distance of 220m, plotted against CAD test thresholds (in SN units).

From a 220m approach distance (Figs. 29 and 31), the threshold limits beyond which deutan subjects perform the TL test as well as normal trichromats is reduced, largely because of R=Y and Y=R errors. From 220m deutans with thresholds > 3 SN units confuse red and yellow lights more frequently. When simulating the 220m approach distance, one deutan observer with a RG threshold of 5.34 SN units also confuses G and Y signal colours (four errors). The results suggest that in order to ensure 100% performance for deutan subjects one requires a CAD threshold of 2.5 SN units or less. The limit of 10 SN units set for 110m for protan subjects should also be reduced to 9 SN units for the larger approach distance of 220m.

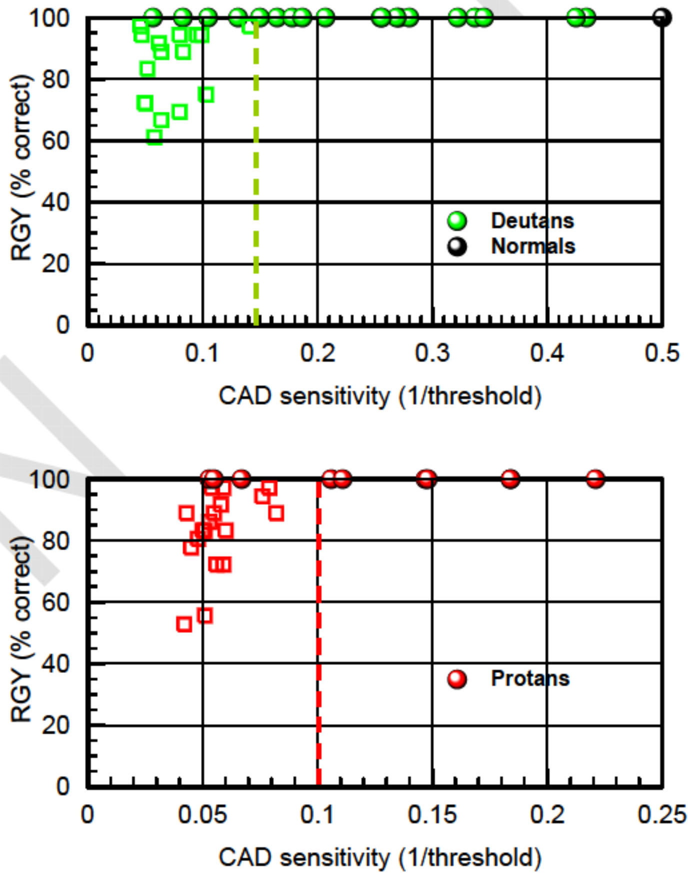
Computing an index of overall chromatic sensitivity

The threshold signal needed to just see the coloured stimulus in the CAD test is expressed as a fraction of the median threshold for normal trichromats. This approach has the advantage that a threshold less than one indicates colour discrimination better than the standard normal trichromat whilst values larger than one 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 outputs 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 small or absent chromatic sensitivity. For the majority of occupational colour vision tests, loss of chromatic sensitivity is more difficult to quantify since the tests do not measure the smallest colour signal strength needed to detect the coloured stimulus in the absence of any luminance contrast cues. 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 each 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. The definitions employed are listed below and yield values that vary 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
CU:	Fraction of plates named correctly
AO-HRR	Fraction of plates 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
TLT:	Percentage correct for all five signal lights colours

Using this approach we were able to compute the subject's mean chromatic sensitivity as derived from all the tests. This index is 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 London Underground transport environment and the exclusion of the very few subjects with poor overall RG chromatic sensitivity that happen to pass the TL test.

The pass / fail threshold limits established experimentally, i.e., 7 SN units for deutans (CAD sensitivity 0.15) and 10 for protans (CAD sensitivity 0.1) are shown in the first two sections of Fig. 31. The last section shows that the very few subjects that pass the TL test with CAD sensitivities less than 0.15 (deutan) and 0.1 (protan) also have very 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 ~ 0.6 (protans).



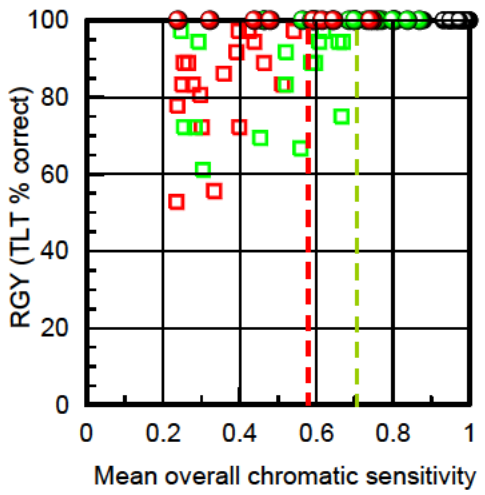


Figure 31: Measures of chromatic sensitivity that justify the pass / fail limits chosen. The top two diagrams compare TL test scores for Red, Green and Yellow signal colours (110m) against CAD test sensitivity (i.e., 1/CAD threshold, expressed in SN units); colour deficient subjects to the right of the dotted line perform the TL test as well as normal trichromats. CAD sensitivities of 0.14 (deutan) and 0.1 (protan) correspond to 7 and 10 CAD threshold units, respectively. Note the change of horizontal scale units for protan observers. The bottom diagram compares TL test performance for Red, Green and Yellow lights plotted against the “mean”, overall colour sensitivity as computed by averaging each subject’s performance on the Ishihara, CU, AO-HRR, TL and CAD tests and the Nagel anomaloscope. Interestingly, deutans with CAD thresholds < 7 and protans with threshold units < 10 achieve relatively high, overall chromatic sensitivity of 0.7 and ~0.6, respectively.

4. Discussion

4.1 Colour vision concerns in the LU environment

It is well known that colour enhances object conspicuity and is often used to code additional information. In overcrowded displays or complex visual scenes, colour allows segmentation of objects and grouping operations which enhance and speed up the acquisition and processing of visual information (Firth, 2001). The primary signal colours employed in the LU environment are red, green and yellow, with blue and white as supplementary colours. The Railway Group Standard requires drivers to recognise the colours of signal lights used in the LU network (Appendix A; RGS, 2002). The standard states that "colour vision shall be normal, as assessed by the Ishihara Plates Test". These requirements are however open to interpretation. The assessment of colour vision using the Ishihara test depends arbitrarily on the number of errors accepted as a pass. For example the Federal Aviation Administration allows for up to 7 errors in the first 15 plates, whilst the Civil Aviation Authority (in the UK) allows no errors (Squire et al., 2005). In order to increase the efficiency of the Ishihara test as a screening test for normal trichromacy, it has been recommended to consider only the first 16 plates and to allow up to a maximum of three 'misreadings' but no errors (Birch, 1997b). The concept of 'misreadings' was introduced to justify why normal trichromats with poorer chromatic sensitivity fail to read correctly some of the numbers that can be confused in the absence of a strong chromatic signal. There is therefore little or no justification in terms of functional colour vision requirements as to the number of errors / misreadings a subject can make on the Ishihara test and still be classed as safe to work as a train driver. Since ~15% of normal trichromats make errors on the Ishihara test, in practice the pass / fail limit must allow for three or less errors to ensure that normal trichromats pass this test. Data obtained from a number of studies at AVRC show that 7.4% of deutans and 1.9% of protans pass the Ishihara test with 3 or less errors. If we account for the larger number of deutan subjects within the population (see Table 1), these findings show that 6.1% of colour deficient applicants may pass current requirements (practice) and are therefore employed as train operators.

In this investigation we assessed 106 subjects using several colour vision tests and the results confirm both the large inter-subject variability and the poor consistency amongst the various tests (Squire et al., 2005). These findings show that colour deficient subjects can produce very different scores on different tests and that even normal trichromats can make errors on some conventional tests. Further, the pseudoisochromatic tests designed for screening are not suitable to either diagnose accurately the class of deficiency involved or to quantify the severity of colour vision loss (Belcher et al., 1958; Birch, 1997b).

Figs. 21 and 22 show how Ishihara scores relate to the colour naming performance on the TL simulator tests. The results reveal that deutan subjects with performance scores higher than 80% on the TL test can produce Ishihara scores that vary from zero to 100% correct. Protans with scores higher than 90% on the TL test can achieve between 1 and 16 correct responses on the 24 plate Ishihara test. As many as 15% of normal trichromats (Squire et al., 2005) can make at least one error on the Ishihara test.

Figs. 23 and 24 show comparisons between the D15, CU and the TL simulator tests. The results show that the severity of the deficiency as assessed by the D15 and CU tests correlates very poorly with the subject's performance on the TL test. Therefore, neither the D15 nor the CU tests provide a good measure of the subject's severity of colour vision loss.

The current findings justify recent concerns expressed by the LU (TfL) in relation to current practices for colour assessment in the railway industry. The observed inconsistency in the results of the Ishihara test and amongst the other occupational colour vision tests examined in this investigation as well as the poor correlation between the outcome of these tests and the level of performance subjects achieve on the functional colour naming task raise important questions about safety and operational issues. In addition, the current practice is also unsatisfactory since the outcome of current testing procedures can be potentially unfair to many train driver 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 Fig. 15). This is the most common type of colour vision deficiency, affecting 8% of the male population (< 1% females) (see table in section 4.4). Congenital yellow-blue deficiencies (involving reduced sensitivity or absence of S-cones) are very rare (1 in ~20000). Acquired loss of colour vision and in particular yellow-blue loss, as a result of systemic or eye disease, or as a side effect of toxicity or medication (see section 1.6 in this report) is, however, much more common. Acquired deficiencies tend to be age-dependent and when unnoticed may compromise safety within certain occupations. Renewal of certification of medical fitness is carried out every five years below the age of 56, every two years between the age of 56 and 62 and yearly above the age of 62 (Appendix A: RGS, 2002). Current tests are not usually designed to detect or measure YB sensitivity so any loss of colour vision that affects yellow-blue discrimination usually remains undetected. The need to test for normal yellow-blue chromatic sensitivity has also become more relevant because of the increased use of additional colours to code information in the modern railway environment.

4.3 Safe colour vision limits for train drivers

The TL simulator system constructed for this project reproduces the spectral composition, the angular subtense and the retinal illuminance of the real TL lights within the tunnel for approach distances of 220m and 110m. Comparisons between the performance of the subjects on the TL and CAD test yield the minimum levels of chromatic discrimination below which subjects with red/green colour deficiency no longer perform the TL task with the same accuracy as normal trichromats. Fig. 27 and 28 shows that deutans and protans with a RG threshold of less than 7 and 10 CAD units, respectively, perform the TL simulator test as well as normal trichromats, when required to name correctly each of the three lights used within the tunnel from an approach distance of 110m. When the approach distance is increased to 220m, the pass / fail limits for deutan and protan subjects have to be adjusted to 3 and 9 CAD units, respectively. These limits ensure that deutan and protan subjects continue to perform as well as normal trichromats from the larger approach distance of 220m (see Figs. 29, 30).

Using the proposed pass and fail limits of 7 and 10 RG CAD threshold units, for deutans and protans, respectively, 20 out of 38 deutans (Fig. 32) and 10 out of 28 protans (Fig. 33) pass the TL simulator test from an approach distance of 110m. Four deutan and three protan subjects with RG thresholds larger than the proposed safe limits also pass the TLT, but these subjects exhibit poor, overall chromatic sensitivity. 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 colour vision tests). 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 have greater difficulty with other 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 vision. Fig. 31 shows that the very few subjects that pass the TL test with CAD threshold limits greater than 7 (deutan) and 10 (protan) units have very 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 ~ 0.6 (protans).

For an approach distance of 220m (Fig. 32), the limit of <2.5 CAD SN units reveals that only three deutans would be classed as safe to drive trains, while twelve subjects that have passed the TL test would be classed as unsafe using these limits. For protans (Fig. 33) the results for 220m are similar to 110m. Instead of 7 being classed as safe to drive trains, five pass and four are classed as unsafe despite passing the TL test.

The analysis shown graphically in Fig. 32 and 33 reveals that for an approach distance of 110m, 42% of subjects with deutan-like deficiency and 25% of subjects with protan-like deficiency would be classed as safe to operate a train under the new proposed pass / fail limits of < 7 and < 10 CAD SN units, respectively. If the limits of < 2.5 and < 9 for deutans and protans, respectively were applied, 8% of deutans and 18% of protans would be classed as safe to operate trains.

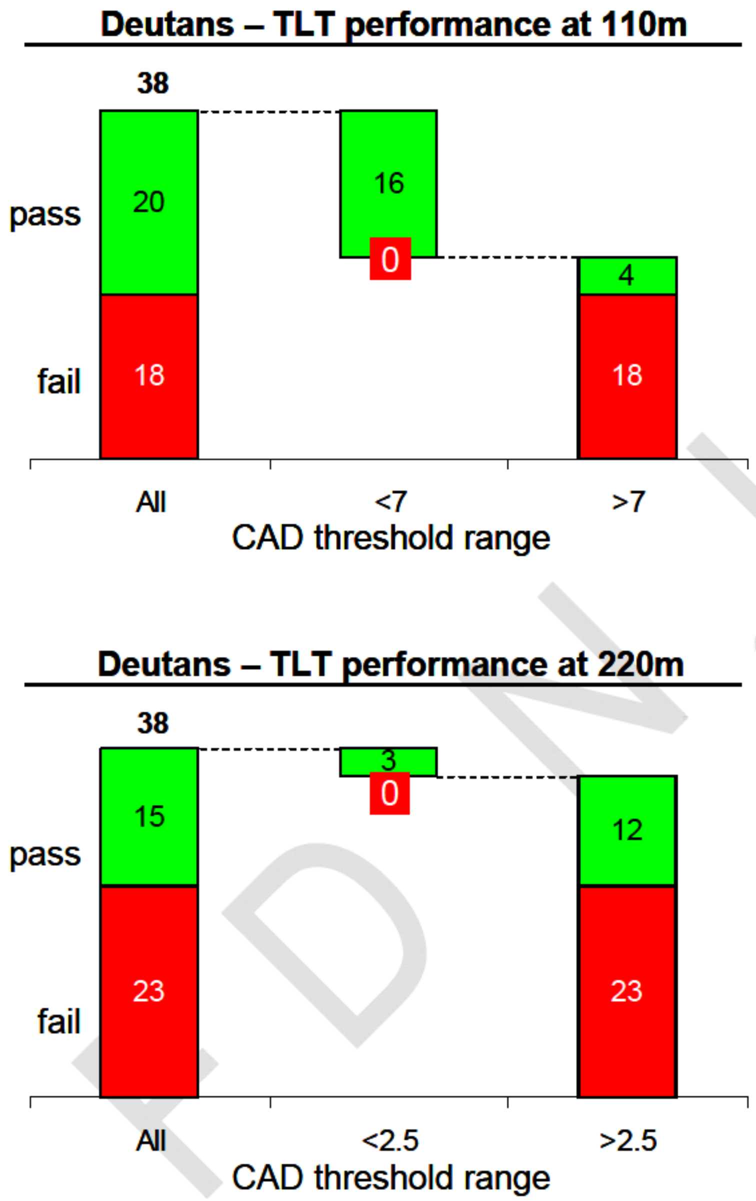


Figure 32: Summary of pass / fail outcome for deutan subjects based on a pass/fail criteria of 7 CAD threshold units; 110m (top section), and 2.5 CAD units; 220m (bottom section).

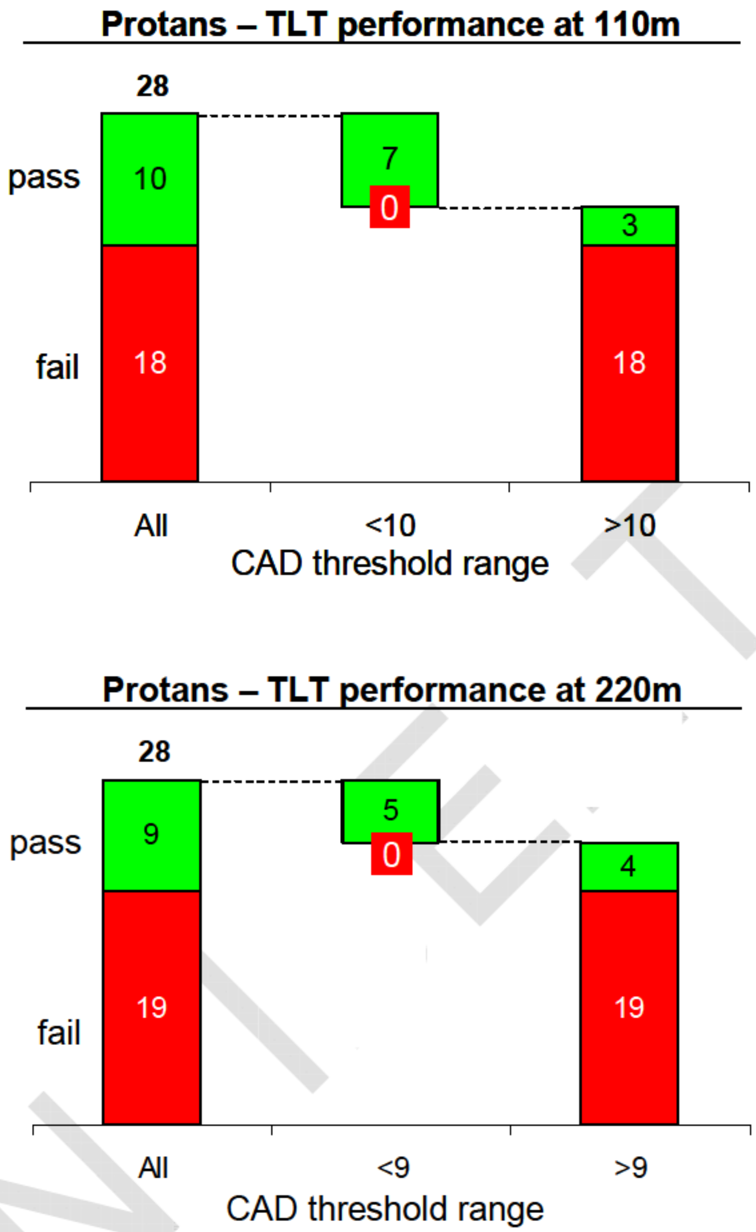


Figure 33: Summary of pass / fail outcome based on the proposed pass/fail criteria of 10 CAD threshold units (top section) and 9 units (bottom section).

The analysis shown graphically in Fig. 32 and 33 reveals that for an approach distance of 110m, 42% of subjects with deutan-like deficiency and 25% of subjects with protan-like deficiency would be classed as safe to operate a train under the new proposed pass / fail limits of < 7 and < 10 CAD SN units, respectively. If the limits of < 2.5 and < 9 for deutans and protans, respectively were applied, 8% of deutans and 18% of protans would be classed as safe to operate trains.

401 colour deficient observers have so far been examined on the CAD test as part of this as well as other ongoing studies. 269 of these subjects had deutan and the remaining 132 had protan deficiencies. If the proposed limits of 7 and 10 SN CAD units for deutan and protan subjects, respectively, were applied to this larger group, **45.7**% of deutans and **22.0**% of protans would pass. These findings suggest that ~ 40% of the total number of colour deficient subjects investigated should be classed as safe to operate trains. If the proposed limits of 2.5 and 9 SN CAD units for deutan and protan subjects, respectively, were applied to this larger group, **8.9**% of deutans and **18.2**% of protans would pass. The percentages shown above are similar to those estimated from the smaller number of colour deficient subjects (n=106) that participated in the LU study. These findings suggest that for the CAD limits proposed for 110m, ~38% of the total number of colour deficient subjects investigated would be classed as safe to operate trains, while the limits suggested for 220m would reduce this number to 11%.

In this investigation we also examined how well normal trichromats and colour deficient subjects perform if all signal colours (i.e., red, green, yellow, white and blue) were used under the very unfavourable viewing conditions inside the tunnel. The results for all five signal colours are shown in Appendix 1 together with a breakdown of the number and type of colour confusions made within each subject group. Normal trichromats make some errors that involve mostly confusions of green and blue lights. Deutan and protan subjects confuse more colours particularly whites with greens and yellows. The approach distance also affects significantly the outcome of the TL test. Normal trichromats, for example, make some errors for an approach distance of 220m, but name correctly all the colours from an approach distance of 110m. If colour deficient observers were required to perform with the same accuracy as normal trichromats, the pass / fail limits become more stringent (see table below). For the larger approach distance of 220m, all deutan and protan observers fail to match the performance of normal trichromats. When the approach distance is reduced to 110m, deutan subjects with CAD thresholds less than 2.5 SN units perform as well as normal trichromats. Protan subjects also require virtually normal colour vision with CAD thresholds less than 4 SN units.

The proposed pass / fail limits are therefore specific for the demanding, colour-related task within the tunnel when only red, green and yellow lights are involved.

The proposed limits ensure that the subjects that are certified as safe perform the TL 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

I. Analysis based on different pass / fail criteria for the Ishihara test

The following table lists the accepted distribution of various classes of colour deficiency amongst Caucasian subjects that make up ~ 8% of the male population (Sharpe et al., 1999).

Accepted Prevalence of Color 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		
41 out of 205 normal trichromats fail the Ishihara test (no errors)*	% fail	20
0 out of 205 normal trichromats fail the Ishihara test (<= 3 errors)†	% fail	0
% deutan-like subjects that fail the Ishihara test (no errors)	% fail	99.3
% deutan-like subjects that fail the Ishihara test (<= 3 errors)	% fail	92.6
% deutan-like subjects that fail the Ishihara test (<= 7 errors)	% fail	84.8
% protan-like subjects that fail the Ishihara test (no errors)	% fail	100.0
% protan-like subjects that fail the Ishihara test (<= 3 errors)	% fail	98.1
% protan-like subjects that fail the Ishihara test (<= 7 errors)	% fail	96.8

*Results based on strict pass criteria for Ishihara test (no errors, no misreadings)

†Results based on allowing up to 3 errors as the pass criteria for Ishihara test

Table 1: Percentage of colour deficient observers that fail Ishihara for different pass / fail criteria.

As part of ongoing studies at the AVRC, 205 normal trichromats and 401 (269 deutans and 132 protans) have been investigated using the Ishihara 38-plate editions.

The data in Table 2 predicts the percentage of colour deficient and normal subjects likely to pass the Ishihara plate (1-24 plates) if no errors, less than three or less than seven errors were allowed. If the requirements are no errors on the Ishihara test ~ 15% of normals would fail and no colour deficient subject would pass. If less than three errors or seven errors were permitted, all normals, and 6.1% and 12.2% of colour deficient subjects would pass, respectively.

Predicted outcome per 1000 applicants using current assessment methods				
Applicants	**1000**	**No. that pass Ishihara (0 errors)**	**No. that pass Ishihara (<= 3 errors)**	**No. that pass Ishihara (<= 7 errors)**
Normals	920	736	920	920
Deutans	60	0	4	9
Protans	20	0	0	1
Total	**1000**	**736**	**925**	**930**
% of normals subject that fail (with no errors) =				**20**
% of total colour deficient subjects that pass (with no errors) =				**0**
% of total colour deficient subjects that pass (with <= 3 errors) =				**6.07**
% of total colour deficient subjects that pass (with <= 7 errors) =				**12.24**

Table 2: Predicted outcome per thousand applicants using the different pass / fail criteria of the Ishihara plate test.

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 drive***
Normals	920	920	0	920
Deutans	60	0	33	27
Protans	20	0	16	4
Total	**1000**	**920**	**48**	**952**

% of of deutan colour deficients that pass =	**46**
% of protan colour deficients that pass =	**22**
% of of total colour deficient subjects that pass =	**40**

** % deutan subjects that pass CAD (pass < 7 SNU) =	45.72
** % protan subjects that pass CAD (pass < 10 SNU) =	21.97

Table 3: Predicted outcome per thousand applicants using the new, CAD based pass / fail limits for 110m.

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 drive***
Normals	920	920	0	920
Deutans	60	0	55	5
Protans	20	0	16	4
Total	**1000**	**920**	**71**	**929**

% of of deutan colour deficients that pass =	**9**
% of protan colour deficients that pass =	**18**
% of of total colour deficient subjects that pass =	**11**

** % deutan subjects that pass CAD (pass < 2.5 SNU) =	8.90
** % protan subjects that pass CAD (pass < 9 SNU) =	18.20

Table 4: Predicted outcome per thousand applicants using the new, CAD based pass / fail limits for 220m.

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 for an approach distance of 110m. The analysis in Table 3 shows that 46% of deutan and 22% of protan subjects meet the pass / fail criteria established experimentally and can therefore be classed as safe to drive. Given the higher prevalence of deutan subjects within the male population, these findings suggest that 40% all colour deficient subjects pass the new guidelines and would therefore be classed as safe to operate trains on the LU network.

Table 4 shows the predicted outcome based on the findings of this study for an approach distance of 220m. The analysis of Table 4 shows that 9% of deutans and 18% of protan subjects can therefore be classed as safe. This thus suggests that 11% of all colour deficient subjects pass the new guidelines.

5. Conclusions

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 train drivers. The current range of colour vision testing methods and lack of an adequate standard demonstrates the need to adopt more objective assessment techniques and to set minimum colour vision requirements that are both safe and fair to the applicants.

The Railway Safety guidelines are open to interpretation and consequently the number of applicants classed as safe to drive trains may vary from passing 12.2% of colour deficient subjects to failing 20% of normals (see Table 2). Further, the applicants that pass could go on to fail the TL task. Equally important, a large percentage of colour deficients that can carry out the safety-critical, colour-related tasks fail the Ishihara and are therefore unfairly disadvantaged. The Ishihara test provides only a rough indication of the severity of colour vision loss and the pass / fail limits have not been validated against the TL task. The Farnsworth D15 or CU tests produce groupings of colour vision deficient subjects that do not correlate well with the TL task. The results also show that one cannot treat as equivalent and hence have the same minimum colour vision requirements for subjects with deutan- and protan-like deficiency.

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 sensitivity is greater in protanomalous than deuteranomalous observers
- Below 60 years of age, normal aging does not affect significantly either RG or YB thresholds provided adequate levels of ambient illumination are employed
- Comparison between the TL test and CAD tests shows that deutan subjects with CAD thresholds < 7 SN units and protan subjects with CAD thresholds < 10 SN units can perform the TL test as well as normal trichromats
- A small number of deutan and protan observers with thresholds higher than 7 and 10 SN units, respectively, passed the TL 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 train drivers ~ 40% of colour deficient applicants would be classed as safe to drive.

6. Appendix

This section describes the results of the analysis obtained if one were to employ all five signal colours (red, green, yellow, blue and white) within the tunnel. The following graphs show how normal, deutan and protan subjects with known CAD thresholds perform the TL test under such conditions.

Normal trichromats make few errors from 220m and no errors from 110m (see Fig. 34b) White is sometimes confused with yellow, green can be confused with blue and blue is occasionally confused with green (see Fig. 34a). In total, normal trichromats made six errors which represent only 0.26% of the total number of presentations.

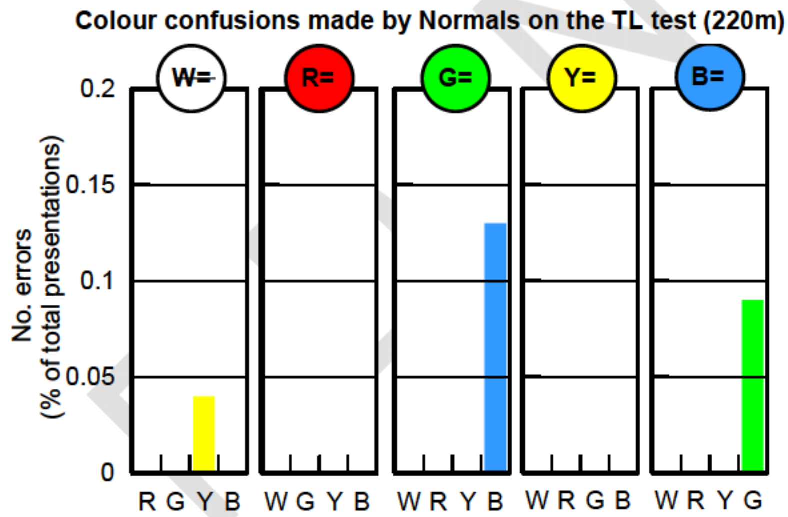


Figure 34: caption on next page.

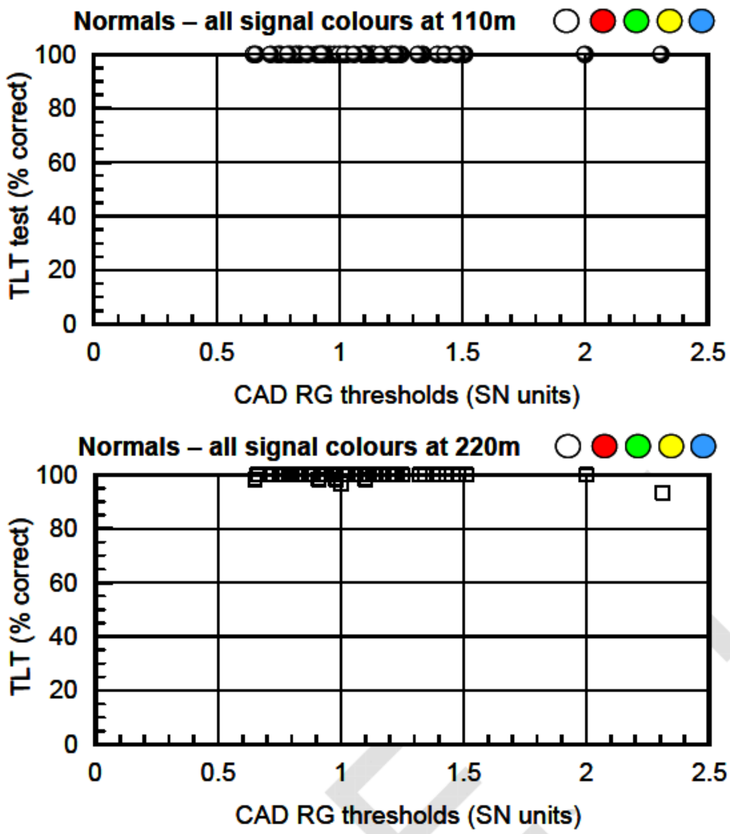
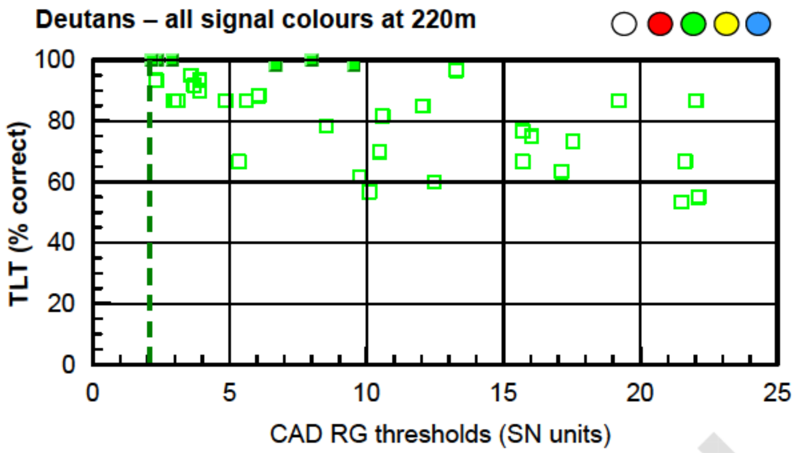


Figure 34: (a)Type and number of errors made by normal trichromats. There were six errors in total and these represent only 0.26% of all presentations when viewed from an approach distance of 220m. (b) Performance of normal observers on the TL test from 110m (top) and 220m (bottom) when all five signal colours are used.

Figs. 35 and 36 show the % correct scores for deutan and protan subjects when required to name correctly all signal colours (i.e., R, G, W, Y and B) plotted against the subject's CAD threshold in SN CAD units. The majority of deutan subjects make some errors from both 220m and 110m. The results suggest that only normal trichromats can carry out this task from an approach distance of 220 m (i.e., subjects with CAD red/green thresholds less than 1.6 SN units), although the pass limit can be increased to 2.5 SN units when the approach distance is decreased to 110m. A score of 98% or higher was considered a pass at 220m (in line with the small number of errors normal trichromats also make from 220m).



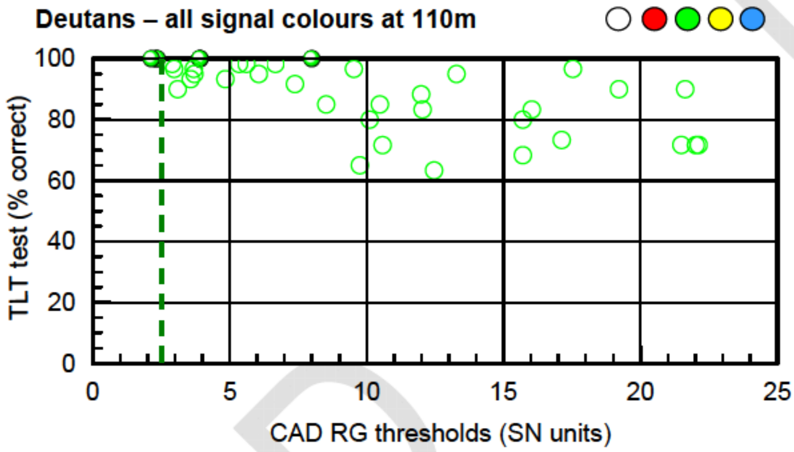


Figure 35: Performance of deutan observers on the TL test from 220m and 110m when all five signal colours are used. The filled symbols are subjects that obtained < 98% (top) and 100% (bottom), i.e., the measured performance scores of normal trichromats, from 220 and 110 m, respectively.

Only two protans performed the same as normal trichromats from 110 m (see bottom section in Fig. 36, filled symbols). However, the RG thresholds of these observers are relatively high and this suggests poor overall RG chromatic sensitivity.

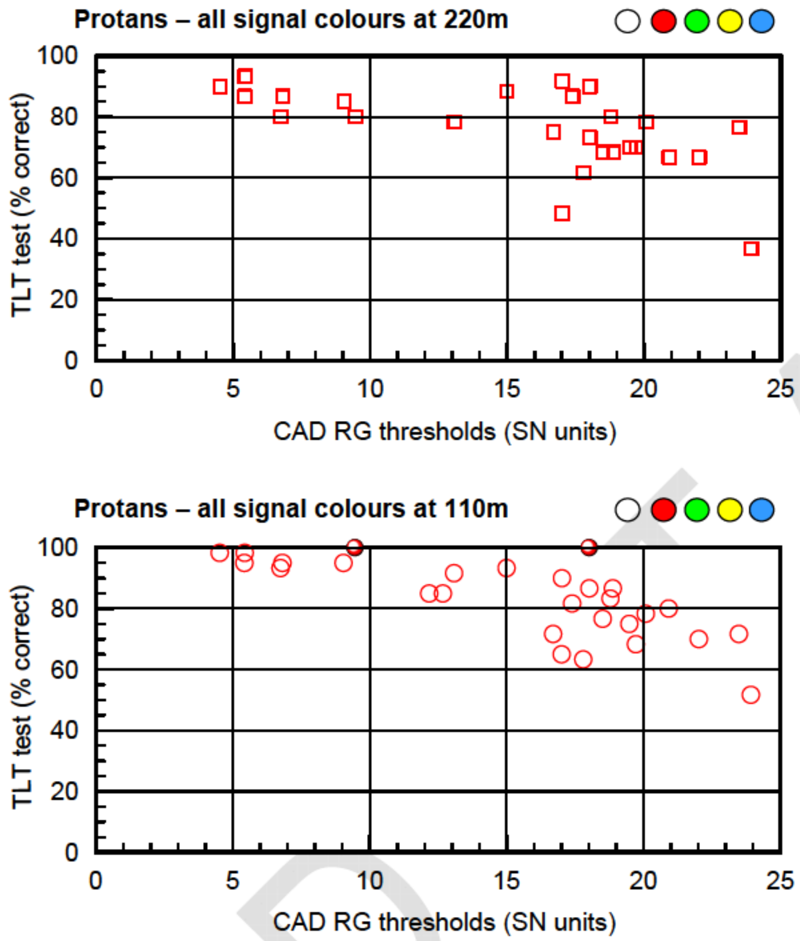


Figure 36: Performance of protan observers on the TL test from 220 m and 110 m when the test requires discrimination of all signal colours. The filled symbols are subjects that obtained < 98% correct (top section) and 100% (bottom section), i.e., performance levels measured in normal trichromats from 220 and 110 m, respectively.

The most commonly confused signal colours in the case of deutan subjects involve the white which is reported as green or yellow, green that is reported as white and yellow that is often reported as red (see Fig. 37). In total, deutan subjects made 324 errors from 220m and 202 errors from 110m. This is equivalent to 16.9% and 10.5% of the total number of presentations, respectively.

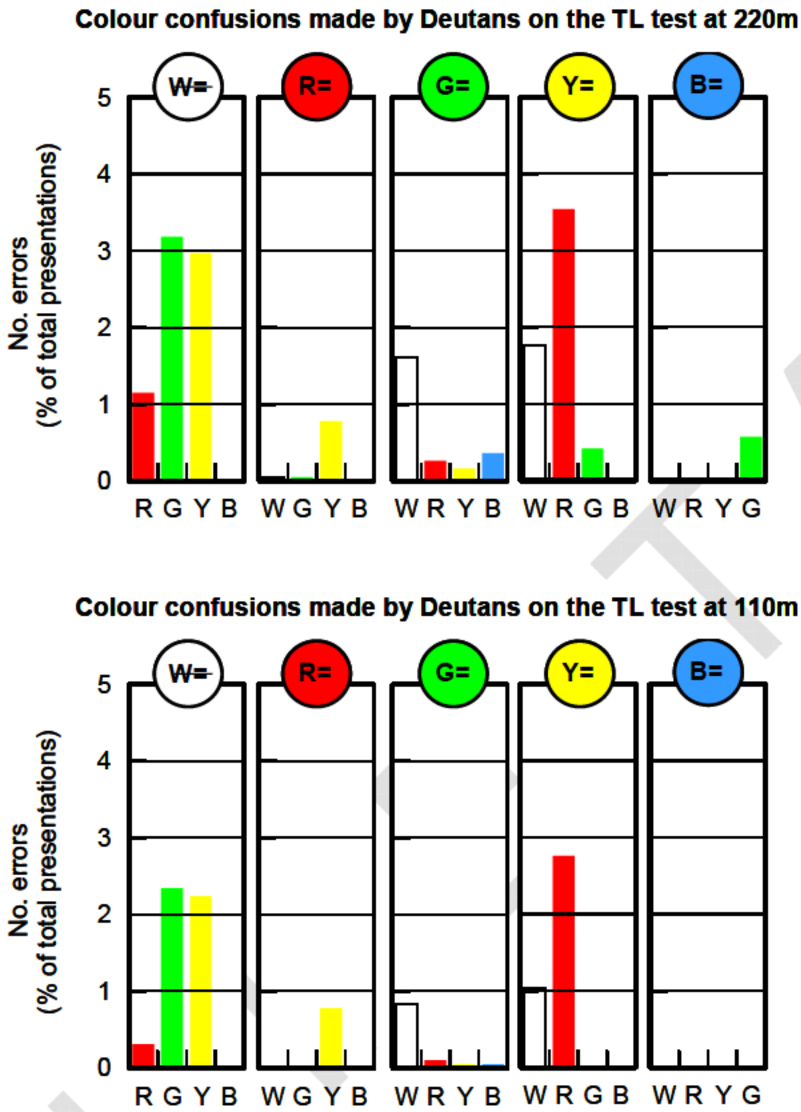


Figure 37: Type and number of errors made by deutan subjects. In total, deutan subjects made 324 errors (16.9%) from 220m and 202 errors (10.5%) from 110m.

The most common errors made by protan subjects involve confusion of white with green and yellow and green with white. In total, protan subjects made 326 errors from 220m and 280 errors from 110m. These percentages represent 19.4% and 16.7% of the total number of presentations, respectively.

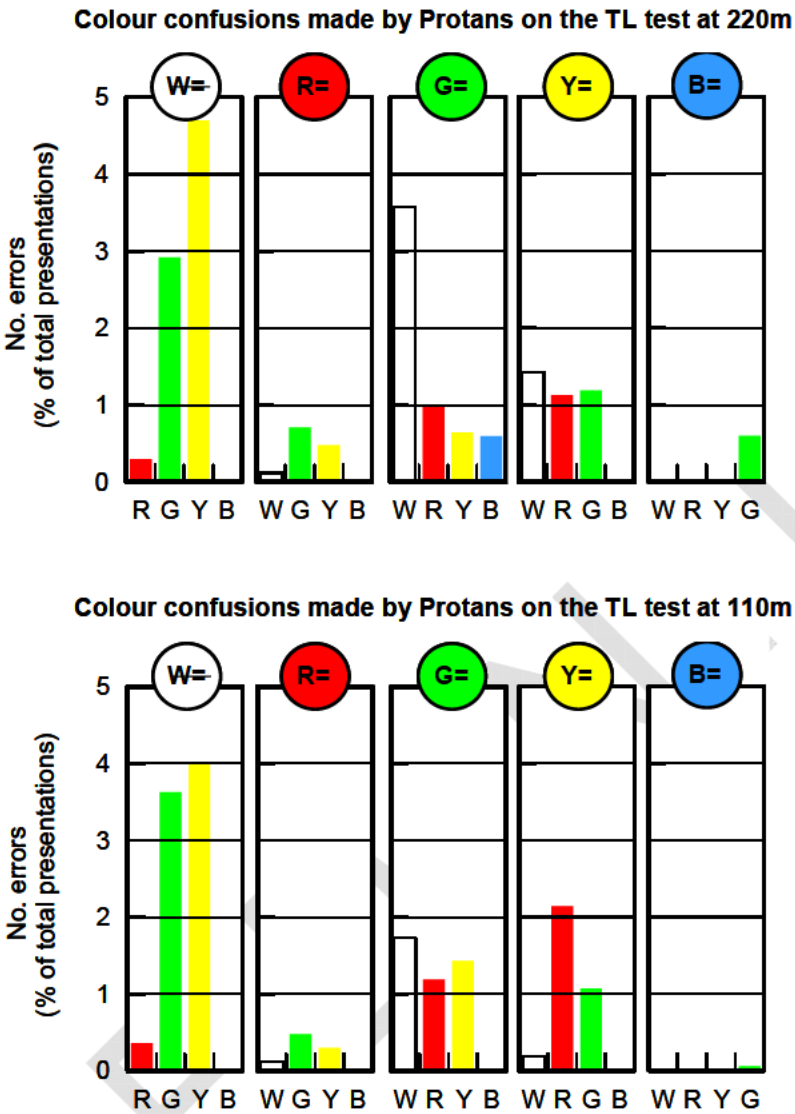


Figure 38: Type and number of errors made by protan subjects. In total, protans made 326 errors (19.4%) from 220m and 280 errors (16.7%) from 110m.

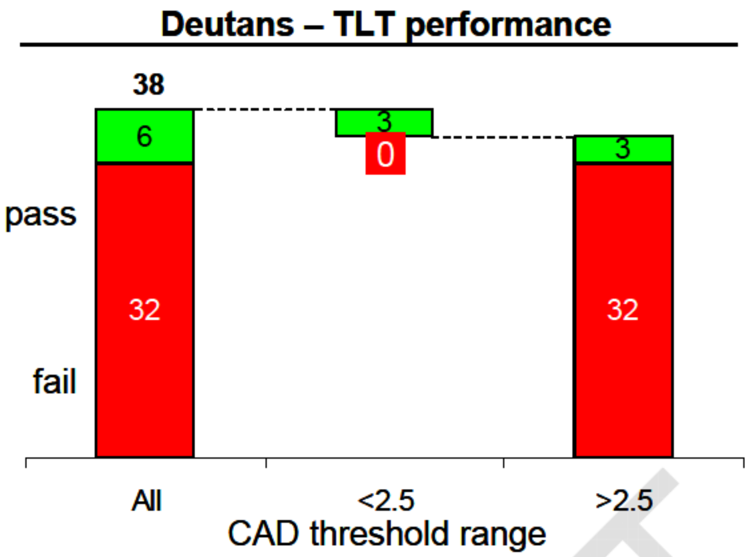


Figure 39: Summary of results for deutan subjects (when all signal colours are employed) for the proposed pass/fail criteria of 2.5 SN CAD units and an approach distance of 110m. All protan subjects perform worse than normal trichromats from both 110m and 220m.

In summary, if all signal colours were employed in the tunnel, almost all colour deficient subjects perform worse than normal trichromats from both 220m and 110m approach distances. Normal trichromacy would therefore be required.

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Philip Wanogho	-	New SQEM JNP
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Liz Daly		
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