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The handicap of abnormal colour vision

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All people with abnormal colour vision, except for a few mildly affected deuteranomals, report that they experience problems with colour in everyday life and at work. Contemporary society presents them with increasing problems because colour is now so widely used in printed materials and in computer displays. Equal opportunity law gives them protection against unfair discrimination in employment, so a decision to exclude a person from employment on the grounds of abnormal colour vision must now be well supported by good evidence and sound argument. This paper reviews the investigations that have contributed to understanding the nature and consequences of the problems they have.

All those with abnormal colour vision are at a disadvantage with comparative colour tasks that involve precise matching of colours or discrimination of fine colour differences either because of their loss of colour discrimination or anomalous perception of metamers. The majority have problems when colour is used to code information, in man-made colour codes and in naturally occurring colour codes that signal ripeness of fruit, freshness of meat or illness. They can be denied the benefit of colour to mark out objects and organise complex visual displays. They may be unreliable when a colour name is used as an identifier. They are slower and less successful in search when colour is an attribute of the target object or is used to organise the visual display. Because those with the more severe forms of abnormal colour vision perceive a very limited gamut of colours, they are at a disadvantage in the pursuit and appreciation of those forms of art that use colour.

Key words: abnormal colour vision, colour blindness, colour codes, conspicuity, equal opportunity, signal lights, VDUs, visual search

I have written on this subject on two previous occasions, once 30 years ago[1] and on the second occasion, 10 years ago.[2] Over these three decades, there have been two important changes to the social environment that impact on those with abnormal colour vision.

The first is technological change. The advent of inexpensive colour printing and the universal adoption of colour computer monitors enable colour to be more widely used for coding information and organising complex visual displays. People with abnormal colour vision now encounter coloured stimuli much more often than in the past. Air traffic controllers now work with colour-coded computer screens rather than black and green radar displays, and airline pilots now place reliance on colour-coded electronic flight instrument displays as well as signal lights. Rail signal controllers no longer pull switch levers and peer out of signal boxes but work with computer displays of the rail network colour coded to show line occupancy. It is now commonplace for manufacturing processes and power and communication networks to be monitored and controlled by coloured visual displays.

The ubiquitous use of colour coding is illustrated by the enquiry I had from a major bank that produces regular reports on the economy for its customers. It sought advice on the use of colour in their graphs of financial performance because a customer with abnormal colour vision had complained of his inability to distinguish colour-coded data sets in their graphs.

The second change is social: the emergence of equal opportunity law. In the past, employers could exclude applicants with abnormal colour vision with little risk that the exclusions would be challenged. Today employers have to be prepared to convince an equal opportunity tribunal that such exclusion is not unlawful discrimination. Discrimination means treating a person with a disability less favourably than a person without the disability.[3] Discrimination is allowable only if it can be shown that the prospective employee could not perform the genuine and reasonable requirements of the employment because of the impairment and that it is not possible to provide special facilities to assist them to do the job.

Discrimination is also allowed to protect the health and safety of employees or the public generally. Equal opportunity tribunals provide the means by which people with abnormal colour vision can challenge their exclusion from employment and employers have to be able to provide convincing evidence to justify refusal to employ a person on the basis of abnormal colour vision.

This is not entirely new. Nearly 100 years ago, in 1905, a British seaman, Mr Trattles, appealed against his failure to be granted a First Mate's Certificate because of his abnormal colour vision.[4] The trouble was that he sometimes passed the Holmgren Wool Test, the test used at the time for testing the colour vision of mariners, and sometimes failed it. His appeal gained publicity in Lloyd's *Gazette* and was even debated in the UK House of Lords. He was given a practical test identifying the signal lights on the Thames River and finally in 1909, he was granted his First Mate's Certificate. Soon after the Holmgren Wool Test was replaced by a lantern test.[5]

There were not many people with abnormal colour vision who were as persistent as Mr Trattles until equal opportunity legislation provided a formalised basis for appeal. The extent to which abnormal colour vision may impede the ability to do a particular job or present a risk to public safety has been vigorously argued on a number of occasions before equal opportunity tribunals over the past 15 years.[6-9]

The tribunals often struggle to understand the technicalities of colour vision and the evidence of mistakes and accidents caused by abnormal colour vision is not as extensive or as rigorous as might be desirable. The colour blind appellants testify that they have no problems with colour because, they say, colour is not important or because they use other cues. Expert opinion tendered to tribunals is often divided and sometimes not especially expert. Balancing the rights of the individual with colour vision impairment against the risk to the employer of economic loss and to public safety has often led to compromise. As a consequence, existing colour vision standards have sometimes been weakened or abandoned.

For example, in Australia, pilots with abnormal colour vision who are unable to recognise the colours of signal lights, as shown by failing the Farnsworth lantern test, can hold a student, private or commercial pilot's licence and may be permitted to fly at night (in Australian airspace) in a radio-equipped aircraft. They may also be able to hold a senior commercial pilot's licence subject to passing an unvalidated practical test.[10] More recently, the Australian National Road Transport Commission abandoned its colour vision requirements for commercial drivers.[11]

This paper reviews the nature and extent of the handicap caused by abnormal colour vision at work and in everyday life and may help optometrists counsel patients who have abnormal colour vision. In addition, it briefly summarises the evidence that bears on the risks to public safety that arise from abnormal colour vision.

WHAT DO COLOUR VISION DEFICIENT PEOPLE SAY ABOUT THEIR PROBLEMS?

A good starting point for understanding the handicap of abnormal colour vision is to ask those who have a colour vision deficiency about their experiences and problems with colour.

More than 200 years ago, in 1794, John Dalton gave his famous lecture[12] describing his own abnormal colour vision. Being a good scientist, he was meticulous in his observations of how colours appeared to him under various lighting conditions and he sought and reported the observations of a number of others who were similarly affected.

Over the next 200 years, we became preoccupied exploring the nature of abnormal colour vision by psychophysical and neurophysiological investigation and paid scant attention to finding out about the everyday experiences of those affected. We stopped talking and listening to people with abnormal colour vision. Presumably, it was thought that subjective reports from people who have never experienced the full gamut of colours were too qualitative and unreliable compared to the data to be obtained from colour matching experiments and recording neural responses. Most of the studies of the personal everyday experiences of the colour deficient were very limited in scope and sample size[13,14] or not fully published in the open literature.[15,16]

Judy Steward and I endeavoured to rectify this. We interviewed 102 people with defective colour vision who were consecutively presenting patients for optometric examination.[17] The interviews were structured by a set of 33 questions that directed a discursive interview. A difficulty with colour was recorded only if the discursive discussion showed it was a significant and regularly occurring problem. The same questionnaire was given to an equal number of consecutively presenting patients with normal colour vision, who rarely reported any problems with colour.

Figure 1 is derived from the data of Steward and Cole[17] and shows the proportion of colour deficient subjects who reported

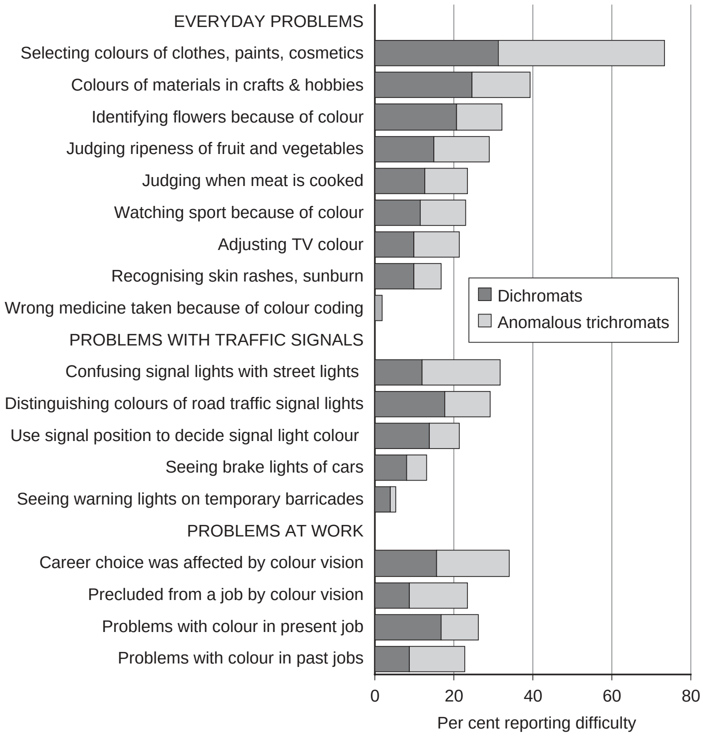

Figure 1. Percentage of people (n = 102) with abnormal colour vision reporting particular difficulties with colour. Data from Steward and Cole.[17] The percentages given by Steward and Cole have been weighted in proportion to the relative numbers of dichromats and anomalous trichromats. The control group with normal colour vision reported none of these difficulties except two per cent reported sometimes confusing road traffic signals with street lights.

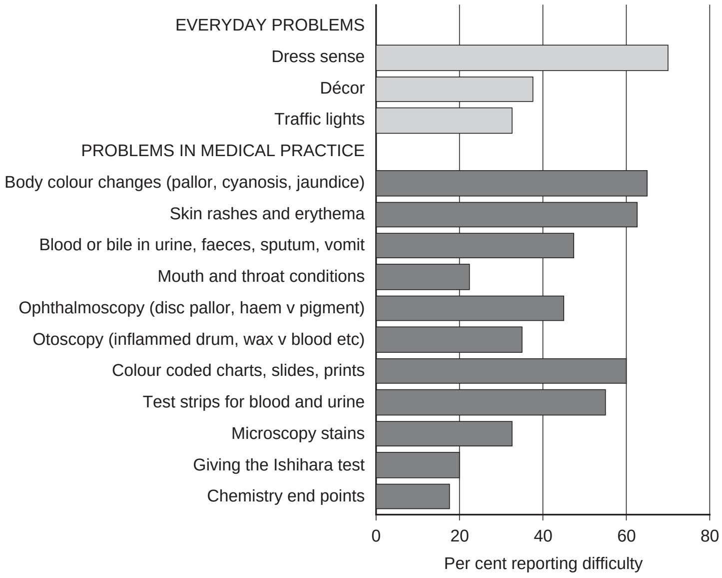

Figure 2. Percentage of medical practitioners (n = 40) who have difficulty with observational tasks in medical practice and everyday life. Data from Spalding.[19,20]

various kinds of everyday problems with colour. Only seven of our 102 colour vision deficient subjects, all deuteranomals, reported no problems with colour and nine reported only one difficulty: most reported three to seven different kinds of difficulty with colour in everyday life or at work.[18]

Spalding[19,29] made a similar study of medical practitioners with abnormal colour vision. He recruited 40 medical practitioners with abnormal colour vision who completed a questionnaire about the difficulties with colour they experienced in their practice of medicine. They were also asked some questions about their everyday difficulties. Four (10 per cent) reported no difficulties with colour but the remainder reported a great number and diversity of problems. These are summarised in Figure 2.

These two surveys of the personal experiences of people with defective colour vision show that all but seven to 10 per cent have significant problems with colour in their everyday life and at work. Those who experience no problems are likely to be mild deuteranomals. The number of problems experienced is roughly related to the severity of their colour vision defect, although clinical tests such as the anomaloscope and the Farnsworth D15 test are not perfect predictors of who will have problems and who will not.[17,19]

CLASSIFICATION OF COLOUR TASKS

Colour is of value in all sorts of ways in negotiating our way through life, from deciding whether fruit is ripe to making it easier to notice objects in a cluttered visual environment. The use of colour in everyday life and in the workplace is extraordinarily diverse.

For this reason, it is helpful to classify tasks in which colour discrimination or recognition is essential or useful into four categories.[1] These are:

Comparative colour tasks

These are tasks in which comparative judgements of colour are made to match a given colour or decide that two colours are different. Examples are in house painting and interior decoration where paints have to be mixed or coloured materials selected to match existing colours exactly. There are also colour critical jobs in the textile, paint and plastics industries where dyes have to be mixed to give an exact match to a specified colour.

Connotative colour tasks[a]

These are tasks in which colours are assigned or have acquired specific meanings, where colour is used to code information. Examples are the colours of signal lights and warning signs, colour codes on electrical components, colour end points in chemical tests, colours of fruits signalling ripeness and body colour as a sign of illness.

Denotative colour tasks[b]

These are tasks where colour is used to mark out objects or to organise complex visual displays. Examples include the identification of an object by its colour (for example, 'my car is the red one') and the use of colour in diagrams and on computer screen displays simply to differentiate elements and provide visual organisation. Colour used denotatively can often facilitate visual search[21] or be used to attract attention because coloured objects tend to stand out in complex visual environments.[22] At times, colour can be used both connotatively and denotatively as it often is in maps, graphs and computer displays, where the colour has a meaning, which may be temporary for the purpose of the particular display, and also serves to organise complex displays (for example, colour in terrain maps can serve to organise a complex display and also convey information such as height above sea level, terrain type or class of road).

Aesthetic colour tasks

These are tasks in which colour is used to create an emotional response or convey a mood. Colour is used in this way in the graphic and decorative arts but also in the design of clothing, interior décor and the built environment. Artists and designers must be able to discriminate and see colours to be able to use colour fully for aesthetic purposes, as must observers of the created object if they are to appreciate the intended aesthetic effect.

COMPARATIVE COLOUR TASKS

Every person with abnormal colour vision is handicapped in comparative colour tasks. They all have reduced colour discrimination, which will impede their ability to discern small colour differences. The loss of colour discrimination is profound for dichromats and often substantial for anomalous trichromats. Some anomalous trichromats have only a small loss of colour discrimination, however, they will make anomalous metameric matches because the action spectrum of one of their cone photopigments is anomalous. This means they will tend to make matches that are not acceptable to a person with normal colour vision.

All people with abnormal colour vision, regardless of the severity of their defect, should be counselled about the difficulties they will encounter in colour matching tasks and they should be advised not to pursue any career in which precise colour matching or the discrimination of fine colour differences is important. Employers are well justified in refusing employment to all persons with abnormal colour vision in manufacturing jobs that require colours to be matched exactly.

There are some occupations in which colour matching is important but the critical task arises only occasionally. House painting is one such example: the bulk of house painting is surface preparation and the application of paint premixed by the manufacturer to a standard colour specified by the owner or architect. The assistance of a co-worker can be obtained when paints have to be specially mixed on site.

Another example is dentistry: the selection of a colour for prosthetic teeth to match the patient's natural teeth is only one part of dental work, albeit a task that is important to patient satisfaction when it does occur. There are as many dentists with abnormal colour vision as in the general population and they are less able to match colours in the range of teeth colours than dentists with normal colour vision.[23-25] They make significantly more errors in matching both hue (colour) and chroma (saturation) but not value (brightness) in the range of colours of teeth.[25] Dentists with abnormal colour vision should know that they have a colour vision impairment and should be advised to rely on the judgement of their dental assistants when selecting prosthetic teeth shades, provided of course that their assistant does not also have abnormal colour vision.

CONNOTATIVE COLOUR TASKS

Signal lights

About 150 years ago, George Wilson[26] was the first to draw attention to the high prevalence of abnormal colour vision and its consequences for safety in maritime and rail transport because of failure to recognise the colours of signal lights. Testing of colour vision for seafarers and railmen was introduced in the 1870s[27] and lantern tests that simulated signal lights were brought into use from the 1890s.[5]

There is little question that most people with abnormal colour vision make errors recognising the colours of signal lights. Figure 3 shows the colour domains recommended by the CIE for signal lights[28] and selected confusion loci for protanopes and deuteranopes to show the signal colours they are likely to confuse. Anomalous trichromats will tend to make the same confusions if their loss of colour discrimination is sufficiently great.

Almost all people with abnormal colour vision (98 per cent) fail the Holmes Wright Type B lantern test, which simulates red, green and white ships' navigation lights viewed from a distance of 1.5 nautical miles, and most (83 to 87 per cent) fail the Holmes-Wright type A lantern test which presents signals that are brighter (200 μlux compared to 13 μlux) and larger (2.9 minutes of arc compared to 0.9 minutes of arc).[29,30]

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[a] Connote means to imply an additional meaning.

[b] Denote means to mark out or distinguish.

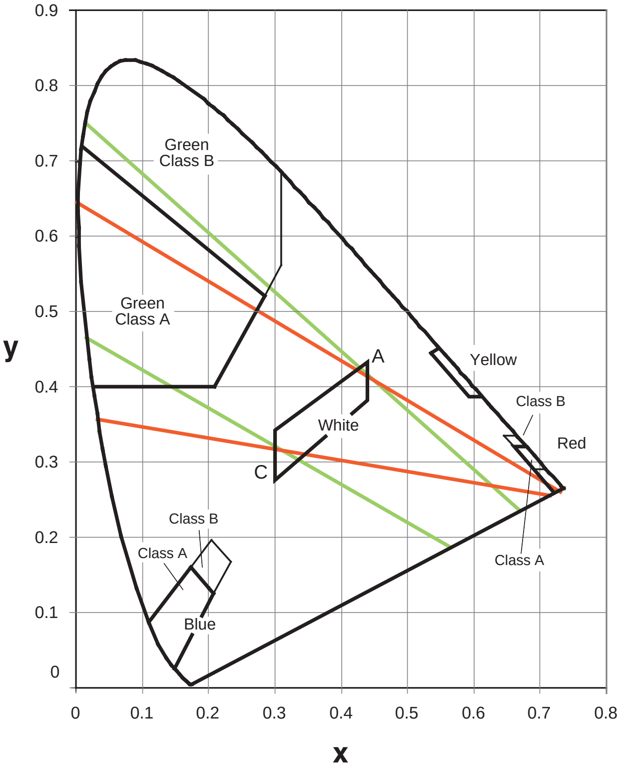

Figure 3. CIE diagram showing the chromaticity domains recommended by the CIE[28] for signal light colours and the confusion lines for protanopia (dotted line) and deuteranopia (dashed line) that pass through illuminants A and C. All colours lying on these lines look the same to dichromats. Not shown is the confusion locus common to both protanopia and deuteranopia along the red-yellow-green spectral locus, indicating that these colours are also confused. The colours with chromaticities on and between the confusion lines passing through illuminants C and A will look white (but of varying colour temperature between 6,740 K and 2,854 K) to protanopes and deuteranopes. The colours on the left of these achromatic confusion lines will look blue to them, with increasing saturation for the chromaticities closer to the spectral locus. The colours on the right of the achromatic confusion lines will look yellow, again with increasing saturation as the colours become closer to the red-yellow spectral locus. Therefore, red-green dichromats will tend to confuse red and yellow, Class B green with yellow and red and Class A green with white.

On the surface, this suggests that almost all people with abnormal colour vision are unsafe in any system that requires recognition of signal lights. However, consideration has to be given to a number of other factors, including how critical recognition of signals is to safety and whether there are other cues that can be used if signal colour is not recognised. Equal opportunity law requires that consideration be given to the magnitude of the social and economic consequences of any mistake or accident arising from failure to respond properly to signals.

MARITIME SIGNALS

Despite the advent of electronic navigational aids, such as satellite navigation and radar, recognition of coastal and harbour signal lights and ships' navigational lights is still critical to safe maritime navigation. Maritime signals can have very low illuminances, of the order of one to 10 µlux, because they often have to be recognised at long distances or seen under conditions of reduced visibility. This means that recognition of maritime signal colours can be difficult even for observers with normal colour vision.

Data from lantern tests simulating red-green-white maritime signals shows that all colour vision deficient observers with the exception of a few deuteranomals make errors recognising maritime signals.[29,30] This is confirmed by the field trial of maritime signals of Kinney, Paulson and Beare,[31] who asked subjects with normal and abnormal colour vision to name the red, green and white colours of a signal lamp flashed from ships one, two and three nautical miles from shore. The laboratory study of Vingrys and Cole[32] provides further data. Figure 4, which is based on the data of these two studies, shows that observers with abnormal colour vision make significantly more errors with red, green and white signals than colour vision normal observers and that their rate of errors increases with decreasing signal illuminance.

The Kinney, Paulson and Beare[31] data also show dramatically that protan observers may fail to see distant red signals because of their reduced sensitivity to red light due to either a lack of an L photopigment (in protanopia) or the displacement of its action spectrum to shorter wavelengths (in protanomaly). It is well documented that both protanopes and protanomals have a significantly reduced visual range for red signals.[33-38] Figure 5, which is derived from the data of Kinney, Paulson and Beare,[31] shows that protans fail to see distant red signals much more often than colour vision normal observers.

It is widely accepted that normal colour vision is essential for safe maritime navigation, especially as the social, environmental and economic costs of maritime accidents can be very high. However, a blanket exclusion of all people with abnormal colour vision could be challenged under equal opportunity law because a few people with abnormal colour vision can recognise maritime signals as well as the worst performing colour vision normal. Figure 3 in Vingrys and Cole[29] shows that five per cent of their colour abnormal observers performed as well as the 98th percentile of colour vision normal observers at the Holmes-Wright Type B lantern

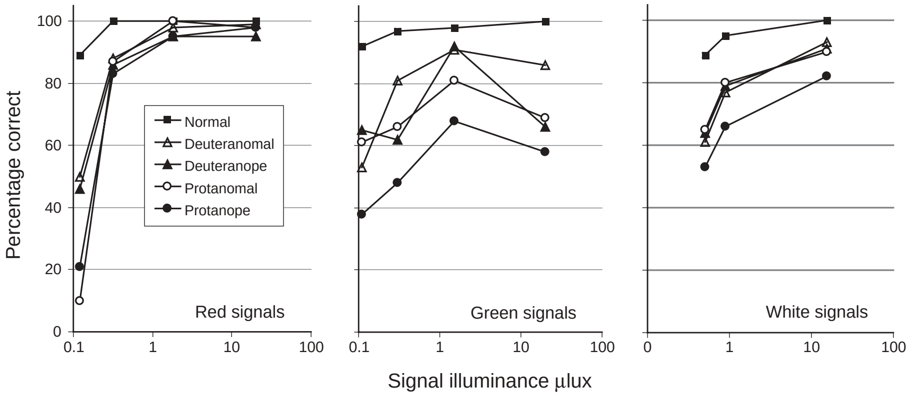

Figure 4. Percentage correct responses of colour normal observers and each class of abnormal colour vision naming red, green and white colours of maritime signal lights of varying illuminance, when the signals are viewed in the dark. The data is from Kinney, Paulson and Beare[31] and Vingrys and Cole.[32] The Kinney, Paulson and Beare investigation[31] was a field study of actual maritime signals; the Vingrys and Cole investigation[32] was conducted in the laboratory.

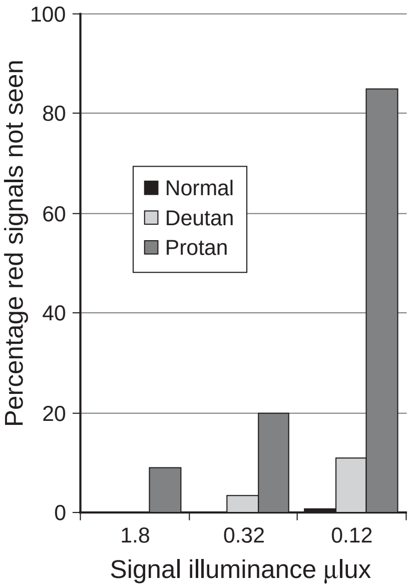

Figure 5. Percentage of red signals not seen by protan observers in the maritime field trial of Kinney, Paulson and Beare[31] as a function of the illuminance of the signal compared to deutan and normal observers. The illuminances arise from a ship's signal lamp one, two and three nautical miles to sea.

test, which simulates ships' navigation lights, while Table IV in Kinney, Paulson and Beare[31] reports that 40 per cent of deutans and 14 per cent of protans performed as well as their worst performing colour vision normal.

On this evidence blanket exclusion of all people with abnormal colour vision from maritime navigational watch-keeping occupations may be discriminatory for at least five per cent of applicants who have abnormal colour vision and possibly as many as 30 per cent. Testing to detect abnormal colour vision using the Ishihara test is simple, inexpensive, accessible and reliable, while lantern tests are not widely available and their administration is more complex and therefore more costly. The cost of providing accessible lantern testing may not be justified by the degree of discrimination involved, although it could be used as a test to adjudicate in the event of dispute.

All patients with abnormal colour vision should be counselled that they are likely to be excluded from maritime employment because of their inability to reliably recognise navigational signal lights and those with a penchant for recreational boating should be warned that they will make errors with maritime signal lights.

RAIL SIGNALS

Train drivers and other rail workers involved in the control of train movements must be able to recognise red, yellow and green signals at distances up to one kilometre, sometimes under conditions of poor visibility due to fog or rain.[39] Rail signals are observed from shorter distances than maritime signals and have higher illuminances but they are used in daylight and may have to be observed against a bright sky background. Rail signals are critical to safe operation and there is little or no redundancy.

Hovis and Oliphant[39,40] found that all but a few mild deuteranomals made more errors than the worst performing colour vision normal subject recognising simulated rail signals viewed from 0.8 km under daylight conditions. Ninety-eight per cent of the colour abnormal observers made more errors than the worst colour vision normal observer (who made six per cent errors).

They found that the Holmes-Wright Type A lantern and a specially designed lantern, the CNLAN, were reasonable predictors of who could and could not recognise rail signals as safely as colour vision normals. They also observe that the Ishihara test with a 'fail' criterion of 10 or more errors was an equally good predictor.

As with maritime navigation, the social and economic cost of a rail accident is such that rejection of all persons with abnormal colour vision from signal-critical rail occupations can be justified even though this may discriminate unfairly against two per cent of colour abnormal applicants. The Holmes Wright Type A lantern could be used as a test when rejection on the basis of failing the Ishihara test is disputed.

AVIATION SIGNALS

The primary signal colour code in aviation is red, green and white with blue and yellow as supplementary colours. Green, white and red are used to signify and delineate the threshold, lateral edges and end of runways, respectively. Centre line signals on runways may be colour coded to indicate remaining runway distance. Blue is used to delineate taxiways, sometimes with a green centre line. Red is used in airport approach signals and for single beacons warning of surrounding high points. Red, green and white are used for navigation lights on aircraft in the same way as for ships. In the event of radio failure, the control tower may use a signal gun displaying a red, green or white signal to communicate with aircraft.

A majority of observers with abnormal colour vision are unable to reliably distinguish the colours of the control tower signal gun[41] and laboratory simulations of aviation signals[42,43] show that colour deficient observers frequently make errors, even when care is taken to chose colours that are optimum for colour deficient observers.[32,43,44]

There is a high degree of redundancy in aviation. For example the layout of the runway and approach path signals delineate the direction of the approach and the shape of runways, so there are shape and orientation cues. On-board electronic navigational aids, radio contact and air traffic control reduce dependence on visual sightings. Pilots with abnormal colour vision seeking exemptions from aviation colour vision standards argue that their inability to recognise signal colours is not a safety risk because of this redundancy.[6,7] This view is supported by the experiment of McKelvey[45] who asked colour vision normal pilots to make operational decisions from colour and black and white photographs of various phases of flight. Only the control tower signal lights were shown to be critically colour dependent.

It is further argued that no one uses aircraft navigation lights to determine the direction and orientation of other aircraft, even though it a useable source of information.[46] Most pilots say they use aircraft signal lights to locate the plane and use fixity-of-bearing to decide whether it is on a collision course. The control tower signal gun, which is used in the event of radio failure, is rarely used.

There are two critical aviation signals for which abnormal colour vision may be a serious handicap. The first is the single red light designating high points near airports. First, this signal has to be seen and protans with their reduced sensitivity to red light may fail to see it and second, the red colour has to be recognised to differentiate it from extraneous street and house lights.

The second is the Precision Approach Path Indicator (PAPI), which is used at all major airports to signal the correct glide path when landing.[c] It comprises a horizontal array of four lights, two of which are red and two white, when the aircraft is on the correct glide path. When the aircraft is too high the red signals turn white and when it is too low the white signals turn red. This is illustrated in Figure 6. Clearly, correct interpretation of the PAPI is critical to safe operation and correct interpretation depends on distinguishing red and white. Cole and Maddocks[47] show that the majority of observers with abnormal colour vision make errors distinguishing red from white under conditions simulating the angular size and illuminance of a PAPI signal system viewed from one nautical mile. Some of their data is reproduced in Figure 7. On this evidence, many colour deficient observers would be unable to use the PAPI system. As expected, protans sometimes fail to see the red signals. This is shown in Figure 7b.

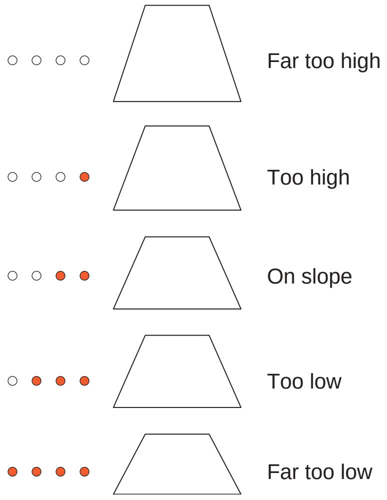

Figure 6. The Precision Approach Path Indicator (PAPI) signal array used to signal to pilots that their aircraft is above, below or on the correct glide path for landing.

Aviation accidents have high social and economic costs, especially if the accident involves large passenger aircraft. There is a high community expectation of meticulous safety standards. A high degree of redundancy in aviation operations is a key strategy in achieving very high levels of safety. If a pilot is unable to distinguish the colours of aviation signals, one element of redundancy is removed and the system becomes less safe. Two investigations[48,49] have shown that colour vision deficient pilots have more accidents, the details of which are summarised by Vingrys and Cole.[50] Pilots of aircraft should have normal colour vision or, if they do not, they should be able to demonstrate that they are able to recognise the colours of aviation signals by passing a lantern test[d] and should not be protans. The Commission Internationale de l'Éclairage[51] recommends that pilots of scheduled aircraft should be required to have normal colour vision and that commercial pilots of freight and non-scheduled passenger aircraft should pass a lantern test and not be protans.

ROAD SIGNALS

Road traffic signals are viewed from much shorter distances than are maritime, aviation or rail signals and as a consequence have very much higher illuminances in the plane of the observers' eyes. Therefore, recognition of signal colour will be easier for colour vision abnormal observers. If they experience uncertainty about signal colour they are assisted by redundant cues

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[c] It should be noted that McKelvey[45] did not include the PAPI system in his flight scenarios but used the T-VASIS approach guidance system. The T-VASIS uses a 'T'-shape coding to signal if an approach is too high or too low. Colour is used in T-VASIS only to emphasise a dangerously low approach.

[d] The Holmes Wright Type A lantern is used in the United Kingdom and the Farnsworth lantern is used in the United States and Australia. The Holmes-Wright better simulates aviation signals and fails protans. The Farnsworth lantern presents stimuli that are brighter than aviation signals and passes 40 per cent of protanomals.[29] It needs to be supplemented by a test to diagnose protan defects such as the Medmont C100 test or a spectral anomaloscope.

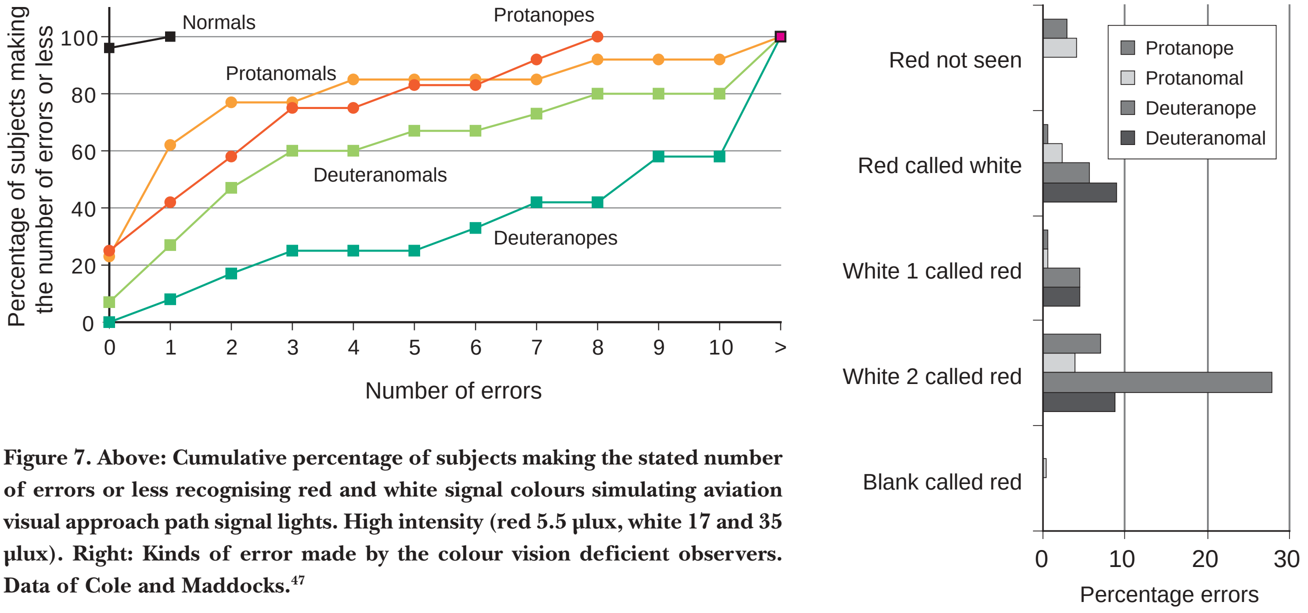

Figure 7. Above: Cumulative percentage of subjects making the stated number of errors or less recognising red and white signal colours simulating aviation visual approach path signal lights. High intensity (red 5.5 μlux, white 17 and 35 μlux). Right: Kinds of error made by the colour vision deficient observers. Data of Cole and Maddocks.[47]

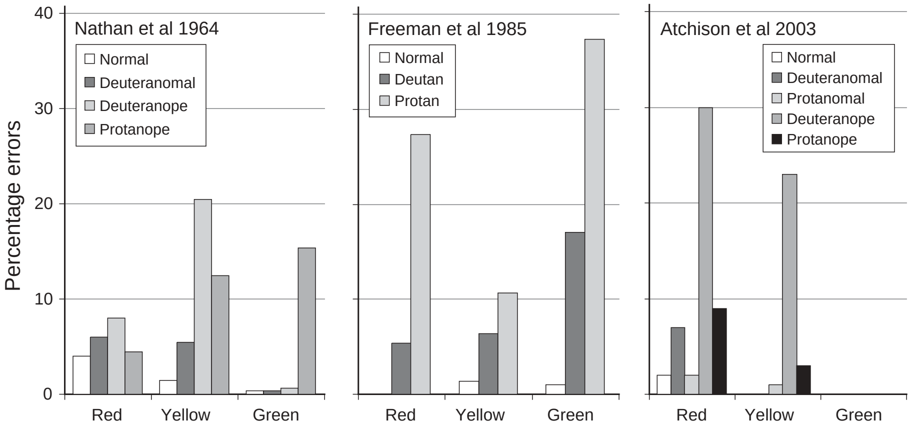

Figure 8. Average percentage errors made by various classes of colour vision subjects naming the colours of simulated road traffic signal lights as reported by three studies.[52-54]

such as the position of the illuminated signal, relative brightness and movement of other traffic. Therefore, it is not surprising that only about 30 per cent of people with abnormal colour vision report that they have problems with road traffic signals (Figures 1 and 2).

There have been three studies of errors made by people with abnormal colour vision in recognising the colours of road traffic signals.[52-54] The results of these three studies are summarised in Figure 8. They were all laboratory simulations of road traffic signals, although a field trial was conducted as part of one of the studies.[53]

There are some noteworthy differences in the results of these three road traffic signal studies, for which there are explanations.

The colour deficient subjects in the study by Atchison and colleagues[54] made no errors with the green signal, while those in the Freedman and associates’ study[53] made many errors. The reason for this difference is that Freeman and associates presented a white signal as well as red, yellow and green signals and allowed ‘white’ as a response. The errors with the green signal in that study were almost all confusions with white. In the field experiment of Freedman and associates,[53] there were no white signals and white was not an allowable response. As a consequence there were very few errors with the green signal.

The errors with the green signal for the protanopic subjects reported in the Nathan, Henry and Cole study[52] are confusions with yellow, due to their inclusion of two green signals with chromaticities toward yellow-green lying in the CIE Class B domain. Yellow-green is likely to be confused with yellow and possibly red, by those with a red-green dichromasy or severe anomalous trichromasy (Figure 3). Because modern road traffic signals almost always use CIE Class A Green, these errors are of little practical consequence. Nathan, Henry and Cole[52] and Atchison and colleagues[54] found that Class A green road traffic signals are recognised without error by all their colour deficient subjects.

Atchison and colleagues[54] found that deutans make a considerable number of errors with red and yellow signals. These are almost all errors where red is called

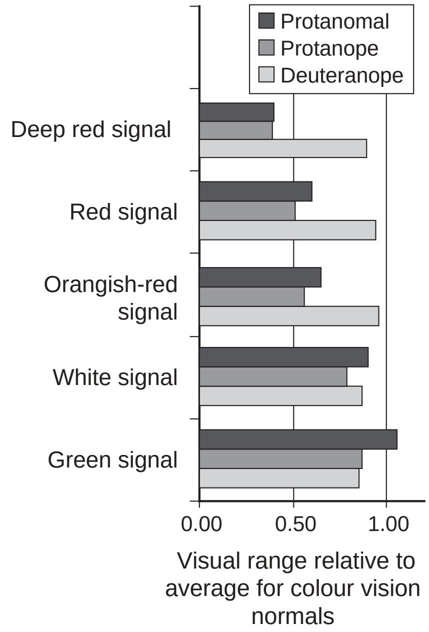

Figure 9. The visual range of red, white and green signal lights for protanomals, protanopes and deuteranopes relative to the visual range for colour vision normal observers. Data of Cole and Vingrys.[35]

'yellow' or yellow is called 'red'. This arises because the red chosen by Atchison and colleagues[54] lies in the CIE orange-red Class B domain for red signals (Figure 3), which the CIE[28] recommends should be used only when reliable recognition of red is not so important. Moreover, they used a yellow near the red boundary of yellow. Fewer errors are made when the colour of the yellow signal is toward the green boundary of yellow.[52,55]

It is evident from these three studies that colour vision deficient drivers will not often mistake the colours of road traffic signals, provided the colours are within the CIE Class A boundaries. However, those with a more severe deficiency will be uncertain and will occasionally make errors. They will also tend to confuse white lights and green signal lights as the Freedman and colleagues' study[53] shows. About 30 per cent of colour deficient people report that they have problems confusing traffic signals with street lights.[17,19]

Their uncertainty is reflected in longer reaction times. Each of the three studies of road traffic signals reported that subjects with abnormal colour vision had longer reaction times. In general, their reaction times are increased by 50 to 100 per cent but this is dependent on the colour and the likelihood of error with that colour. While the increased reaction time reflects uncertainty about the colour, it may not be of great practical significance to road safety as in theory an additional 250 to 500 ms in response time adds only four to eight metres to stopping distance at a speed of 60 km/h.

However, this uncertainty is very much reflected in a much larger reduction of the distance from the signal at which the signal colour was recognised than might be expected. Verriest and co-workers[34] had colour vision normal and abnormal subjects drive toward traffic lights and measured the distance from the signal at which they correctly named the colour. When there were three signals on the mounting post and only one illuminated, giving a positional cue, average recognition distances for both protan and deutan observers were generally 60 to 70 per cent of those of the colour normal observers. For red signals, protan observers had an average recognition distance about 50 per cent of normal. When there was only one signal displayed on the mounting post and no positional cue, recognition distances were 30 to 35 per cent of normal for both protan and deutan observers.

Protans have the additional problem of their relative insensitivity to red light so that their visual range for signals is considerably reduced.[33-35,56,57] Figure 9 shows that both protanopes and protanomals have a visual range for red signals that is 40 to 60 per cent of that for colour vision normal observers. This loss is of some practical significance. It should be noted that the ability of protanomals to see red signals is reduced as much as it is for protanopes.[35,36] Although there is variability among protans in the extent to which they have diminished ability to see red lights, all protans have a red signal visual range that is less than that of the worst observer with normal colour vision.[57]

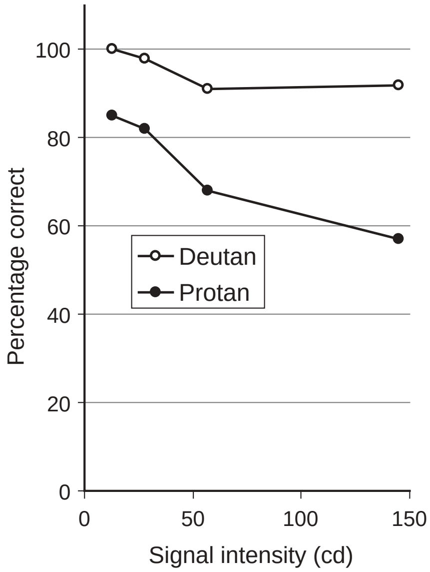

Figure 10. The effect of increasing the intensity of red signals on the chance of correct recognition of the colour. Data of Freedman and associates[53] (Table 23). Intensity has been scaled up in the figure to a 200 mm diameter signal.

Modern traffic signals have high intensity and therefore, are visible from long distances, so the protan's reduced visual range for red road traffic signals will be a serious problem only when the signal is seen against a bright sky. It will also be a problem for low intensity red signals, such as tail lights, temporary barrier lights and red retro-reflective signals.

There is a curious dilemma for protans. If red signals have too low an intensity, protans may fail to see the signal at a safe distance. If the red signal is too bright, it will be seen as yellow. Freeman and associates[53] studied the effect of signal intensity on signal light recognition and Figure 10 has been constructed from their Table 23. It shows a dramatic decline in correct recognition for red signals as signal intensity is increased. Similar results were found in their field trial. The same phenomenon was reported by Raramei, Bimler and Cavonius[58] and by Huang and colleagues.[38] This is a concern as standards for road traffic signals[59,60] call for red road traffic signals to have an intensity of at least 200 cd and the new LED signals can have much higher intensities. These intensities give protans a good chance of seeing the signal[33,53,56] but on the evidence of Freedman and associates[53] and Huang and colleagues,[56] they will have a greater chance of failing to recognise it as red.

It is reasonable to presume that drivers with abnormal colour vision have a greater risk of accident because of the chance of errors identifying signal colour, longer reaction times and for protans, their reduced visual range for red signals.

There are two studies that show that people with abnormal colour vision have a significantly higher rate of road accidents[34,61] but there are also several studies that have failed to show an association between abnormal colour vision and road accidents. For this reason there is divided opinion on whether abnormal colour vision is a risk factor for road accidents, however, the studies that failed to show an association between abnormal colour vision and road accidents had samples that were too small to give sufficient statistical power. There is a strong case that drivers with abnormal colour vision, especially those with a protan deficiency, are at greater risk of accident.[57,62]

Patients with abnormal colour vision should be counselled on the problems they are likely to encounter with road traffic signals and protans in particular should be told that they may have difficulty seeing barricade signal lights and car and bicycle retroreflectors. There is a strong case for professional drivers to be subject to a colour vision standard, as they have more exposure to risk and have more at risk because they may drive passenger vehicles, vehicles of large mass or those that carry hazardous loads. The Commission Internationale de l'Éclairage has recommended that professional drivers should pass a lantern test and not be protans.[51]

Surface colour codes

Surface colour conveys information in the natural environment, signalling things like the ripeness of fruit, the freshness of food, the changing seasons and physical illness. Surface colour is also used to convey information in man-made information systems, increasingly now that colour printing and colour computer monitors are so commonplace.

NATURALLY OCCURRING SURFACE COLOUR CODES

It is well known but only anecdotally that people with abnormal colour vision often fail to see fruits on trees or are uncertain about fruit ripeness. Indeed these kinds of abilities may have driven natural selection. Post[63] observed that the prevalence of abnormal colour vision is very low in hunter-gatherer societies, rises in settled agricultural societies and is greatest in industrial societies. Post argues for Darwinian selection, as normal colour vision is important for survival in the hunter-gatherer and not unimportant in simple agricultural societies. Trichromatic colour vision may have developed because it confers advantage in detecting ripe fruits: the colour vision of some primates is well matched to the task of detecting fruits among foliage.[64,65]

How fruits, flowers and foliage can look to people with abnormal colour vision is well illustrated by transformations of the colours of a digitised colour image to the colours seen by them.[66,67] Examples of these transformations have been published and are worth studying.[68,69]

People with abnormal colour vision often admit that they have problems seeing natural colours that convey useful information. Steward and Cole[17] report that about 30 per cent of people with abnormal colour vision said they had problems judging the ripeness of fruits, detecting flowers and judging when meat was cooked (Figure 1).

Spalding[19] reports that 40 to 60 per cent of his sample of colour deficient medical practitioners said they had problems detecting the colour signs of illness such as pallor, redness, cyanosis and jaundice (Figure 2). Campbell and co-workers[70,71] found that significantly more colour deficient doctors failed to see rashes, jaundice and the presence of blood in body products in colour photographs of medical conditions than those with normal colour vision. They were also significantly less confident than the colour normal control group when asked to rate their confidence in making judgements from the clinical photographs.[71] The difficulty colour deficient doctors have detecting blood in body fluids is confirmed by Reiss and associates[72] in a similar study using clinical photographs. Spalding[73,74] has described his own personal experiences in medical practice associated with his deuteranopia, reporting his difficulty seeing the pallor of anaemia, cyanosis and detecting blood in body products. Cockburn[75] has described his problems in optometric practice, arising from his extreme deuteranomaly, seeing redness of inflamed eyes, skin rashes and differentiating retinal pigment and haemorrhage.

The problems of medical diagnosis for physicians with abnormal colour vision have long been known. One hundred and fifty years ago, Wilson[26] reported on the problems encountered by five physicians with abnormal colour vision and 70 years ago, Tocantins and Jones[76] studied the problems of nine medical students in a class of 70, who had abnormal colour vision. Spalding[20,77] strongly recommends that the colour vision of medical students should be tested and that they should be counselled on the kinds of problems they will have in their studies and in medical practice and on how they might deal with them. This might also be desirable for optometry students.

MAN-MADE SURFACE COLOUR CODES

Although surface colour coding is most often used redundantly to reinforce a message conveyed primarily by means of alphanumeric or symbolic coding, there are some circumstances where surface colour is the only or the primary means of conveying information. An example is the colour code indicating values on resistors and capacitors. Sometimes redundant colour coding becomes the primary code because alphanumeric labelling is not discernible from long distances, which can be the case for storage containers, gas cylinders and fire extinguishers.[78]

For surface colour codes to be useable the colours must be chosen so that observers can reliably assign a name to each colour even when a colour is seen in isolation. The CIE[79] has published international recommendations for the chromaticity domains and luminance factors for nine surface colours, red, orange, yellow, green, blue, purple, white, grey and black for use in visual signalling. A 10th colour, brown, is sometimes used although the CIE recommends it be used only as a redundant code.

It might be expected that almost all observers with abnormal colour vision would be unreliable with surface colour codes because there are up to 10 colour categories. On the other hand, they are assisted by brightness differences between colours and the fact that surface colours usually present a larger surface area than signal lights.

The ability of observers with abnormal colour vision to make reliable categorical colour identification of surface colours can be tested by asking them to name colours. Cole and Orenstein[80] asked 102 subjects with abnormal colour vision and an equally-sized age-matched control group to name the colours of material, paint and cotton samples using the 10 categorical colour names. They found that about 40 per cent of their colour vision deficient subjects and two-thirds of their anomalous trichromats who passed the Farnsworth D15 test could name the colours as well as the worst performing colour vision normal subject.

Walraven and Leebeck[81] and Voke[16] found that about one-third of colour abnormal observers could name the 10 colour codes used on resistors as well as the worst performing colour normal subject. Verriest and Uvijls[82] reported that about 15 per cent of their 90 subjects with abnormal colour vision perform as well as colour vision normal observers naming the colour codes of a range of different types of resistors and capacitors. In contrast, Ricklefs and Wende[83] reported that none of their 20 colour abnormal observers could name resistor colour codes without error.

There appears to be only one study of ability of people with abnormal colour vision to identify the colours of telecommunication and electrical cables. Voke[16] found that none of her 23 anomalous trichromats made errors naming the eight colours of single telecommunication wires and 60 per cent of them made no errors selecting coloured wires to make up pairs to match sample twisted pairs. However, all the dichromats in her study made errors.

Observers with abnormal colour vision make errors naming red and black markings on flight progress strips used in air traffic control and naming the colours of boundary lines on multi-coloured terrain maps.[84-86] Mertens and Milburn[87] report that 24 per cent of their 75 anomalous trichromats could name the red and black colours of markings on flight progress strips without error under an illuminance of 59 lux. This illuminance was chosen because it was representative of illuminances in en route air traffic control centres. Of 30 dichromats, all made errors with this task except one deuteranope. Colour normal subjects made no errors.

It is clear that about 15 to 40 per cent of people with abnormal colour vision can correctly name surface colour codes, even when there are eight to 10 colour categories. Most of those who make no errors have a mild colour vision deficiency as shown by passing the D15 test or being classified as mild by the AOHRR.

However, all these studies of surface colour code recognition by people with abnormal colour vision used good illumination, of the order of 400 to 600 lux. Their colour naming performance drops sharply under lower levels of illumination. Walraven and Leebeck[81] found that at illuminances of less than 10 lux all colour abnormal subjects, including those classified as mild by the AOHRR test, made more errors than the worst colour normal subject. When Mertens and Milburn[87] tested their subjects' ability to name red and black markings on flight progress strips under an illuminance representative of the lowest level of lighting at an en route control centre (14 lux), the proportion of anomalous trichromats who could do the task without error decreased from 24 to 15 per cent.

There is no question that with a few exceptions, those with a more severe colour vision loss will make many errors recognising surface colour codes, as Figure 11 shows. While many with a mild colour defect can recognise surface colour codes reliably, they will be more prone to make errors under low levels of illumination than those with normal colour vision.

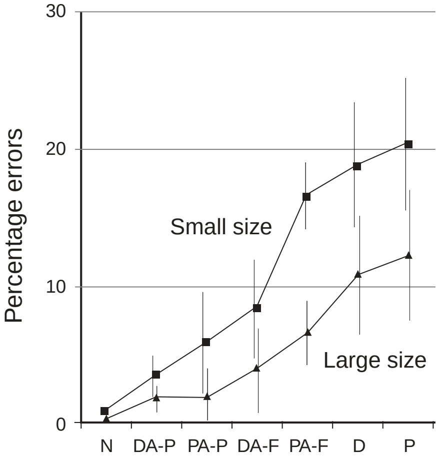

Figure 11. Mean percentage errors naming colours of materials and paints for the different classes of colour vision. The colours were red, orange, brown, yellow, green, blue, purple, black, grey and white. The large size stimuli subtended 5 to 10 degrees, the small size 0.03 to 2.5 degrees. N = normal; DA-P = deuteranomal passing the D15; PA-P = protanomal passing the D15; DA-F = deuteranomal failing the D15; PA-F = protanomal failing the D15; D = deuteranope; P = protanope. Vertical bars are standard errors. Data of Cole and Orenstein.[80]

VDU GENERATED COLOUR DISPLAYS

The advent of colour computer monitors has provided greater opportunity for surface colour coding and, because of the diversity of applications for computers and the flexibility of software, surface colour coding may be used in unforeseen ways.

Each of the RGB guns of a computer monitor can be set at one of 256 steps so that 256^3 (16,777,218) colours are possible. Web designers have agreed to a Websafe palette of 216 colours based on

Figure 12. Top: The Websafe palette of 216 colours. Middle: Transformation of the Websafe palette to the colours perceived by deuteranopes. Bottom: Transformation of the Websafe palette to the colours perceived by protanopes. © 2004 British Telecommunications plc. Reproduced with permission.

six steps of each of the RGB guns ($6^3 = 216$), so there is some constraint in the diversity of colours used. It is pleasing that there is also some awareness of the needs of users with abnormal colour vision. Programs are available to transform web page colours to simulate their appearance for dichromats,[88-90] so designers can test how they will see the colours they have chosen. Figure 12 is reproduced from the British Telecommunications plc internet site URL: http://btexact.bt.com/colours and shows the full palette of 216 Websafe colours and their appearance as seen by dichromats.

Despite this awareness of the special needs of people with abnormal colour vision, they will experience problems with VDU generated colour displays, either because too many colours are used or the designer has not taken their needs into account.

Twenty years ago, Bergman and Duijnhouwer[91] showed that subjects with abnormal colour vision made significantly more errors and were significantly slower in their responses than those with normal colour vision, naming seven colours (red, green, yellow, blue, magenta, cyan, white) generated on a computer screen.

Precipitation in weather radar displays is colour coded and may present problems to those with abnormal colour vision. Mertens and Milburn[87] found that only two per cent of protanomals could name the colours of a weather radar display without error, although 43 per cent of deuteranomals and 10 per cent of deuteranopes could. However, here is the trap: the colours in their radar display were light and dark green, light and dark yellow and light and dark red. In Australia, the colours used are light and dark blue, yellow, green, pink and red. There is no assurance that a fixed set of colours will be used in any particular VDU display, let alone that they might be chosen to give greatest assistance to users with abnormal colour vision.

The German navy introduced a sonar system with a monitor display that coded stationary objects yellow and those moving toward and away from the sonar point of reference in red and green. A significant number of sailors, those who had abnormal colour vision, could not use it satisfactorily because they could not differentiate the colours.[92] This is an example of the designers failing to consider the needs of colour deficient users or wrongly assuming that all users would have normal colour vision.

Ramaswamy and Hovis[93] in a study of VDT displays used for the control of train movements found that more than half of their 52 colour defective observers could perform as well as the 99th percentile performance of the colour normal control group in naming eight colours (red, yellow, green, blue green, blue, purple, white and grey) generated on a VDT screen. Mahon and Jacobs[94] found that observers with abnormal colour vision, except mild deutans who passed the D15, made 30 to 40 per cent errors naming the six colours used on aviation electronic flight instrument displays (white, red, green, amber, blue and magenta).

CHEMICAL COLOUR INDICATORS

There are several chemical tests that rely on colour to signal the endpoint of chemical change. Wilson[26] discovered that abnormal colour vision had a high prevalence in the mid 19th Century because he was a professor of chemistry and had observed that a number of his students had problems with colour indicators of chemical endpoints. Tocantins and Jones[76] reported that all nine colour deficient medical students whom they investigated were invariably wrong in titration of an unknown acid mixture and three with more severe colour loss made underestimations of the percentage of phenolsulphonephthalein in urine. Some of the colour vision deficient doctors who completed Spalding's questionnaire[19] recalled their difficulty with titrations in chemistry, as does Cockburn in a paper in this issue.[75] It has also been shown that doctors and diabetic patients with colour vision deficiency make errors with the Glucostix test of urinary glucose.[95,96]

Histopathologists use a variety of coloured stains to aid diagnosis, some of which have colours that may be confused by observers with red-green abnormal colour vision. Poole and associates[97] found that histopathologists with abnormal colour vision (n = 28) made significantly more errors than those with normal colour vision (n = 242) with 10 pairs of projected slides using stains with colours that were most likely to cause problems. On average, those with normal colour vision made 0.8 errors (out of 20), while those with abnormal colour vision made 2.8 errors. Number of errors was related to the severity of the colour vision defect. The authors recommended that aspiring histopathologists have their colour vision tested and those with a colour deficiency be helped to develop safe work practices. Goudie,[98] a former professor of pathology, rejects this conclusion, stating that his severe colour vision deficiency has never been more than a minor inconvenience as 'a moment's help from a colleague … solved any difficulty ... with colours' and is supported in this view by an editorial in *The Lancet*[99] and by a pathologist whose first teacher of pathology was colour blind.[100] This is the equal opportunity debate again: where the rights of those with colour vision impairment to pursue their chosen career have to be balanced against the likelihood and severity of adverse health outcomes. However, Poole and associates[97] remark that some of the mistakes made in their cross sectional study were clinically important.

WHO CAN RECOGNISE SURFACE COLOUR CODES?

While those with a severe colour vision deficiency are unreliable naming surface colours, between 15 and 30 per cent of those with a mild defect can recognise them as well as colour vision normal observers, at least when they are well illuminated. Margrain, Birch and Owen[101] argue that mild deuteranomals can identify the surface colours likely to be encountered by fire fighters. They determined the chromaticity co-ordinates of the colours and concluded from knowledge of the colour confusions of the various classes of abnormal colour vision that deuteranomals, who pass the D15 test, would be able to recognise them and therefore, should be acceptable for employment as fire fighters.

None of the standard clinical tests is an exact predictor of which of those with a mild deficiency can or cannot recognise surface colours. Walraven and Leebeck's[81] data suggest that all classified as 'mild' by the AOHRR can recognise surface colour codes but Verriest and Uvijls[82] and Ramaswamy and Hovis[93] do not confirm this. A good proportion of those who pass the Farnsworth D15 test can recognise surface colour codes reliably but some cannot.[80,93] Cole and Orenstein[80] and Ramaswamy and Hovis[93] suggest that a practical test of colour naming should be used to select those whose deficiency is so mild that they can recognise surface colours without error.

Because surface colour codes can vary so widely, there is a case for the exclusion of all people with abnormal colour vision from occupations in which recognition of surface colour codes is of critical importance, especially if the colours may be viewed under low levels of lighting.

DENOTATIVE COLOUR TASKS

Colour as an identifier

Colour is often used denotatively to identify an object, for example in phrases such as 'my car is the red one' or 'put this in the yellow file'. The task of using or acting on information containing colour as an identifier is essentially that of colour naming, data for which has been described in the preceding section.

Observers with abnormal colour vision will be unreliable in associating colour names with coloured objects primarily because many colours will look the same. More than 200 years ago, Dalton[12] observed that the colours of red sealing wax looked the same as the yellow-green of a laurel leaf. In addition, they may be unreliable because colours can change their appearance dramatically with change of illuminant. Dalton[102] observed that the colours of the flowers of *Pelargonium zonale* looked sky blue to him by daylight but appeared yellowish 'with a tincture of red' by candlelight. Mollon, Dulai and Hunt[103] showed that the deficiency of blue light in candlelight relative to daylight is sufficient to shift the chromaticity of *Pelargonium zonale* flowers from the blue side of the deuteranopic achromatic confusion locus to the yellow side.[e] Thus, a change of illuminant from daylight to incandescent light may cause dichromats to perceive a bluish colour as yellowish. This will make them unreliable in using colour names as an identifying characteristic.

Colour is often used as an identifier in police work. Goldberg,[105] senior medical officer in the Los Angeles Police Department, sent me the responses of four applicants for entry into the police force, who had abnormal colour vision and who were given a practical test of their colour naming ability. They were taken for a walk in daylight and were asked to name the colours of cars, clothing and buildings. Common colour errors were to name black as dark green, grey as green or pink, light green as grey or silver, light brown as green and dark green as black. Even blue, which is expected to be a colour that might be correctly named, was misnamed as silver or green.

Colour in school

Colour is used as a didactic tool in school, mostly informally as an identifier and as a means of grouping objects or ideas. Sometimes it is used systematically. Gattegno[106] proposed the use of colour to identify the 48 English phonemes and popularised the use of colour in elementary mathematics by developing the Cuisenaire method, which uses coloured rods to represent numbers and mathematical relationships.[107] It might be expected that children with abnormal colour vision will have some problems with colour at school and it is possible that these problems might impede learning.

The jury is out on that question. Wilkinson[108] reviewed the very few empiri-

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[e] We know that Dalton was a deuteranope because he instructed that on his death his eyes should be examined to establish the presence of a blue coloured filter in his eyes that he thought might be the cause of his colour vision impairment. His eyes have been preserved by the Manchester Museum of Science and Industry so a posthumous DNA analysis could be conducted 150 years after his death.[103,104]

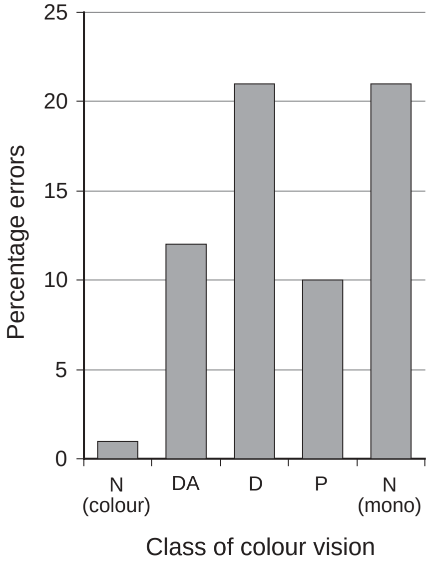

Figure 13. Percentage errors made finding information in an electronic flight instrument display of navigational information. N (colour) = colour vision normal subjects observing a redundantly colour coded display; N (mono) = colour vision normal subjects observing the same display in monochrome. DA = deuteranomal; D = deuteranope; P = protanope. The colour vision deficient observers were shown the redundantly colour coded display. Data of Cole and Macdonald.[113]

cal studies that endeavoured to relate abnormal colour vision to learning deficiencies and found them lacking in design and equivocal in their outcome. More recently, Grassivaro Gallo and colleagues[109] found significantly lower school achievement as assessed by school marks for 82 children with abnormal colour vision compared to 82 colour normal children matched by age and class, although curiously there was no difference in their marks for art. Snyder[110] recounting his experiences as a person with abnormal colour vision, comments that his kindergarten teacher drilled him to learn the names of colours and was dismayed at her lack of success, which made him feel anxious and different. He says he was greatly helped by having his abnormal colour vision diagnosed early in primary school and that he quickly learned to use other cues to enable him to assign the correct names. He learned, for example, that the colour of grass was brown in winter and green in summer, even though he could not see the difference.

Colour organising complex displays

Colour is often used denotatively to organise complex visual displays. In these applications, no particular meaning is attached to the colours: the colour simply serves to organise, delineate or give emphasis to particular elements of the display. This device is used in print, where colour may be used to box text, link related subjects or simplify a complex flow chart. It is commonly used in this way in computer screen displays.

The electronic flight instrument system displays (EFIS) used in aircraft are colour coded but not necessarily with assigned meanings. This redundant colour in a navigational flight instrument display reduces errors and speeds response times in the extraction of information from complex displays.[111,112] Cole and Macdonald[113] showed that observers with abnormal colour vision made significantly more errors and were slower than colour vision normal observers in the same task. Figure 13 is based on part of their data.

This suggests that colour vision deficient observers will be slower and will make more errors when extracting information from complex visual displays that are organised by colour, although it should be noted that all the colour deficient subjects in the Cole and Macdonald experiment[113] had failed the Farnsworth lantern test. It is possible that those with a mild colour vision deficiency may not be at such a disadvantage.

Colour in search

It is well established that colour is a useful attribute for visual search.[21] Sometimes a coloured object in a complex visual scene ‘pops out’ and is immediately obvious. It has been proposed that this arises from parallel processing of colour and form.[22] It might be expected that people with abnormal colour vision will be less successful in visual search when colour is one of the attributes of the target object.

O’Brien and co-workers[114] found that deuteranopes were significantly less likely to notice redundantly colour coded road signs than colour vision normal observers in an experiment that required the subjects to report features that attracted their attention in projected photographs of road scenes. They were less likely to notice red, orange and green signs but noticed yellow and blue road signs as often as the colour vision normal subjects. This is consistent with our understanding that deuteranopes perceive yellow and blue, so signs marked with these colours are as colourful for them as for colour vision normal observers. O’Brien and co-workers[114] also reported that deuteranopes were significantly less likely to notice road traffic signals suggesting that the red or green colour of the illuminated signal attracts attention for colour vision normal observers, but these colours being less colourful for dichromats are less likely to attract attention.

Cole, Maddocks and Sharpe[115] found that subjects with colour vision deficiency were less successful and slower than colour vision normal subjects in searching for a redundantly colour coded target in a background of differently shaped distracters. They were helped by the redundant colour coding although not to the same extent as were the colour vision normal observers.

Cole, Maddocks and Sharpe[115] conclude that people with abnormal colour vision should not be employed in occupations in which visual search is a critical task.

Colour and sport

Colour is used in sport to mark out and distinguish: players wear coloured uniforms, snooker balls are coloured and the colour of a ball in cricket or golf may affect how well it is seen against its background.

Steward and Cole[17] found that one in four people with abnormal colour vision reports problems with colour in sport, the most common problems being confusing the uniforms of opposing teams, losing red golf balls in the grass and mistaking the colours of snooker balls. Recreational sailors who have abnormal colour vision will have problems with coloured navigational marks and signalling flags as well as signal lights at night.[31,75] Goddard[116] reports that

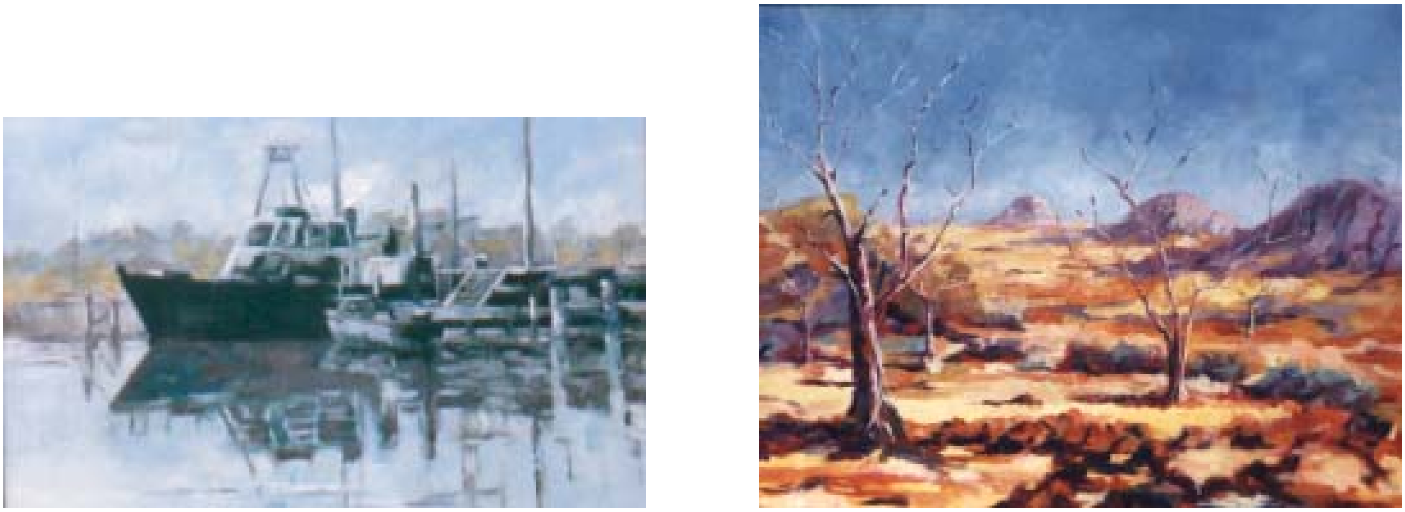

Figure 14. Oil paintings by an artist with extreme deuteranomaly. Left: An early painting that is almost monochrome using blue with some yellow. Right: A more colourful later painting in which the colours are confined to reds and blues. From Cole and Nathan.[122] A similar constraint in the use of colours can be seen in the work of a deuteranopic artist reported by Marmor and Lanthony.[121]

he is unable to hit the red cricket ball as accurately and reliably as he can hit white rounders or baseball balls or a black squash ball. He thought this might be due to his abnormal colour vision making it harder for him to see the red cricket ball against green grass. He explored this hypothesis by testing the colour vision of 280 first class county cricketers using the Ishihara test and found the prevalence of abnormal colour vision to be four per cent, nearly half that reported for the general male population, a difference that is statistically significant. This suggests that there is self-selection—that cricketers with abnormal colour vision tend not to proceed to first class cricket. The batting average for the players with abnormal colour vision was slightly less than that for players with normal colour vision and when their cricket league introduced the white ball the batting average of the colour deficient cricketers improved. However, neither of these differences reached statistical significance, which is not surprising as his sample was only 12 colour deficient cricketers and, if self-selection had occurred, these would be those with a mild colour vision deficiency.

AESTHETIC COLOUR TASKS

There are numerous occupations and everyday activities in which colour is judged for its aesthetic attributes, whether it be to do with harmonious combinations of colour or the mood that the colours are intended to evoke. Clearly, those with abnormal colour vision must be at some disadvantage, especially dichromats, because they see fewer colours.

There has been little formal study of the disadvantage that might be suffered by those with abnormal colour vision in their appreciation of art works, graphic design, interior décor or architecture or the problems they may have in active pursuit of endeavours in these fields.

Steward and Cole[17] report that nearly 75 per cent of their sample of people with abnormal colour vision said they had problems with selecting the colours of clothes and paints and 40 per cent of Spalding's[19] subjects said they had problems with décor (Figures 1 and 2).

Pickford[117-119] has reported on the problems experienced by colour vision deficient artists and art students. Ravin, Anderson and Lanthony[120] give an account of a 19th Century artist, Charles Meryon, who was known to have abnormal colour vision from the letters he wrote to his father. His few surviving works in colour are almost monochrome and he decided later in his career to abandon painting in favour of etching. A more contemporary artist, Jen Johannsen, is known to be a deuteranope and his works reveal his dichromasy by the limitation of his colour palette to blue and yellow, the two colours that are perceived by dichromats.[121] This is also evident in the work of an artist with extreme deuteranomaly who uses just red, orange, yellow and blue to create colourful and attractive work even though his palette is constrained to long and short wavelengths colours.[122] His earlier work tends toward monochrome with maritime studies in blues and blue-greys with touches of yellow. Figure 14 shows two examples of his work.

Clearly people with abnormal colour vision should be advised that their aesthetic judgements of colour may differ from those with normal colour vision and that they should think carefully before entering careers in the visual arts.

CONCLUSIONS

Almost all people with abnormal colour vision have problems in our increasingly colourful world, yet they cope very well. Rarely is it evident from their behaviour and actions that they have abnormal colour vision. Sometimes, it is not evident even to them. Steward and Cole[17] found 25 per cent of their anomalous trichromats and even five per cent of dichromats presenting for routine eye examination did not know they had abnormal colour vision.

They would cope even better if they knew they had abnormal colour vision and were provided with sound advice on their impairment and its consequences. They would also be helped by good ergonomic design that ensures that there is always a redundant source of the information conveyed by colour and if thought was given to their needs, when colours were chosen. There is some evidence of increasing awareness of their needs among designers,[123] however, there is a limit to providing ergonomic solutions to overcome the handicap of abnormal colour vision. Even the optimum choice of the colours in a red-green-white signal system provides only a small reduction in the chance of error for maritime and rail signals.[32] Judd[124] made the well argued proposal that red, green and blue should be used for instrument panel signal lights and this does provide assistance, although protanopes are still prone to make errors.[44]

There is a need for good career guidance for young people with abnormal colour vision. Thirty per cent of people with abnormal colour vision said their career choice was affected by their colour vision[17] and some of Spalding's doctors[19] said that they should have been guided to colourless branches of medicine. There is a number of occupations that involve tasks, such as precise matching of colours that people with defective colour vision simply cannot do. There are others, such as the graphic arts, for which an inability to appreciate the full gamut of colours is a handicap and people with abnormal colour vision should think twice before pursuing them.

People with abnormal colour vision, or at least those with a severe impairment, should be precluded from those occupations where their inability to recognise colour poses a risk to public health and safety. This risk may arise because colour recognition is critical to safe operation and there is little or no redundancy, for example in maritime navigation and train driving. There are occupations, especially those in which high social and economic costs are associated with accident, in which risk is minimised by a high degree of system redundancy. Colour coding of signals or visual displays may be one layer of redundancy and the employment of operators unable to recognise colour diminishes the level of redundancy and increases risk.

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