Studies of normal and deficient colour vision with relevance to occupational environments

Joseph David Hickey

Doctor of Philosophy

Applied Vision Research Centre
School of Health Sciences
City University London

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THE FOLLOWING PARTS OF THIS THESIS HAVE BEEN REDACTED FOR DATA PROTECTION/CONFIDENTIALITY REASONS.

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SYMBOLS AND ABBREVIATIONS

'	Minutes of arc
°	Degrees
AO-HRR	American Optical (Hardy, Rand and Rittler)
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
CAA	Civil Aviation Authority
CAD	Colour Assessment and Diagnosis
CD	Chromatic Displacement
Cd/m^2	Candelas per metre squared
cGMP	Cyclic guanosine monophosphate
CIE	Commission Internationale de l'Eclairage
CMF	Colour matching function
CRATO	Colour Requirements for Air Traffic Operators
CRT	Cathode Ray Tube
CU test	City University test (2^{nd} edition)
D15	Farnsworth dichotomous D15 test
dLGN	Dorsal lateral geniculate nucleus
ERG	Electroretinogram
FIT	Feature Integration Theory
GDP	Guanosine diphosphate
GTP	Guanosine triphosphate
HW-A	Holmes Wright lantern type A
HW-B	Holmes Wright lantern type B
IPRGC	Intrinsically photosensitive retinal ganglion cell
JAR	Joint Aviation Regulations

K pathway	Koniocellular pathway
λ	Wavelength
L cone	Long wavelength sensitive cone
L' photopigment	Anomalous L cone pigment found in deuteranomalous trichromats
LC	Luminance Contrast
LCD	Liquid Crystal Display
λ_{max}	Wavelength of peak absorption
m	Metres
M cone	Medium wavelength sensitive cone
M pathway	Magnocellular pathway
M' photopigment	Anomalous Mcone pigment found in protanomalous trichromats
MCA	Maritime and Coastguard Agency
mm	Millimetres
nm	Nanometres
NPV	Negative Predictive Value
PAPI	Precision Approach Pathway Indicator
P_e	Expected proportional agreement
P_o	Observed proportional agreement
PPV	Positive Predictive Value
R^2	Square of the correlation coefficient
RG	Red-Green
RPE	Retinal pigment epithelium
RRD	Rapid Response Driver
S cone	Short wavelength sensitive cone
SNU	Standard Normal Unit
UCS	Uniform chromaticity space
V(λ)	Luminous efficiency function

V1	Primary visual cortex
VS	Visual Search
YB	Yellow-Blue
Σ	Sigma (sum)

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DECLARATION

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ABSTRACT

The studies described in this thesis aim to assess the importance of normal colour vision in visually demanding, colour-related tasks that are often safety-critical and aim to improve our understanding of how congenital deficiencies can affect the processing of colour signals and the corresponding changes in visual performance.

The first study compares the colour vision requirements within different professional environments. 519 subjects were tested: 141 normal trichromats, 268 deutans and 110 protans. All subjects carried out the Ishihara 38-plate test, the CAD test and the Nagel anomaloscope, and sub-populations were examined with the AO-HRR plates, the Farnsworth D15, the City University test (2nd Ed.), the Holmes-Wright type A and B lanterns. Inconsistencies of outcome amongst the various tests and potential alternative practices are discussed.

The second study focuses on understanding the discrepancies in performance observed on lantern tests when the subject's task is to report the colour of small signal lights presented against a dark background field. These conditions were simulated using a psychophysical luminance pedestal technique. Variations in the measurement of chromatic sensitivity over the visual field, as well as the detection of targets where colours are combined with luminance contrasts, are discussed and explanations considered with regard to underlying retinal physiology.

The last study investigates the use of colour signals in ATC (air traffic control) applications. The work carried out addresses current failings in acceptance criteria for applicants, and provides alternative methods of assessing suitability. The chromatic discrimination thresholds of normal trichromats and colour deficient subjects were related to performance on a set of visual search tasks selected to be more representative of typical colour usage in large field visual displays. Display parameters under which the performance of colour deficient observers could be comparable to that of normal trichromats are examined with regard to updating occupational acceptance criteria.

1 INTRODUCTION AND LITERATURE REVIEW

1.1 ANATOMY AND PHYSIOLOGY OF THE VISUAL SYSTEM

The purpose of the eye is to convert electromagnetic radiation into neural signals that, when processed in the brain, provide information about the spatial, temporal and chromatic properties of the environment. The eye is capable of capturing this information over a 14-log unit range of light levels - approximately 10^{-6} cd/m^2 to 10^8 cd/m^2 - and within a relatively narrow range of wavelengths (380-780nm) (Hood & Finkelstein, 1986).

1.1.1 The structure of the eye

The eye is roughly spherical and is conventionally divided into three main layers: the external layer (the cornea and the sclera, connected by the corneal limbus), the intermediate layer (the iris, choroid and ciliary body) and the internal layer (the retina). Light initially passes through the cornea and anterior chamber. This initial transfer between the atmosphere and the eye accounts for approximately two thirds of the refractive index of the eye (Wald & Griffin, 1974). Subsequently, light enters the pupil, the diameter of which is controlled by the iris. The iris is a circular, pigmented muscular structure comprised of two muscle groups: the dilator pupillae (which increases the diameter of the pupil on contraction) and the sphincter pupillae (which decreases the diameter of the pupil on contraction). Together they regulate the amount of light entering the eye depending on external light levels.

The light passing through the pupil is focused by the crystalline lens. The lens is transparent and biconvex in shape; the overall shape of the lens is adjusted by contraction or relaxation of ciliary muscles attached to the zonule fibres that hold it in place. These adjustments, known as accommodation, allow for fine focusing of the light entering the eye. For viewing at further distances, relaxation of the ciliary muscles causes the lens to be flattened, increasing focal length, whereas for nearer viewing the ciliary muscles contract to make the lens more convex and reduce focal length.

Light focused via the crystalline lens passes through the vitreous chamber produces an inverted image at the plane of the retina. The retina is roughly circular with a diameter of ~30-40mm and consists of 10 sub layers (Figure 1-1). It contains the photoreceptor cells that respond to the incoming light and send corresponding signals to the brain via axons leaving the eye via the optic disc, a roughly circular structure approximately 1.5mm in diameter that contains no photoreceptors and is responsible for the 'blind spot' in the human visual field. The photoreceptors are very metabolically active and therefore require a rich blood supply provided by the choriocapillaris from the central retinal artery, which also enters the eye via the optic disc and serves the inner retinal layers.

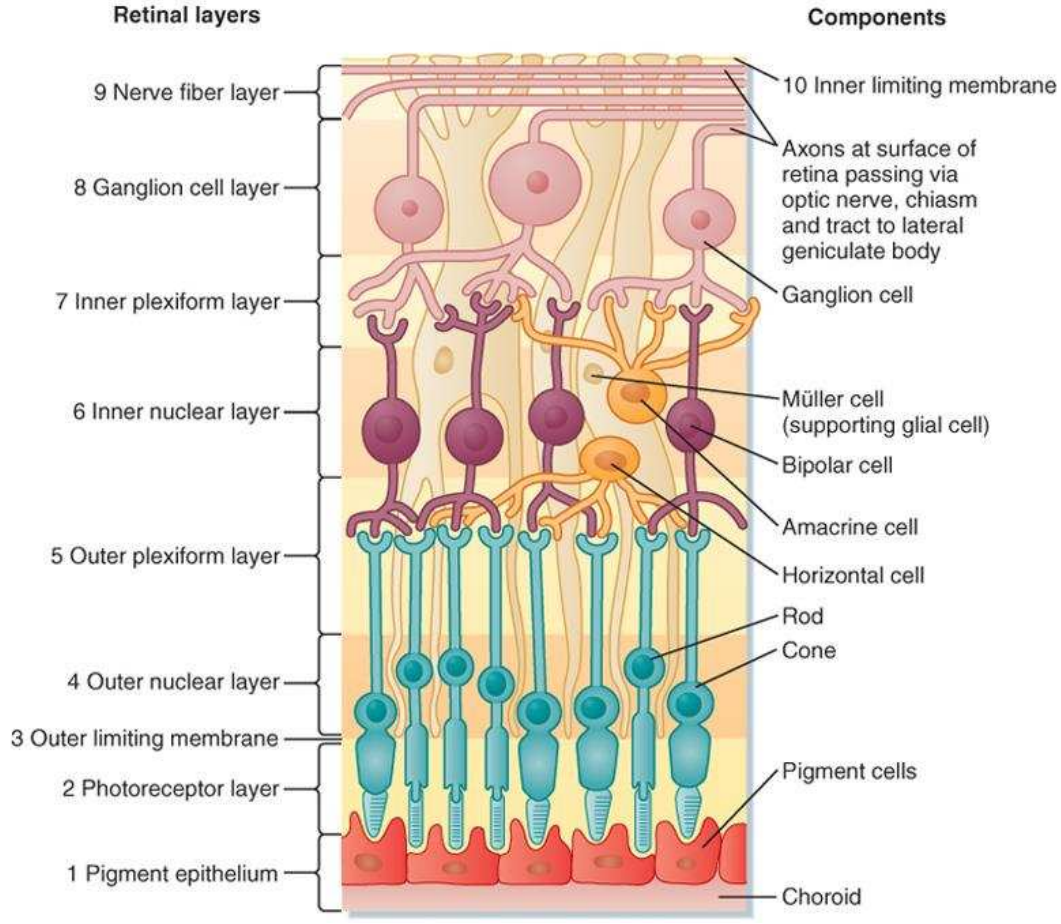


Figure 1-1: The layers of the retina, from Koeppen, B. M., & Stanton, B. A. (2009) in Berne & Levy Physiology (6th edition).

The macula is the central region of the retina, extending approximately 5.5mm in diameter. It contains the macular pigment, which is composed of lutein and zeaxanthin: two xanthophyll carotenoids that absorb short wavelength light and cause the macula to have a yellowish appearance on examination. The primary function of the macular pigment appears to be to protect the retina from oxidants; however other possible functions include the reduction of glare and chromatic aberrations, and the improvement of contrast (Whitehead et al, 2006).

At the centre of the macula is the fovea, the central 0.35mm of which is the foveola; the location of the retina corresponding to the highest visual acuity. This region shows many adaptations in the form of cone morphology; density and post-receptoral connections that allow it to perform this function (see section 1.1.2).

Light passes through the inner sections of the retina – those that are closest to the pupil – and is absorbed by photoreceptors in the photoreceptor layer (layer 2 in Figure 1-1); the light that isn't absorbed by the photoreceptors is subsequently absorbed by the retinal pigment epithelium (RPE), the outermost layer of the retina that provides a barrier between the photoreceptors and the choroidal blood supply (layer 1 in Figure 1-1). The RPE contains a dark pigment that absorbs light and hence reduces the amount of scattered light within the eye. In addition the RPE also carries out various functions to support the photoreceptors. Following the initial stages of phototransduction (see section 1.1.3) the photopigment molecule is converted into an isomer that initiates changes in the photoreceptor cell leading to signaling. This isomer cannot be re-isomerised by the photoreceptor itself, and in the case of rod photopigment, is transferred to the RPE where this takes place, before being returned to the photoreceptor outer segments (Strauss, 2005). The outer segments of the photoreceptors themselves are under constant oxidative stress, and therefore require regular replacement. Phagocytosis by the RPE helps to remove the damaged outer segments that are shed during this process (Steinberg, 1985).

Further support of photoreceptor function is provided by the Müller cells. These cells have a nuclei located in the inner nuclear layer, and project to form the outer limiting membrane together with astrocytes. Cone photopigment is recycled rapidly following phototransduction by the Müller cells; the rapidity of this process appears to be critical for extending the range of light levels to which cones can respond, and also in dark adaptation (Wang et al, 2009). Additionally they improve visual performance by reducing scattering of light passing through the inner retina. Their cell feet are funnel-shaped; this is likely for the purpose of gathering light for guidance through the retina, a function that they perform exceptionally well with minimal loss of intensity or wavelength (Reichenbach & Bringmann, 2013). Müller cells also perform a range of supportive functions: they phagocytose discarded outer segments of cone cells and assist in the production of new ones, regulate the contents of the extracellular environment via homeostasis, regulate the firing of neurons by the release of neurotransmitters and provide antioxidative support for photoreceptors. Additionally Müller cells provide a physically supportive structure that cushions the photoreceptors in the case of an impact, and can differentiate into new photoreceptors as a response to retinal damage (Reichenbach & Bringmann, 2013).

1.1.2 Photoreceptors

The human retina contains five classes of photosensitive pigments which can be found in rods, short- (S), medium- (M) and long- (L) wavelength-sensitive cones and intrinsically photosensitive retinal ganglion cells (IPRGC's). The rods and cones are the primary cells that contribute to vision.

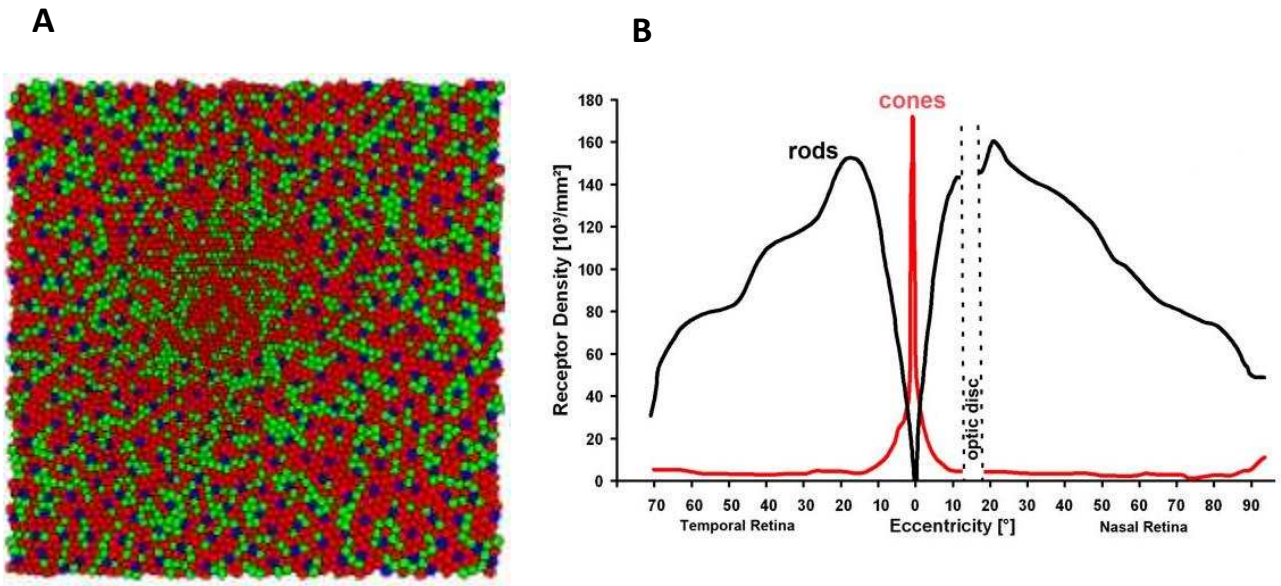


Figure 1-2: (A) the photoreceptor mosaic, showing the relative distributions of L, M and S cones. The fovea is indicated by the lack of S cones, from Sharpe et al, 1999, and (B) the varying populations of photoreceptors as a function of retinal eccentricity, adapted from Osterberg 1935.

The normal human retina contains approximately 4.5 million cones and 92 million rods (Curcio, 1990). At the fovea the cone cells are most densely packed, where they outnumber the rods. The peak cone density of the fovea varies greatly between individuals, with an estimated range of between 100000 and 324000 cones per mm^2 (Curcio, 1990). The centre of the fovea has a rod-free zone subtending 1.25° on average (Curcio, 1990); due to the poor spatial and temporal resolution of rods this allows for optimum central visual acuity. L and M cones are more numerous throughout the retina than S cones, which only constitute between 4% and 8% of cones, and the central 0.3° - 0.4° of the fovea contains just L and M cones (Figure 1-2). The eye's optics cause short-wavelength light to be poorly focused on the central retina and it is therefore an advantage to have the central

fovea free of S cones (Calkins, 2001). Cone density decreases with eccentricity from the fovea centralis while rod density increases rapidly from the rod-free zone to a peak at around 20° eccentricity, and then declines more gradually towards the periphery, as per Figure 1.2 (B).

Light entering the pupil at the centre causes a greater response in the photoreceptors than peripheral light of the same wavelength and intensity. This is known as the Stiles-Crawford effect, which is explained by the directional sensitivity to incoming light shown by the cones (Stiles & Crawford, 1933). The cones generally face in the direction of centre of the pupil, and therefore the chance of quantal catch of light entering at the plane of the pupil is increased (Figure 1-3).

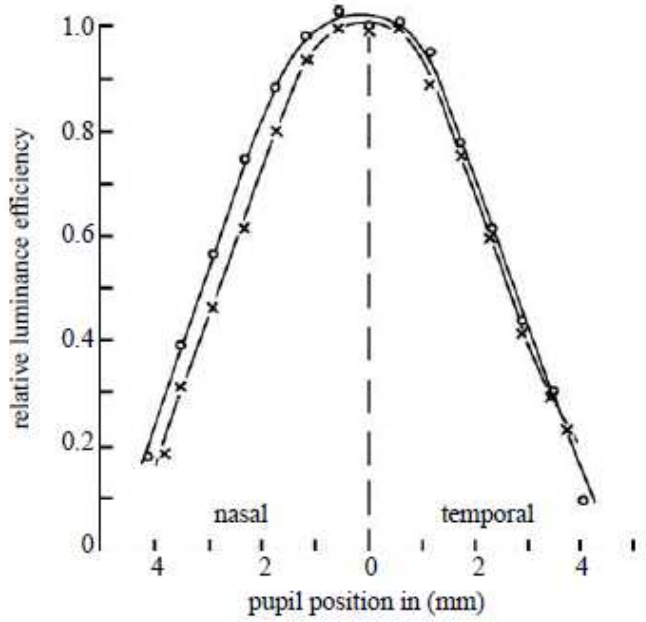


Figure 1-3: Relative luminance efficiency for a light source of fixed wavelength and intensity at varying eccentricities on the retina; the two curves represent measurements from the same subject taken 3 months apart, from Westheimer, 2008.

The rod and cone cells have a relatively similar structure: both types of photoreceptor comprise an outer segment, an inner segment, a nucleus and a synaptic terminal, shown in detail in Figure 1-4:

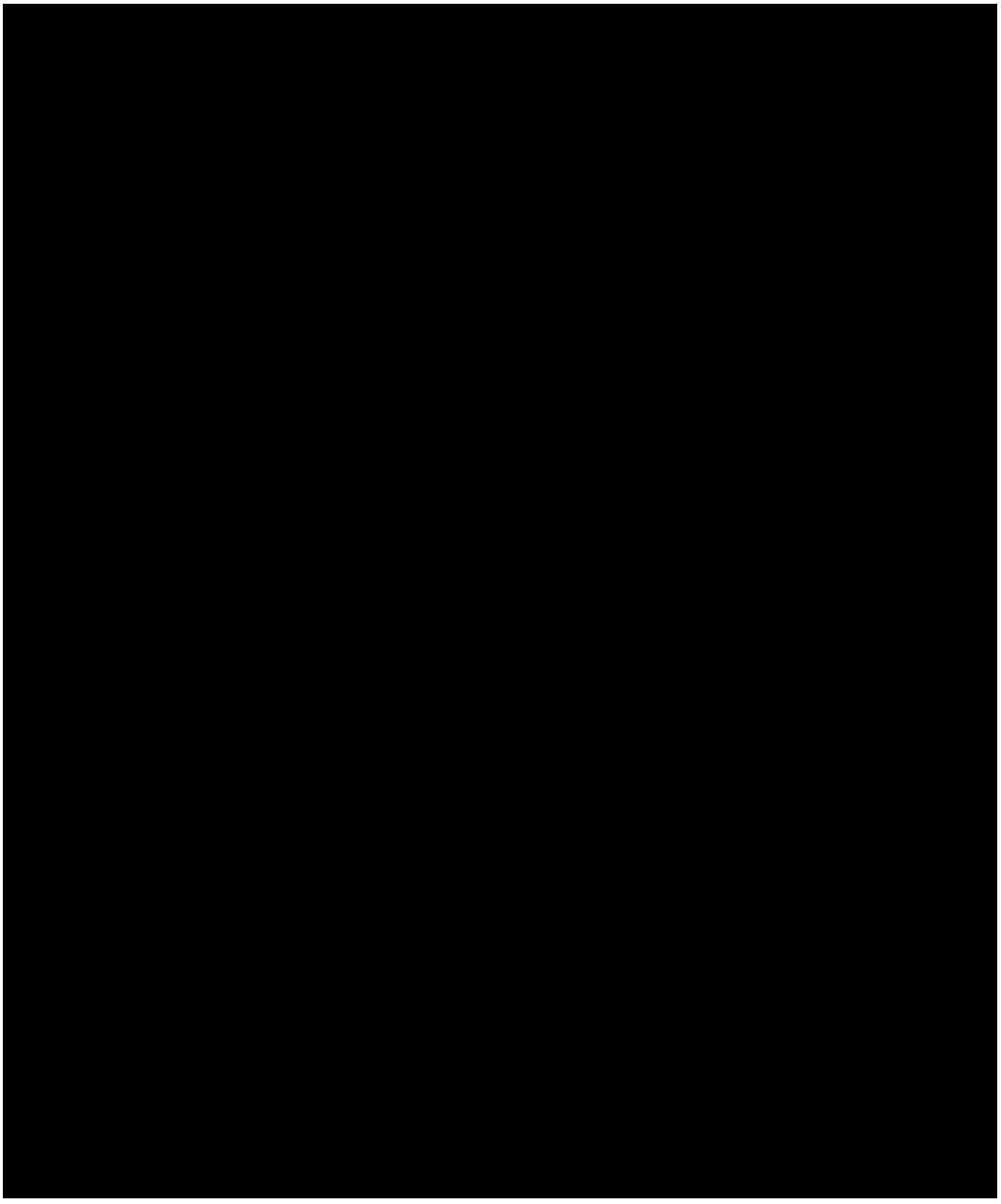


Figure 1-4: Schematic diagram of the rod (B) and cone (A) photoreceptor cells, from Westheimer, 2008.

The outer segment lies closest to the retinal pigment epithelium and consists of a stack of disk-like structures, the membranes of which contain the visual pigments. These disks are joined together in cones but are detached in rods; this arrangement increases the probability of photon absorption by visual pigment and the initiation of phototransduction. The inner segment is responsible for the

production of visual pigments which are then transported to the outer segment via the connecting cilium. It contains various organelles suited to this task (the endoplasmic reticulum, the Golgi apparatus and numerous mitochondria). The nucleus, or cell body, contains the cell's DNA and regulates its expression in order to control cell function. In the absence of light, the photoreceptor's cyclic guanosine monophosphate (cGMP) sodium channels are open, allowing an influx of sodium ions (Na+) that maintain a state of depolarization, providing a constant signal that contacts the bipolar and horizontal cells (termed a 'dark current'); this release is interrupted during phototransduction, signaling the second-order neurons (Kandel et al, 2000).

Rods have peak sensitivity at ~498nm, however they become saturated under photopic conditions. In the mesopic range (0.001 to 3 cd m^{-2}) input from rods and cones are combined. This can occur via gap junctions or via rod signals from A*II* amacrine cells being transmitted to bipolar cells responding to cone signals, although it is likely that there are more sites facilitating rod-cone interaction (Buck, 2003). Under scotopic light conditions (10^{-2} to 10^{-6} cd m^{-2}) vision is entirely mediated by rods. Many rod signals converge on the same second order neurons and it has been estimated that the signals from the ~92 million rods of the retina are transmitted to the brain by only ~1.25 million optic nerve fibres (Makous, 2003). The resulting signal amplification accounts for their ability to detect very low levels of light, but also their poor spatial resolution.

Cones have higher spatial and temporal resolution than rods, are active within the mesopic and photopic ranges and are the photoreceptors that allow for colour vision. The cell bodies of cones are distributed close to the outer limiting membrane, with the outer segment pointing towards the back of the eye. The discs of the outer segment contain a photopigment that consists of an opsin protein linked to a chromophore known as 11-*cis*-retinal; the type of opsin determines the spectral sensitivity of the cone. There are three cone classes each with a different opsin that responds maximally to different wavelengths, and have different absorption spectra which overlap, described in section 1.2.1 (Sharpe et al, 1999).

The recently discovered iPRGCs are a small population of retinal ganglion cells that contain the photosensitive pigment melanopsin. They do not play a central role in visual perception however they may make a subtle contribution. The main functions of the iPRGCs appear to be regulation of circadian rhythms via photoentrainment, and a contribution to the pupillary light reflex; recent work indicates that there are distinct sub-populations of iPRGCs for these two functions (Chen et al, 2011).

1.1.3 Phototransduction

When a photon of light is absorbed by one of the photopigment molecules bound to the outer segment, the process of converting the light into a neural signal is initiated. The 11-cis-retinal chromophore is converted to the all-trans-retinal isomer, which provides a viable binding site for the G-protein transducin. The G-protein coupled receptor subunit Gα exchanges its guanosine diphosphate (GDP) for cytoplasmic guanosine triphosphate (GTP), and then detaches to activate cGMP phosphodiesterase. This leads to an overall decrease in cGMP within the photoreceptor cell, causing the closure of ion channels, the hyperpolarisation of the cell membrane and cessation of glutamate release, which in turn signals the second-order neuron (Pugh & Lamb, 1993). This process has been most extensively studied in rods; cones are believed to operate in a similar manner, however the study of phototransduction in cones has been slowed by the difficulty of obtaining suitable samples (Kawamura & Tachibanaki, 2008). A schematic representation of the process of phototransduction is shown in Figure 1-5.

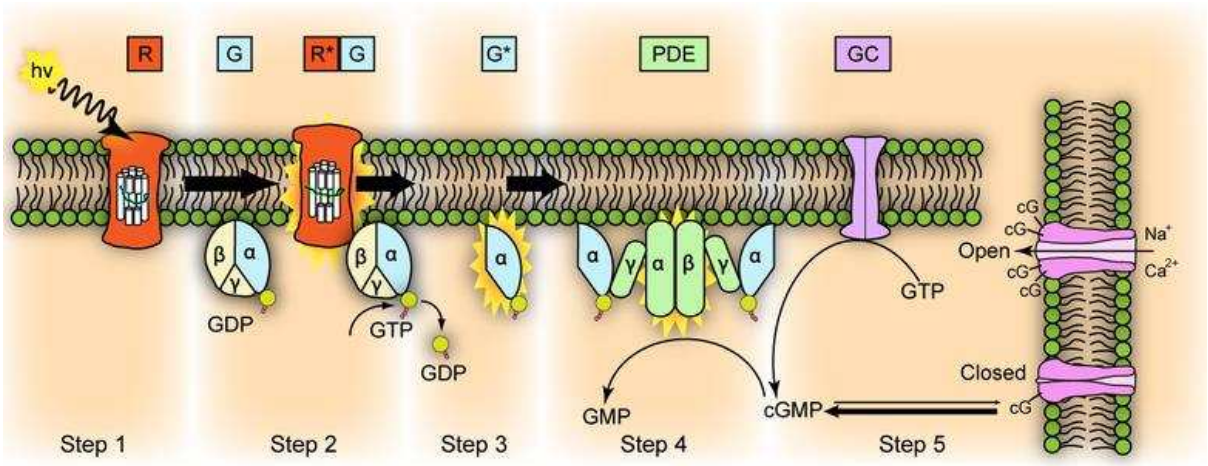


Figure 1-5: Schematic diagram of the process of phototransduction, from Leskov et al, 2000. A photon of light (HV) is absorbed by one of the photopigment molecules (R) bound to the outer segment. The chromophore is converted to the all-trans-retinal isomer (R), which provides a viable binding site for the G-protein transducin. The G-protein coupled receptor (G) α subunit exchanges its guanosine diphosphate (GDP) for cytoplasmic guanosine triphosphate (GTP), and then detaches to activate cGMP phosphodiesterase (PDE). This leads to an overall decrease in cGMP within the photoreceptor cell causing the closure of ion channels, the hyperpolarisation of the cell membrane.*

Following absorption of light and initiation of the signalling cascade, it is necessary that the response is inactivated as rapidly as possible in order to ensure high temporal resolution. It has been demonstrated that there are both fast and slow mechanisms contributing to inactivation; the slow acting mechanisms are more related to dark adaptation and the regeneration of photopigment (Burns & Lamb, 2003). Initially the all-trans-retinal is phosphorylated by pigment kinases, and is then bound by the protein arrestin; these steps greatly reduce its catalytic ability and prevent further phototransduction. Slower processes then hydrolyse the chromophore from the all-trans isomer back to the initial 11-cis-retinal state (Burns & Lamb, 2003).

1.1.4 Post-receptoral processing

Photoreceptors initially synapse with second order neurons in the outer plexiform layer: the horizontal and bipolar cells (see Figure 1-1). Bipolar cells contact with multiple photoreceptors to

pass neural signals on to the ganglion cells, except for in the case of the central fovea where each bipolar cell contacts one cone only. There are 11 types of bipolar cells: 1 that receives input from multiple rod cells and 10 that receive input from cone cells. This forms the first stage of what is known as the vertical pathway, which transmits photoreceptor responses to the brain via bipolar and ganglion cells respectively.

Bipolar cells synapse with ganglion cells in the inner plexiform layer, the axons of which leave the eye via the optic disc and transmit signals to various areas of the brain. Midget bipolar cells synapse with midget ganglion cells to form the first stage of the parvocellular pathway (commonly shortened to the 'P pathway'), and diffuse bipolar cells synapse with parasol ganglion cells to form the first stage of the magnocellular (M) pathway, however it is unclear whether the bipolar cells receiving input from S cones begin to segregate into the koniocellular (K) pathway at this stage or whether this occurs later in the ganglion cells (Kaplan, 2005). Although there are more than 20 types of retinal ganglion cell (Rodieck, 1998), the most common are the midget ganglion cells which form ~80% of all retinal ganglion cells, and parasol ganglion cells which form ~10%. Midget ganglion cells constitute the majority of projections to the parvocellular layer of the lateral geniculate nucleus (LGN) and transmit signals from L and M cone cells, whereas parasol cells constitute the majority of projections to the magnocellular layer and transmit luminance contrast information including signals from rods (Martin & Grünert, 2004). Small bistratified ganglion cells are less common and carry signals from S cones to the koniocellular layer (Dacey & Lee, 1994).

In the outer plexiform layer, horizontal cells regulate cone responses by providing inhibitory feedback and help to establish receptive fields: areas of the retina in which the activity of a central cone is modulated by the state of surrounding cones within the field in an antagonistic fashion. This organisation is functionally beneficial in that the response of cones around the area on which light is focussed is reduced (Thoreson el al, 2008). Rods also receive inhibitory feedback from horizontal cells, and under conditions where light levels exceed their operating range they act as relay cells for

horizontal cell – cone interactions (Szikra et al, 2014). Amacrine cells in the inner plexiform layer are believed to perform a similar function by providing feedback for bipolar and ganglion cells. The resulting receptive fields correspond to the activity of retinal ganglion cells, which can be described as having an ON centre / OFF surround or an OFF centre / ON surround. For ON-centre ganglion cells, activation of photoreceptors that signal bipolar cells at the centre of the receptive field causes ganglion cell activation – increasing with the percentage of the central photoreceptors being activated – whereas stimulation of photoreceptors in the surrounding region causes inhibition. The converse is true for OFF-centre ganglion cells, where activation of central photoreceptors is inhibitory and activation of peripheral photoreceptors produces excitation. There is considerable overlap of receptive fields to the extent that each point on the retina corresponds to several ON and OFF centre ganglion cells, and specific channels are formed by making comparisons between the signals of opponent regions of the ganglion cell receptive fields (Kandel et al, 2000). Both luminance and chromatic information is extracted from the receptive field by comparing the antagonistic responses of the centre and surround for different ganglion cell types. Two main channels are formed in this manner: the achromatic luminance contrast channel in which spatial variations in luminance are extracted by comparing L and M cone inputs (L+M), and the chromatic channel which is sub-divided into the red-green (RG) and yellow-blue (YB) channels, discussed further in section 1.2.1.

The chromatic and luminance pathways are largely independent of each other at this stage. As previously stated the magnocellular pathway is largely responsible for transmitting luminance contrast information and the parvocellular pathway is responsible from transmitting chromatic information. However there are reported interactions between luminance and colour within the retina and under certain conditions. This constitutes the earliest stage of visual processing.

1.1.5 Post-retinal processing

Axons of the retinal ganglion cells extend through the nerve fibre layer and leave the eye at the optic disc to form the optic nerve. They project to the optic chiasm where they decussate: nerve fibre axons originating nasally cross to the contralateral hemisphere whereas temporal axons remain ipsilateral. The nerves then continue through the optic tracts to various targets: the dorsal lateral geniculate nuclei (dLGN) in the thalamus, the superior colliculus or the pretectum in the midbrain, the hypothalamus and several other midbrain nuclei.

The superior colliculus has a retinotopic organization at each of its layers and is important in directing saccades to areas of the visual field that require attention, and is also involved in coordinating hand-eye movements (Lünenburger et al, 2001; Stuphorn et al, 2000). Optic nerve projections to the pretectum are involved in the pupillary light reflex (Clarke & Ikeda, 1985), whereas projections to the hypothalamus are related to circadian rhythms (Saper et al, 2005).

The dLGN not only functions as a relay centre between the retina and higher processing areas of the brain, but also modulates information flow to the cortex based on behavioral states such as attention (Sherman & Guillery, 2004). Most of the optic nerve fibres synapse with neurons in the dLGN, and their connections are segregated into 6 functionally distinct layers separated by interlaminar layers. By convention these layers are numbered 1-6, with 1 being the most ventral. Nerve fibres originating from the retinal ganglion cells in the M pathway synapse with magnocellular cells (M cells) in layers 1 and 2, and nerve fibres from the retinal ganglion cells in the P pathway synapse with parvocellular cells (P cells) in layers 3, 4, 5 and 6. Layers 2, 3 and 5 receive ipsilateral input and layers 1, 4 and 6 receive contralateral input. Nerves in the K pathway terminate in between the magnocellular and parvocellular layers in the interlaminar regions.

Each layer forms a neural map of the visual field, and the layers are aligned such that a single point in the visual field can be represented by drawing a line perpendicular through each of the layers. In this way, the sensory input from the nasal retina of one eye is aligned with the input from the

temporal retina of the other. As with retinal ganglion cells, the neurons of the dLGN have a centre-surround organisation (Sherman & Guillery, 1996).

Outputs from the dLGN via the optic radiations constitute the majority of inputs to the primary visual cortex (area V1), part of the posterior occipital cortex located mostly in the calcarine sulci. This area is also sometimes referred to as the striate cortex due to its striped appearance caused by the axons projecting from the LGN. Each hemisphere contains an area V1, and both sides are connected by the corpus callosum. The retinotopic organisation shown in the dLGN is preserved in area V1, and it is referred to as having 6 main layers. Inputs from the LGN terminate in layer 4 and send collaterals to layer 6; layer 4 is further subdivided into layers 4A, 4B, 4Ca, and 4Cβ. Parvocellular LGN neurons project to synapse with cells in sub-layer 4Cβ, whereas magnocellular neurons project to sub-layer 4Cα. Koniocellular neurons project to regions between the M and P layers. The human V1 is thought to contain around 140 million neurons, and approximately 50% of these correspond to the fovea; this over-representation of the central visual field is an adaptation to improve visual performance for this region (Wandell, 1995). Signals are then sent to the extra-striate cortical areas V2, V3, V4 and V5 for further processing, as well as feedback to the LGN.

1.2 COLOUR VISION

1.2.1 Normal trichromacy

Human colour vision is said to be trichromatic as it derives from the three cone classes in the retina (S, M and L), each containing photopigments with peak spectral sensitivities in different parts of the visible spectrum.

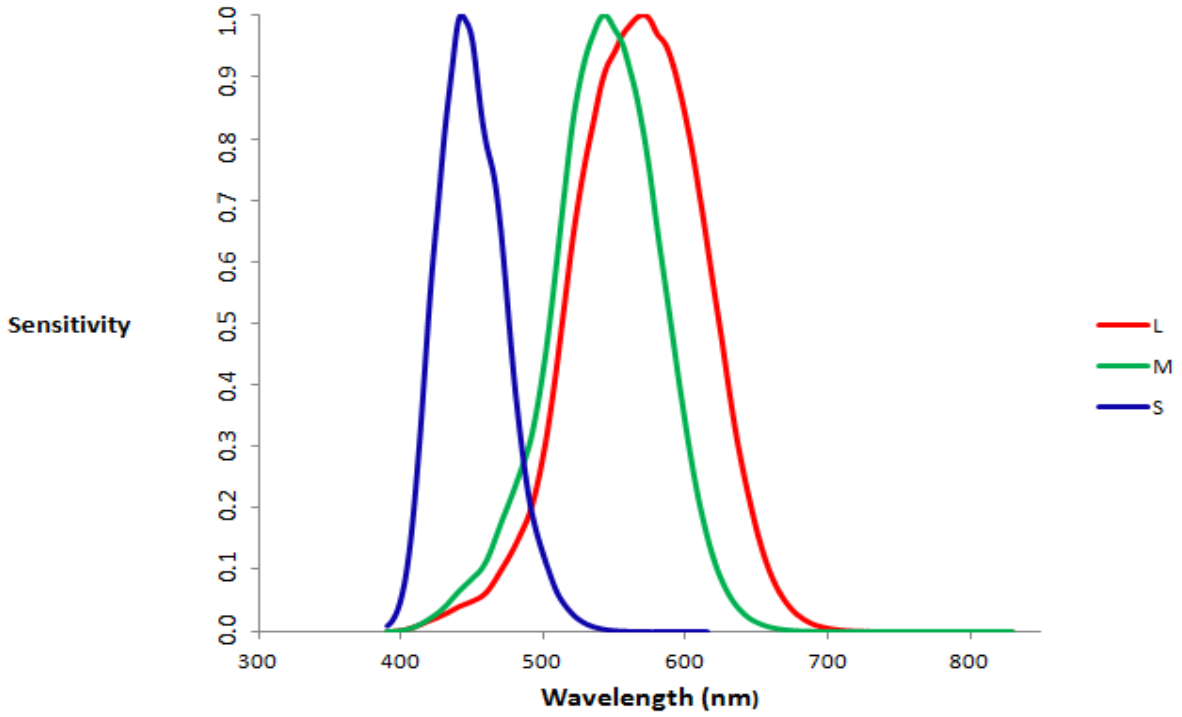


Figure 1-6: Cone spectral sensitivities measured at 2° by Stockman & Sharpe; data was obtained from the Colour & Vision Research Laboratory website (www.cvrl.org, 4th October 2013, plot step size = 1nm). The psychophysical estimates of L, M and S cone responses are plotted in arbitrary units as a function of wavelength.

Various attempts have been made to determine the spectral sensitivity functions, otherwise known as cone fundamentals, for each of the cone classes. Microspectroscopy, a technique in which the transmittance of a test beam of light is compared with a second reference beam, was employed to record absorptions of the photopigment-containing outer segment of photoreceptor cells by (Dartnall et al, 1983) in seven human eyes. The estimated absorption spectra separated into four distinct groups, with wavelengths of peak absorptions (λmax) of 419nm (S-cones), 496.3nm (rods), 530nm (M-cones) and 558nm (L- cones). Psychophysically, attempts have been made to establish cone fundamentals based on colour matching. It is possible to isolate the response for a single photoreceptor class by using a background adaptation field of a wavelength known to suppress the other photoreceptor classes, and employing a target the detection of which is based on the response of the isolated photoreceptor (Stockman & Sharpe, 1999) This procedure provides a better estimate

of sensitivity in the case of dichromats, who have only two cone classes (Smith & Pokorny, 1975), however this is based on the assumption that the spectral sensitivities of the remaining cone classes are similar to those of normal observers. This technique was expanded by (Stockman & Sharpe, 2000), who used genetic analysis to isolate a group of dichromatic observers with a normal genotype for the present photoreceptor classes to create an updated set of cone fundamentals, in which the short-wavelength sensitive cones (S-cones) have a peak sensitivity at λ=442nm, the middle-wavelength sensitive cones (M-cones) have a peak sensitivity at λ=543nm and the long-wavelength sensitive cones (-cones) have a peak sensitivity at λ=570nm (Sharpe et al, 1998; Stockman & Sharpe, 2000).

The absorption spectra indicate the range of wavelengths that the cones are sensitive to; within these regions there is a chance for a photon of that wavelength to be absorbed by the photopigment, the probability of this occurring are highest at the peak wavelength sensitivities. The wavelength of light only affects the probability of a photon being absorbed, and any information about the spectral composition of the light is lost in the photoreceptor signal that is generated. Increasing luminous flux increases the probability of photon absorption; however any information regarding intensity is also lost in the signal generated. This is known as the principle of univariance; it is not possible to tell the difference between a change in light wavelength or intensity from the afferent photoreceptor signal alone (Rushton, 1972). It is only by making a comparison between the inputs of the cones that the visual system is able to determine these properties of light.

The opponent process theory describes the mechanism by which the cone inputs are compared in order to produce the percept of colour from the univariant cone responses. It was first described by Hering in 1870 who noted that certain colour combinations are not possible (greenish red and yellowish blue), and proposed three groups of opponent photoreceptors (black and white, red and green, yellow and blue) (Hering, 1964), later supported by hue cancellation experiments (Hurvich et

al, 1957) and confirmed by electrophysiological recording (Lee & Dacey, 1997) and has since been refined to the following system shown in Figure 1-7.

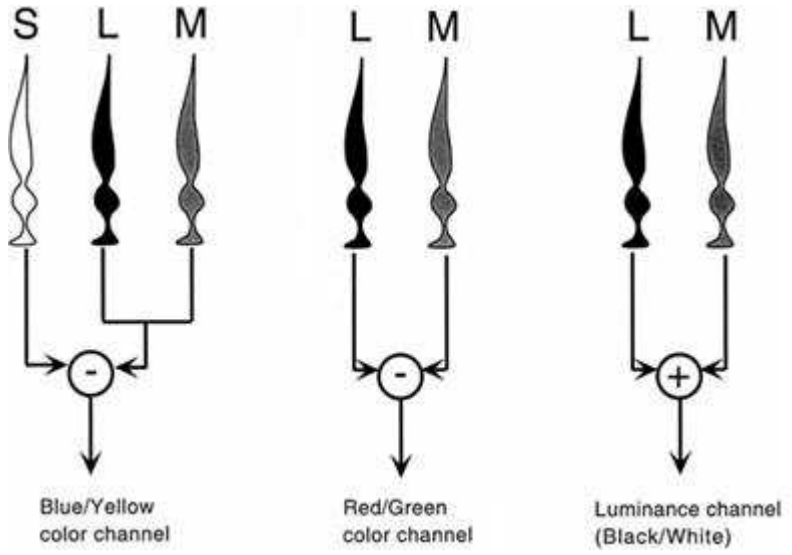


Figure 1-7: Schematic representation of the principal visual opponent pathways in the human retina. The YB channel is derived by comparing the combination of L and M cone signals with the S cone signal; the RG channel is based on a comparison of L and M cone input; the luminance channel is based on summed contribution of L and M cone inputs.

The RG channel transmits a signal corresponding to the subtraction of the L and M cone responses; the perception of either red-ish or green-ish colours is dependent on the ratio of the two signals (if the subtraction produces a greater value for L, 'red' is signalled, whereas a greater value for M signals 'green'). The YB channel signal is based on the subtraction of the S-cone signals from the sum of the L and M cone signals (S-(L+M)): where the signal for S is greater than the sum of the L+M then the response is 'blue', and when the signal for S is lower than L+M the response is 'yellow' (Calkins, 2001). The channels formed in this manner remain largely segregated throughout various stages of processing.

1.2.2 Colour reproduction

The accurate reproduction of colour underpins the reliability of tests of colour vision and psychophysical tests investigating the visual system (as well as being important in industrial and design contexts). In order to achieve this, colours can be mathematically described in a colour space.

The first of these was devised by the Commission Internationale de l'Eclairage (CIE) in 1931. This system allows the specification of a given colour based on the additive mixture of three primary colours, and is derived from the colorimetric matching experiments of Wright (Wright, 1928-1929) and Guild (Guild, 1932). The primaries are defined as three specific colours that cannot be created by making an additive mixture of the other two primaries, and in the RGB system any colour can be specified by its relative proportions of the three primaries, which are known as tristimulus values:

$$C = R(R) + G(G) + B(B)$$

where *R, G, B* are the three primaries and R, G, B are the amounts of each primary for the colour C.

The colour matching data for many normal trichromats obtained by Wright and Guild were used to produce the colour matching functions (CMFs) for a theoretical standard observer. The CIE 1931 colour space therefore attempts to represent colours based on how wavelengths of light are detected by the cone photoreceptors (Walraven et al, 1990). The standard observer is known as the CIE 1931 2° standard observer; as chromatic sensitivity varies across the retina due to the different spatial distributions of the three cone classes, it was necessary to set the measurements at a fixed eccentricity from the fovea, in this case 2 degrees. The colour matching functions did, however, result in negative values for certain colours, which would have complicated the representation of the colour space. The CIE therefore used a linear transformation of the RGB colour matching functions to produce three theoretical primaries known as X, Y and Z. The three tristimulus values (X, Y and Z) in this system are always equal to the CIE reference white, a theoretical colour that has a uniform energy level at all wavelengths within the visual spectrum (Wyszecki & Stiles, 1982). The CMFs for the CIE 1931 2° standard observer are $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$, where $\bar{x}$, $\bar{y}$ and $\bar{z}$ relates to spectral sensitivity and (λ) indicates the wavelength of light.

For the standard observer, the colour of an object can therefore be specified by the equations:

$$X = \sum_{380}^{780} p\,(\lambda)\bar{x}(\lambda)\Delta\lambda$$

$$Y = \sum_{380}^{780} p\,(\lambda)\bar{y}(\lambda)\Delta\lambda$$

$$Z = \sum_{380}^{780} p\,(\lambda)\bar{z}(\lambda)\Delta\lambda$$

where p is the spectral power distribution of light transmitted from the object (Wyszecki & Stiles, 1982).

In order to specify a colour within the CIE 1931 colour space, the relative proportions of X, Y and Z are needed, which are denoted as *x, y* and *z*. The sum of *x, y* and *z* also always equals 1, and therefore in order to specify a colour only two of these chromaticity coordinates are required. While any two of the three could be used, it is conventional to use *x* and *y* as per the CIE 1931 chromaticity diagram, which is plotted as shown below:

A **B**

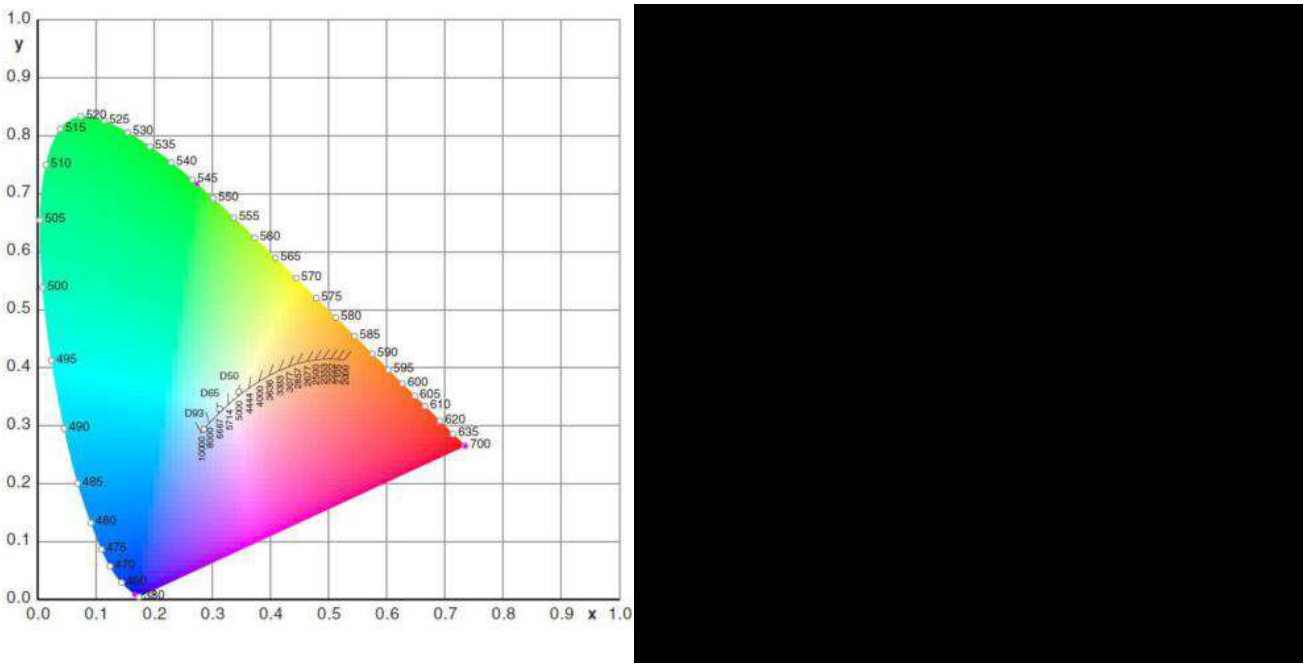


*Figure 1-8 (A) the CIE 1931 chromaticity diagram, adapted from Tsuei & Sun, 2011. The curved border is the spectral locus over which the wavelengths are plotted; the straight line is the line of purples, a range of non-spectral colours that join the red and violet ends of the spectral locus. Whites are located near the centre of the diagram; the Planckian locus displays the achromatic point for light of varying colour temperatures. (B) colours plotted in the CIE 1931 chromaticity diagram can be described as additive mixtures of two spectral hues, known as the dominant and complementary wavelengths, which are connected via a straight line through the illuminant. For colour **C**, the dominant wavelength is at **DW** on the spectral locus; the complementary wavelength is at **CW**. The complementary colour **CC** can produce white, **W**, when mixed with **C**. Adapted from webvision.med.utah.edu, accessed 19/11/2013.*

It should be mentioned that while the CIE 1931 colour space is still widely used as a standard system of describing colour, its accuracy in a physiological context has been disputed by numerous studies. When constructing the CIE CMFs, it was decided that they should be a linear combination of the previously established CIE luminous efficacy function, V(λ), which is now known to contain underestimated values for wavelengths below 460nm, and it has also been questioned as to

whether the CMFs should be a linear combination of the luminous efficiency function in the first place (Judd, 1951; Stockman & Sharpe, 1998).

For normal trichromats, the chromatic discrimination for colours in the CIE 1931 diagram can be plotted as MacAdam ellipses: areas of the diagram in which the average normal trichromat will likely not see any difference in colour. In the original series of experiments, the observer was required to make colour matches for a given reference colour of fixed chromaticity by adjusting that of an adjacent colour in various different directions in colour space, within a central 2 degree field at a fixed luminance of 47.7 cd $m^{-2,}$. When plotted in CIE 1931 colour space, the standard errors for colour matches along the different colour directions produce an ellipse around the x, y coordinates of the reference colour; for a given observer all colours within this ellipse of standard errors appear the same as the reference colour (MacAdam, 1942). It should be noted that for dichromatic observers, the major axes of ellipses plotted will extend from one edge of the spectral locus to the other; these axes can be plotted as dichromatic confusion lines, demarking regions in which all colours will be confused, the orientation of which will differ depending on the type of dichromacy.

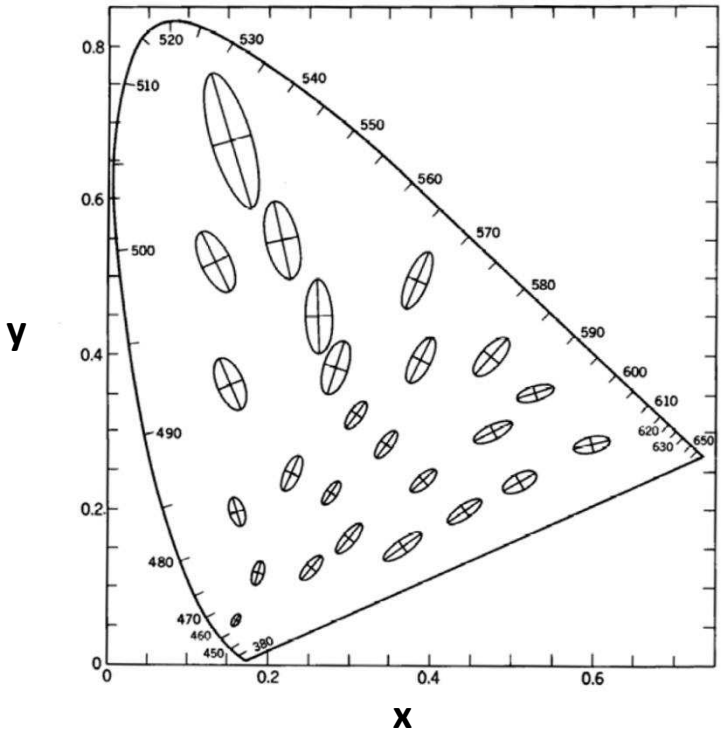


Figure 1-9: MacAdam's chromatic discrimination ellipses for a normal trichromatic observer plotted in CIE 1931 colour space. In order to make the effect more discernible, the axes of each ellipse in this diagram were shown 10 times their actual length. Reproduced from (Wyzecki & Styles, 1982) after (MacAdam, 1942).

As per Figure 1-9, it is clear that the perception of colours for the normal trichromatic observer measured by MacAdam is not uniform in the CIE 1931 diagram. This has prompted the creation of new colour spaces in which the perceived difference in colour is proportional to the distance between two sets of coordinates in all directions. The CIE 1960 Uniform Chromaticity Space (UCS) diagram was created by transforming the 1931 x, y coordinates by the following equations, which result in more perceptually linear scaling throughout the colour space:

$$u = \frac{4x}{-2x+12y+3}$$

$$v = \frac{6y}{-2x+12y+3}$$

This was modified in the updated 1976 (u', v') chromaticity diagram in which v' = v x 1.5 to improve scaling. The 1976 L*, u*, v* (often abbreviated to CIELUV) and L*, a*, b* (CIELAB) spaces include

luminance as a third dimension and are designed to allow for estimation of the perceptual differences between stimuli in terms of luminance as well as colour.

Colour spaces have also been designed that represent coloured stimuli in terms of the excitations produced in the L, M and S cone mechanisms. The MacLeod & Boynton (1979) colour space plots the estimated responses of the three cones in an isoluminant plane. This is a 2-dimensional colour space in which the cone contrasts (i.e. the level of quantal catch produced) at the photoreceptor stage can be predicted for a given stimulus. The Derrignton-Krauskopf-Lennie (1984) space (DKL) describes colours in terms of the responses produced in postreceptoral mechanisms, with a constant S – (L+M) and (L – M) axes in an isoluminant plane, and a third (L + M) axis representing the luminance dimension. It should be noted that this colour space assumes that S cones have no contribution to luminance; however in conditions of high L cone adaptation, S cones can contribute to the detection of luminance for flicker- and motion-defined stimuli (Lee & Stromeyer, 1989; Stockman et al, 1991).

1.2.3 Variation in human colour vision

Although colour vision can be viewed as being either normal or defective, in reality there is a great deal of variation in the chromatic sensitivities of those who do not have defective colour vision, and there are many known factors that contribute to this.

It has been established that there is substantial variation in the genetic sequences that code for the cone photopigments, which results in varying spectral sensitivities. The genes for L cone and M cone opsins have been identified on the X chromosome at Xq28, whereas the S cone opsin is autosomal and is located on chromosome 7, 7q32 (Nathans et al, 1986). (These locations correspond with the patterns of inheritance of colour vision deficiency; the defective genes responsible for deutan (M cone affected) and protan (L cone affected) deficiencies being located on the X chromosome result in these deficiencies being more prevalent in males, with females requiring defective genes from both parents in order for the deficiency to be expressed). Table 1-1 provides a summary of the prevalence of congenital colour deficiencies.

Deficiency type	Percentage of male population affected	Percentage of female population affected
Deuteranomalous trichromatism	4.82	0.36
Deuteranopia	1.14	0.01
Protanomalous trichromatism	1.04	0.03
Protanopia	1.01	0.02
Tritan deficiencies	Less than 0.02%*	
Total percentage	**8.01**	**0.42**

*Table 1-1: Estimated prevalence of congenital colour vision deficiencies; combined data from Sharp et al, 1999 and Birch, 2001. *Rare incidences of tritan deficiencies make estimation of prevalence difficult, with different studies citing relatively large differences in percentages.*

The close proximity of the L and M cone pigments on the X chromosome is thought to be a result of gene duplication during evolution. This organisation is not very stable, and results in a high possibility for gene deletion, duplication or hybridization, which in turn can lead to variant L and M photopigments and hence abnormalities in colour vision. The spectral shifts between these two visual photopigments are attributed to differences in amino acid sequences found in exons 2, 3, 4 and 5. Exon 5 causes the largest shifts in peak sensitivity, while substitutions in exons 2-4 produce much smaller shifts and may be responsible for the subtle differences underlying anomalous and normal colour vision (Neitz et al, 1999).

Variation in normal colour vision can also be partly attributed to variations in the relative cone population ratios between individuals. Several studies involving either direct imaging of the retina or post-mortem examinations of donated eyes have all reported significant variation in the L:M cone ratios; although it has been estimated that there are twice as many L cones as M cones, reported variations have described the L:M ratio as varying from 1.1:1.0 to 16.5:1.0 (Hofer et al, 2005).This has been shown to affect colour vision to some degree: spectral sensitivities measured with the flicker electroretinogram (ERG) technique showed that L and M cone responses to flicker were related to a subject's L:M ratio, and hence relative cone ratio likely affects a subject's chromatic sensitivity for medium and long wavelength light (Brainard et al, 2000). However, the relatively

similar chromatic detection thresholds found in normal trichromats, in spite of the large variation in L:M ratio, may be due to post-receptoral adaptive gain-control mechanisms (Kremers et al, 2000).

A number of other variable factors relating to cones can affect colour vision. The outer segment of cone photoreceptors varies in length as a function of retinal eccentricity: colour matching experiments and retinal densitometry have revealed that the outer segments of foveal cones are longer than peripheral cones. These lengths relate to photopigment density; the longer the outer segment, the more photopigment will be present in that cone and hence the chance of quantal catch is increased (Bowmaker & Dartnall, 1980; Elsner et al, 1973). Similarly, cone density of the retina affects quantal catch. Adaptive optics has allowed in vivo examination of the cone packing density of the retina, and this has been found to vary significantly amongst subjects of similar ages, and reduce with age (Song et al, 2001).

Sensitivity to short wavelength light can also vary between individuals. The crystalline lens filters out wavelengths below 400nm in order to prevent damage to the retina, and the level of absorbance increases with age. Measurement of the variation in rod sensitivity in the peripheral retina, where macular pigment is absent, has shown that density of lens pigment can vary by up to ±25% in individuals within similar age groups (van Norren & Vos, 1974). When considering variation in spectral sensitivity for normal trichromats as a whole, it should also be taken into account that ageing increases the density of lens pigment and so the variation will be even greater for the general population.

Individual variations in macular pigment optical density may also affect chromatic sensitivity. Although it is known that the macular pigment selectively absorbs short wavelength light, the contribution to yellow/blue chromatic sensitivity appears to be negligible, with measured chromatic discrimination thresholds having no correlation to levels of macular pigment (Barbur et al, 2010). Increased macular pigment levels may, however, improve a subject's red/green chromatic sensitivity (Rodriguez-Carmona et al, 2006).

1.2.4 Congenital colour vision deficiencies

Congenital colour deficiencies are described as being protan (L cone affected), deutan (M cone affected), tritan (S cone affected) or monochromacy (the retina contains either one class of cone (single cone monochromacy), or no cones (rod monochromacy)). Deficiencies are further sub-classified as those that have residual sensitivity to wavelengths within the relevant part of the visual spectrum, based on a variant photopigment (anomalous trichromacies: protanomaly, deuteranomaly and tritanomaly), or those where the response of a particular cone class is absent (dichromacies: protanopia, deuteranopia or tritanopia). As stated in section 1.2.3, the close proximity of the L and M genes increases the chances of errors during meiosis (cell division), and so colour deficiencies affecting the detection of medium or long wavelength light are the most common (Neitz et al, 1999).

Anomalous trichromacies originate from genetic anomalies producing variant photopigments that have spectral sensitivities outside of the normal range. Deuteranomalous subjects rely on a normal L photopigment and a variant L' pigment in place of a normal M; protanomalous subjects rely on a normal M photopigment and a variant M' pigment in place of a normal L. These variant photopigments have spectral sensitivities that are shifted compared with the pigment that they replace: the L' photopigment in deuteranomalous trichromats is closer to the L pigment than the normal M; the M' photopigment in protanomalous trichromats is closer to M than the normal L. The separation of the variant pigment from the normal varies and relates to severity of colour vision loss.

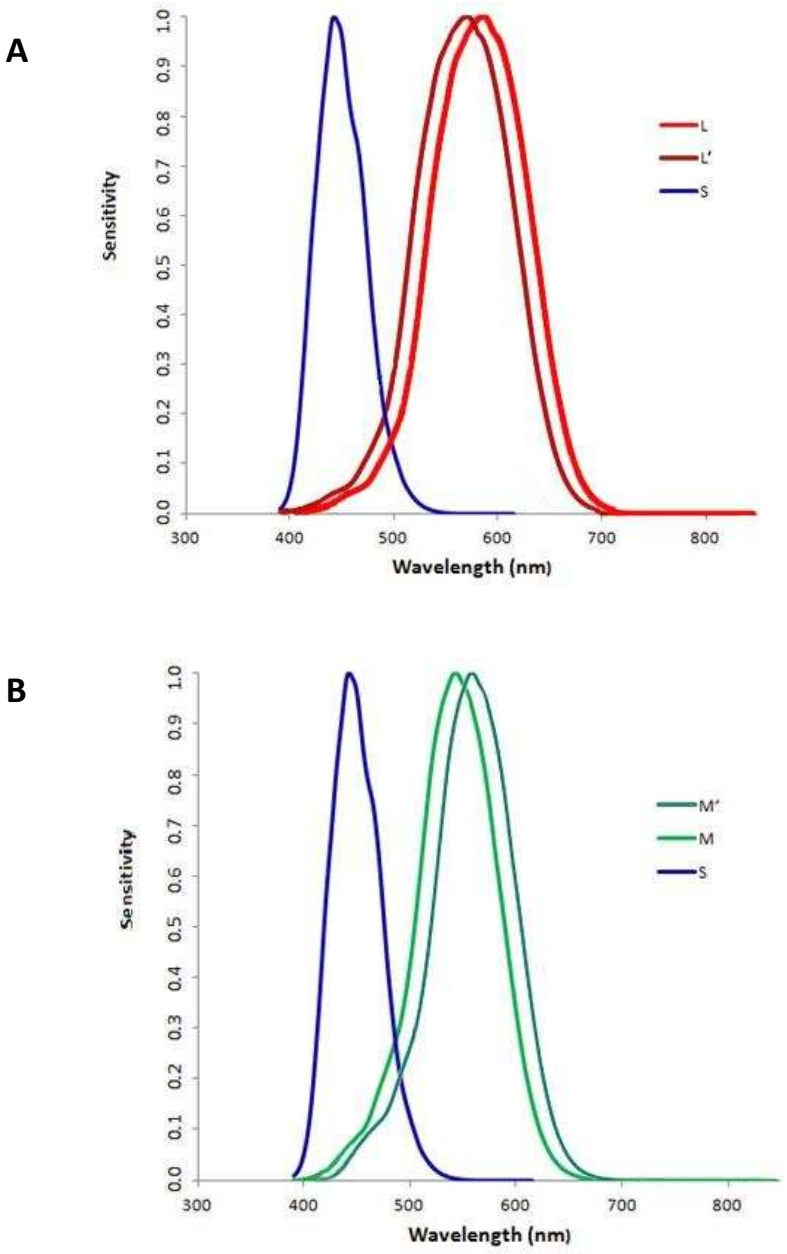


Figure 1-10: Examples of spectral sensitivity functions for deutans relying on a normal S and L cone, and a variant L' cone (A) and protans relying on a normal S and M cone, and a variant M' Cone (B).

Spectral sensitivity of colour deficient subjects varies greatly: anomalous trichromats may have spectral sensitivity just outside of the normal range and not be aware of their deficiency unless they undergo colour vision testing, however they may also be severely affected and have chromatic sensitivity similar to that of dichromats. The separation for M and M' is generally smaller than for L

and L' and therefore as a group, protans are considered generally more severe than deutans, and this accounts for some of the results shown in colour vision testing.

In the case of dichromacy there may be a reduction in the number of cones in the retina, or there may be a normal number of cones with the affected type lacking the normal photopigment. Furthermore, dichromats may have the normal pigment for the unaffected L or M cone, or they may also have a variant pigment, which accounts for the varying colour perception shown amongst dichromats of the same classification (Sharpe et al, 1999).

This affects the luminous efficiency function for colour deficient subjects of all types, as luminance is calculated by the sum of the L and M cone inputs. This sum will be different for colour deficient individuals who will have different levels of response to a given light source that contains medium or long wavelengths, compared to a normal trichromat. In addition, those with a protan deficiency may see reds as being significantly darker than other colours, as the absence of a normal L cone pigment results in the loss of spectral sensitivity in that region of the visible spectrum. This has implications for protan subjects working in occupational roles where the detection of a red light is safety-critical Deutans, on the other hand, will not experience greens as being darker as this region of the visible spectrum is still somewhat covered by the overlapping spectral sensitivities of the S and L cones (as demonstrated in Figure 1-6).

1.2.5 Acquired colour vision deficiencies

Acquired deficiencies are often associated with damage to the retina and therefore can be accompanied by loss of visual acuity (Birch, 2001). There are many potential causes of acquired colour vision loss which makes classification somewhat more difficult compared with congenital colour deficiency. While congenital colour vision deficiency is present from birth, is relatively unchanging in terms of severity (discussed further in 1.2.6) and is binocular, acquired colour vision deficiency is related to disease, injury or drug use and therefore can change in severity based on the progression of the underlying cause and can be monocular. Consequently, loss of colour vision can

be an important indicator of early-stage ocular disease that precedes visually observable pathology or loss of visual acuity. The viability for loss of chromatic sensitivity as a method of early diagnosis has been demonstrated for numerous conditions such as diabetes (Barbur et al, 2012), age-related macular degeneration (AMD) (O'Neill-Biba et al, 2010) and glaucoma (Pacheco-Cutillas, 1999).

A form of acquired colour vision loss not related to retinal damage is cerebral achromatopsia. As implied by the name, this condition involves a loss of colour vision originating from lesions in the ventral occipital cortex, and affects colour vision without damage to the retina. This involves a complete loss of chromatic sensitivity, but no reduction in spatial or temporal vision. Loss of colour vision can be complete or affect only part of the visual field (hemiachromatopsia), and can often be accompanied by prosopagnosia (the loss of the ability to recognise faces) and the inability to retain topographical information (Zeki, 1990).

Ageing has also been shown to be related to a loss of chromatic sensitivity; however this effect can often be difficult to distinguish from the effects of disease. With age there is a reduction in retinal illuminance due to a decrease in pupil size, an increase in lens pigment density and an overall reduction in the number of photoreceptors and post-receptoral cells (Winn et al, 1994; Knoblauch et al, 1987). Colour vision thresholds measured via the CAD test indicate the lowest chromatic discrimination thresholds occur at approximately 20 years of age. From 20 years, RG thresholds increased by approximately 1% per year in a linear fashion, with YB thresholds similarly increasing by approximately 1.6% per year (Barbur & Rodriguez-Carmona, 2015). There are many potential factors that could contribute to these observations.

As mentioned, ageing of the crystalline lens causes a reduction in retinal illuminance and is linked to reduced YB sensitivity (Shinomori et al, 2001). However there is also evidence that neuronal changes due to ageing cause increased noise in visual pathways. The numbers of retinal ganglion cell axons decrease linearly over lifespan by up to 40%, and retinal ganglion cell body count may also decrease (Calkins, 2013)

Loss of myelinated axons in the visual pathways is likely due to their relatively high metabolic demands combined with the diminishing resources that come with age. Additionally, neuronal loss or structural re-organisation within areas of the visual cortex may impair cognition and visual processing (Peters et al, 2000).

While defective colour vision may not impede those affected in carrying out most tasks in everyday life, certain occupational tasks require a certain level of chromatic discrimination in order to carry out the role effectively and safely. There are many tests of colour vision, and these are often utilised to determine a subject's eligibility to perform these roles. The diagnosis of defective colour vision and the challenges involved in setting appropriate pass/fail criteria will be discussed in the next chapter.

2 EVALUATION OF OCCUPATIONAL COLOUR VISION TESTS

2.1 OVERVIEW OF EXISTING COLOUR VISION TESTS

In occupational roles where colour vision is required, either to perform important tasks or to ensure safety, it is important to establish valid criteria upon which the suitability of applicants can be judged. The most simplistic approach would be to refuse all colour deficient subjects from these roles. However this would reject approximately 8% of male and 0.4% of female applicants; depending on the testing procedure used, some people with normal colour vision may also be rejected while some mild colour deficient subjects may pass. It is therefore of importance that the pass/fail limits used are matched to the requirements of the job, and that the testing procedure is accurate enough to prevent unsuitable applicants from passing or suitable applicants from being rejected. The aim of this chapter is to examine and compare the colour vision requirements within different professional environments.

2.1.1 Pseudoisochromatic plate tests

The first pseudoisochromatic plate test was developed by the German ophthalmologist Jakob Stilling and was described in his book 'Die Prüfung des Farbensinnes beim Eisenbahn- und Marinepersonal: The examination of the sense of colour of railway employé and pilots' (1877). Although there had been previous attempts to construct colour vision tests that would confuse dichromats in the 19th century, these had proven unsuccessful as they tried to place a solid target of one colour on an 'equiluminant' background of another, and it was not possible to do this with enough precision to cause confusion (Mollon, 1989). Stilling divided the target object and the background into smaller segments, and varied the luminance of these segments in order to prevent edge detection that was not based on colour. These plates were all of the vanishing type, in which the target could be seen by a normal trichromatic observer but not by a colour deficient (Shevell, 2003). Since then other variations of pseudoisochromatic plate design have been devised, including the hidden digit plates (in which the object is detected by a colour deficient but obscured for the normal trichromat) and

the transformation plates (in which one object is detected by the normal trichromat, and additional segments of specific colours around the object cause the colour deficient to see a different object). Later, classification plates were also devised that aimed to diagnose colour deficient subjects as being either protan or deutan. There have been many different pseudoisochromatic plate tests developed in the 20th century; by far the most widely used of these is the Ishihara test, with the American Optical (Hardy, Rand and Rittler) plates being the next most common (Birch, 2001).

2.1.2 The Ishihara Test

First published in 1917, the Ishihara test is the most widely employed pseudoisochromatic plate test for the screening of congenital colour deficiency. It incorporates plates of the vanishing, hidden digit, transformation and classification types, and has shown to be very sensitive in terms of detecting deficiencies (Belcher et al, 1958). There have been many versions printed; the standard version contains 38 plates, 25 of which contain numerals and 13 of which contain convoluted lines that a subject is required to trace a path. Typically, the last 13 plates are not used in clinical examination except for those instances where a subject is not capable of reading numbers. Currently there are the 24-plate 'abbreviated' edition and the 14-plate 'concise' editions available, however these do not contain some of the more sensitive plates of the 38-plate edition and hence are not recommended for clinical use (Birch & McKeever, 1993).

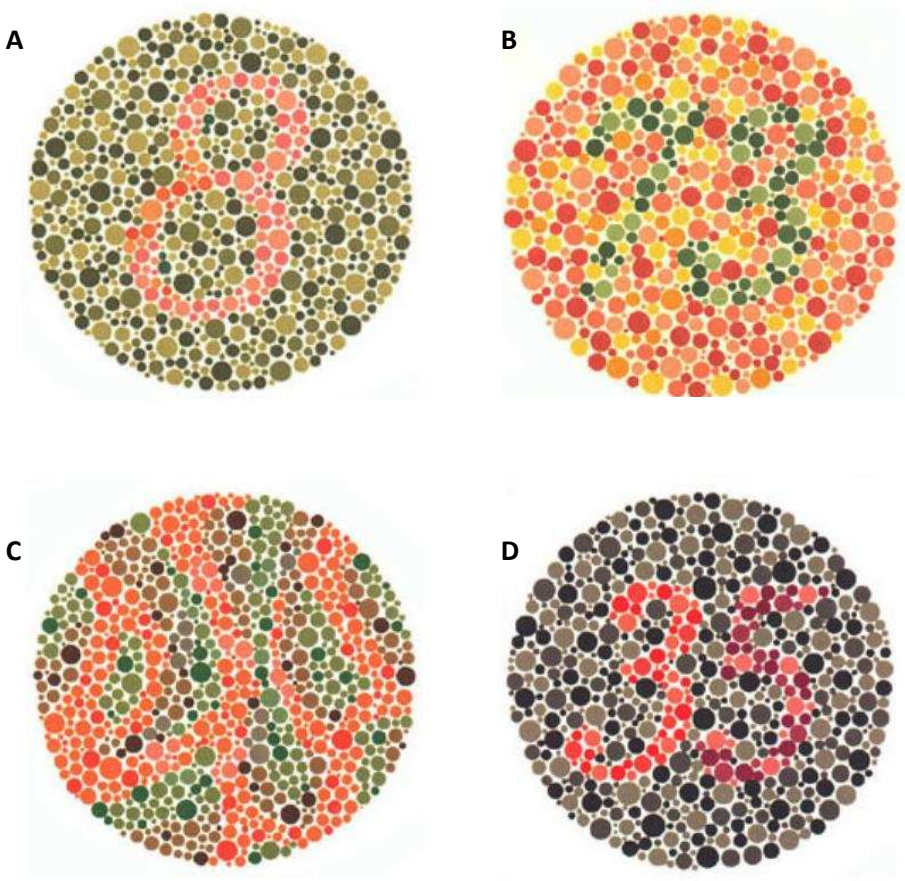


Figure 2-1: Examples of the types of plates used in the Ishihara test (38 plate edition): (A) a transformation plate; while a normal trichromat would see the number '8', colour deficient subjects would see '3' (B) a vanishing plate; the number '73' would not be visible to most colour deficient subjects (C) a hidden digit plate; normal trichromats would not see a number whereas congenital colour deficient subjects may see the number '5' (D) a classification plate; while normal trichromats would see '35', colour deficient subjects may see only one of these digits: typically protan subjects would only see the '5' and deutan subjects would only see the '3'.

The subject is sitting approximately 75cm away from the book containing the plates; the plates are perpendicular to the line of vision positioned on a tray at 45^{o} below the illumination. Although the manufacturer's instructions state that natural daylight would be an adequate illuminant, it varies greatly with the time of year. In clinical situations controlled artificial lighting is preferable; CIE standard illuminant C, designed to contain a spectral power distribution approximate of average daylight, is suitable for this.

Normal subjects who make mistakes generally do so by 'misreadings', generally attributed to a subject perceiving a loop of the serif font as being completed rather than incomplete (for example reporting a '6' where the correct answer is '5'), and can be identified as different from a typical error

based on the common errors made by colour deficient observers on that plate (Birch & McKeever, 1993). The chances of a misreading occurring are linked to the strength of the chromatic signal generated by the numeral; variability in the chromatic sensitivities of normal trichromats means that the less sensitive subjects with a weaker perceived chromatic signal will be more likely to make misreadings (Rodriguez-Carmona et al, 2012). It is conventional to set the pass criteria as three or less errors on the first 25 plates, however for normal trichromats to always pass, there must be 4 or less errors allowed (Birch, 2001). This is problematic, as even when 3 or less errors constitutes a pass, 10% of deutans and 1% of protans will also pass (Rodriguez-Carmona et al, 2012). Increasing the number of errors allowed would further reduce the sensitivity of the test. In addition, the numbers of errors made on the Ishihara test does not relate significantly to the severity of colour vision loss (Rodriguez-Carmona et al, 2012).

The Ishihara test is used to screen applicants for many occupational roles; where misreadings or errors are made it is common practice to use a secondary colour vision test in order to assess the severity of colour deficiency. Where the 38 plate edition is used, a fail will usually constitute one error on the first 25 plates. Currently the Joint Aviation Requirements (JAR) - a list of requirements for aviation certification agreed by several countries in Europe - stipulates that an applicant should make no errors on the first 15 plates (Joint Aviation Authorities, 2002)

2.1.3 The American Optical (Hardy, Rand and Rittler) plates (AO-HRR)

The AO-HRR plate test attempts to identify protan, deutan and tritan deficiencies, and to roughly determine the relative severity of these deficiencies (Hardy et al, 1954). For these reasons it is often used in conjunction with the Ishihara test, which does not distinguish between tritans and normal trichromats and provides no indication of the severity of a deficiency. In order to prevent some of the ‘misreadings’ that can be caused by the serif font of the Ishihara test, the AO-HRR plates use geometric shapes – crosses, circles and triangles – with one or two shapes on each page (as shown in Figure 2-2). There are 20 plates plus 3 example plates – the first two and the last four plates use

colours that can be confused by tritan subjects, while the remaining 14 screen for deutan and protan deficiencies. All plates are of the 'vanishing' design. The test is carried out in the same light conditions and from the same viewing distance as the Ishihara test.

A **B**

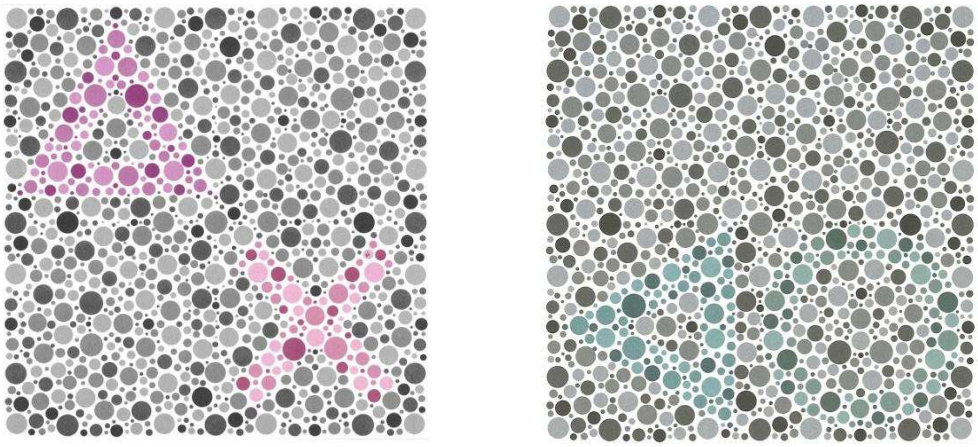


Figure 2-2: Examples of two of the plates used in the AO-HRR test.

The grading of severity using the AO-HRR test is based on the saturation of the colours of the target objects. The targets of the initial plates are relatively low in saturation, and there is an increase as the subject progresses through the test. For this reason the test is often administered in reverse order. This aspect of the test is fairly insensitive and it is only possible to reliably determine whether a subject has a slight or a severe deficiency (Birch, 1997).While not used as an occupational screening colour vision test in the UK, it is still popular as a companion test to the Ishihara. This is largely due to the ability to assess severity of deficiency to an extent, and to screen for tritan deficiencies. One error on any of the 20 plates usually constitutes a fail.

2.1.4 The Farnsworth D – 15 test

The Farnsworth dichotomous D15 test (Richmond, USA) consists of 16 circular caps containing Munsell sample colours with a value of 5 and a chroma of 4 that form an incomplete hue circle containing colours at intervals in this circle that can be confused by all types of congenital colour deficient. It is carried out under the same lighting conditions as the pseudoisochromatic plate tests (average daylight illumination; CIE standard illuminant C). The test is presented in a rectangular tray

and one cap, known as the pilot cap, is placed at one end of the tray while the rest are taken out. The subject is asked to place the cap that is most similar in colour to the pilot in the tray next to it, and then to continue doing this based on the last cap that they selected such that the caps are arranged in a progressive sequence of similarity. Following this, the order in which a subject has arranged the caps is recorded and plotted on a circular diagram with superimposed axes indicating the confusion lines for deutans, protans and tritans; where a confusion in the order occurs and the order of caps selected by a subject causes the plot to cross over from one side of the diagram to another, the direction of this crossing is used as an indicator of the type of colour deficiency (see Figure 2-3). If the confusion is only between two adjacent caps then this is not taken as an indicator of severe deficiency and generally one adjacent transposition is accepted as a pass.

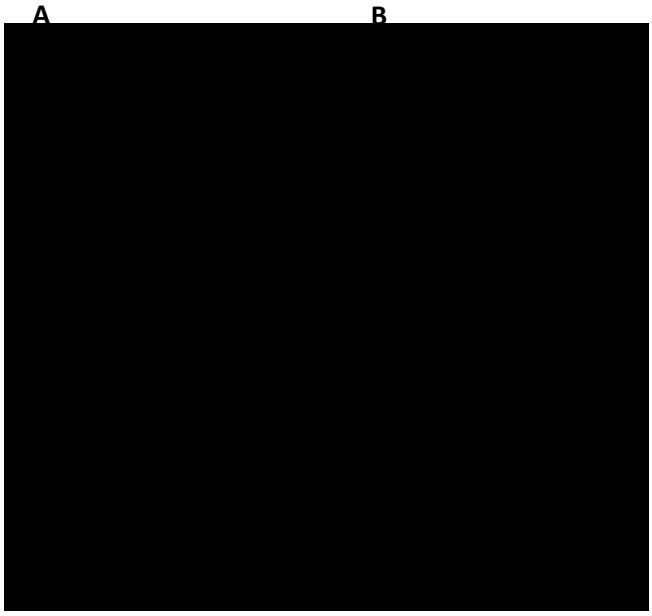


Figure 2-3: Circular plots of the D -15 cap arrangements made by (A): a subject that passes without error, (B): a severe protan subject, (C): a severe deutan subject and (D): a tritan subject. Adapted from Vingrys & King-Smith, 1988.

Due to the colour differences between adjacent caps, the difficulty of the test was designed such that those who pass should be able to judge surface colours, and therefore generally subjects with a mild or a moderate colour deficiency should be able to pass without error (Birch, 2001).

The D15 is currently employed by the fire service in the U.K. to screen potential applicants; the protocol involves screening with the Ishihara test, and if a deficiency is suspected then the D15 is used in combination with the Nagel anomaloscope. It has been advised that protan subjects of any severity, and severe deutan subjects, are not suitable as firefighters. If a subject is capable of passing the D15 and is confirmed as deutan or normal on the Nagel, then they are deemed to have met these criteria (Margrain et al, 1996).

2.1.5 The City University test (2nd Edition)

The City University test (CU test) (Keeler Ltd, UK) was designed to replicate the diagnostic ability of the Farnsworth D15 but to present it in a different format, as some subjects can find the concept of arranging the caps into a progressive order difficult (Birch, 1984). It uses the same Munsell sample colours arranged as 5 circles per page (see Figure 2-4) and therefore has a difficulty such that mild/moderate colour deficient subjectsshould be able to pass.

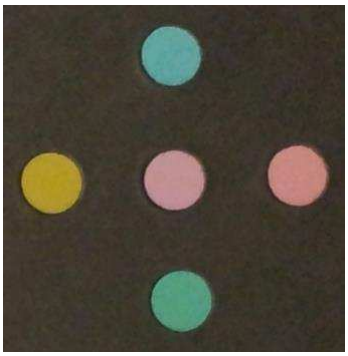


Figure 2-4: The Munsell sample colours shown on page 2 of the CU test (2nd edition). Depending on the outer circle chosen as a match for the central one, a different diagnosis is inferred: the top would be a tritan confusion, the left a deutan confusion, the bottom a protan confusion and the right would be a normal response.

The subject is asked to identify the outer circle that is most similar in terms of colour to the central one. On each page the four outer circles comprise one that is next in the D15 sequence (the normal response), and three that are colours that are each within the isochromatic confusion zone with respect to the central colour for protan, deutan and tritan observers; the subject's responses therefore indicate the type of deficiency present (if the deficiency is significantly severe for

confusion to occur). There are 10 pages, with the last 4 being somewhat more difficult due to a reduced colour sample size.

The CU test is currently employed by the UK police force to determine the suitability of an applicant to be a Rapid Response Driver (RRD); the pass criteria state that 3 or less errors is acceptable. The 2nd edition of the CU test is no longer available, however the 3rd edition is. It is important to note that the 3rd edition has not been validated in terms of effectiveness.

2.1.6 The Nagel anomaloscope

The Nagel anomaloscope was first introduced in 1907, and has for a long time been viewed as the 'gold standard' instrument – i.e. the method of diagnosis thought to have the highest level of accuracy - used for differentiating between protans, deutans and those with normal colour vision, and further classifying congenital colour deficient subjects as dichromats or anomalous trichromats. The Nagel anomaloscope type 1 (Schmidt, Haensch GmbH and Co., Berlin, Germany) will be discussed here; a type 2 was also released that attempted to classify tritan deficiencies (Birch, 2001).

The Nagel presents a circular bipartite field subtending 3° in Maxwellian view. As illustrated in Figure 2-5, the lower hemi-field is illuminated with a monochromatic yellow light source (589nm) the luminance of which can be varied; the upper hemi-field being a mixture of red (650nm) and green (546nm), the ratio of which is also adjustable. The subject is required to make Rayleigh matches – adjustments to both halves of the bipartite field until both appear identical in terms of luminance and colour – and the proportions of each light used in a match indicate the type of deficiency (Rayleigh, 1881). Following this, the range of the red/green mixture ratio that a subject can match with any luminance value of the monochromatic yellow is determined.

Figure 2-5: Diagram of the control of the bipartite field, pictured in the centre, that can be adjusted in one half based on a mixture of monochromatic green (546 nm) and monochromatic red (670 nm), and the other based on the brightness of a monochromatic yellow (589 nm). Adapted from Schiefer et al, 2007.

Based on the principle of univariance, for a Rayleigh match to occur the two halves must produce equal levels of quantal catch in the L and M cones; if the subject is a protan, and hence less sensitive to the monochromatic red element of the upper field, they will need to increase the proportion of red light in the mixture in order to make a match. Similarly, deutan subjects will require a greater proportion of green light in the upper field (Wright, 1946). The Nagel quantifies the ratio of red to green in the upper field as being between 0 (monochromatic green) to 73 (monochromatic red); typically those with normal colour vision will be able to make a Rayleigh matches when the proportions of the two lights are approximately equal (with a midpoint typically in the range of 35-40, examined further in 2.4.1), whereas deutans will match a range of mixtures between 0 and 40 and protans between 40 and 73. In the case of dichromats, with only one functioning class of cone that is sensitive to the primaries used in the anomaloscope, it follows that they will be able to match the full range of the upper field simply by adjusting the luminance of the lower field. The luminance

value chosen is important in determining the type of dichromacy; protanopes will require a significantly lower luminance at 73 than at 0.

It is important to note that effective diagnosis using the Nagel requires an experienced examiner, who is capable of interpreting whether the subject has made a match or not based on their responses.

With relevance to the Nagel being the gold standard for colour vision assessment, a recent model based on the genetic analysis of cone photopigment genes in congenital colour deficient subjects predicted that in some cases subjects with variant L and M cones could make Rayleigh matches within the normal range (Barbur et al, 2008). This, combined with the fact that examiner interpretation may not always lead to the correct diagnosis, means that the Nagel could be considered to be an 'imperfect gold standard'.

2.1.7 The Holmes – Wright lanterns (type A and B)

The Holmes-Wright lanterns types A and B (HW-A and HW-B) were designed specifically to determine a subject's suitability for occupational roles where the discrimination of signal lights is necessary; the type A for the UK armed forces and until recently for the Civil Aviation Authority (CAA), and the type B for the merchant navy (Holmes and Wright, 1982). Both lanterns contain filters allowing the presentation of three colours – red, green and white – the chromaticities of which are within the CIE-approved specifications for signal lights (Vingrys and Cole, 1983). The colours are presented in pairs, arranged vertically in the case of the type A and horizontally in the case of the type B, and the 9 possible combinations of the three colours are presented in each run. As per the protocol for the HW-A, the examiner first shows an example of each of the lights before the test followed by three runs of the 9 combinations in mesopic lighting conditions, followed by a period of 12-15 minutes of dark adaptation and a repeat three runs in scotopic lighting conditions. The HW-B has no demonstration but instead an introductory setting is used in which only one light is shown at a time, with a larger aperture than for the rest of the test. The HW-B lights are shown through a

smaller aperture in the main test than those of the HW-A, and there are five runs of the 9 colour combinations carried out in scotopic lighting conditions only. Both lanterns are viewed from a distance of 6 metres; for the type B this is intended to simulate viewing the navigation lights of a ship from 2 miles away (Birch, 2001).

The pass criteria for the HW-A is 'no errors on the first run of either lighting condition, or if errors are made, no error on the following two runs of either lighting condition'.

Currently seafarers who fail the Ishihara test use the lantern type B as a supplementary test to determine suitability for employment (according to the Maritime Coastguard Agency (MCA) protocol for colour vision testing – deck officers and those with night lookout duties are required to pass). A pass on this test requires the subject to make no errors on the introduction round followed by no errors in the following runs (Work Instruction MCA 710/001). The HW lanterns are no longer in production; an attempt at a replacement was the CAM lantern (Evans Instruments, Ltd), however this has not been validated scientifically in terms of effectiveness and therefore will not be used in this study.

2.1.8 The Colour Assessment and Diagnosis (CAD) test

Based on a similar principle to the pseudoisochromatic plate tests, the Colour Assessment and Diagnosis (CAD) test employs spatially-structured chromatic stimuli that are embedded in an array of achromatic luminance checks that subtend 3.3° x 3.3° degrees of visual angle in the centre of a background adaptation field of a specified chromaticity (x = 0.305, y= 0.323 with respect to the CIE 1931 colour space).

As opposed to the static luminance contrast (LC) noise of traditional pseudoisochromatic tests, the CAD employs dynamic luminance contrast noise in which all checks on the display vary randomly in luminance within a specified percentage of the background luminance throughout the presentation, every 40-80ms. The array of checks has a spatially averaged luminance level equal to the background

adaptation field at all times. Despite the fact that the parvocellular retinal ganglion cells have receptive fields that respond to both luminance contrast and chromatic information, these two pathways are later separated and it is possible using the technique of spatio-temporal noise masking to isolate the chromatic component without affecting the luminance contrast component (Barbur & Ruddock, 1980). The amplitude of the dynamic luminance contrast noise does not affect the subject's ability to distinguish the chromatic properties of the stimulus at or above threshold; however, increasing amplitude causes an almost linear increase in detection thresholds for an achromatic stimulus (Barbur et al, 1994). The coloured stimuli, in the form of a 5x5 square of checks that subtends 0.8 degrees of visual angle, moves diagonally within the array of luminance contrast noise at a speed of 4° per second; the direction of motion is varied randomly for each presentation. The colours are specified as chromatic displacements (CDs) in Euclidian distance away from the background chromaticity coordinates in 16 directions, 12 corresponding to the red-green and 4 yellow-blue colour directions, in CIE 1931 colour space. The CDs are calculated according to the following equation:

$$CD = \sqrt{(x_t - x_b)^2 + (y_t - y_b)^2}$$

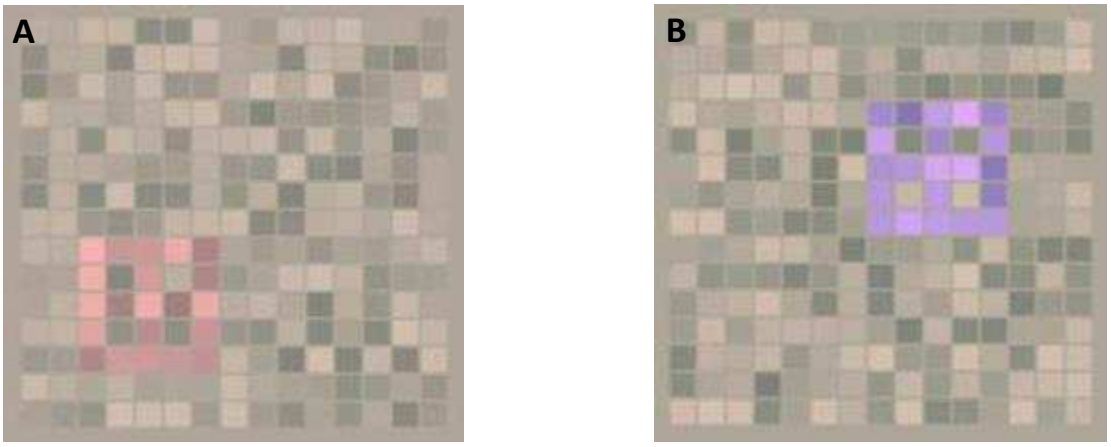


Figure 2-6: The CAD test employs dynamic luminance contrast noise to isolate a subject's response to the chromatic signal generated by the moving stimulus. Stimulus colour is specified as a chromatic displacement away from background chromaticity coordinates in CIE 1931 colour space: in this case displacements of angles 330° (A) and 240° (B).

The subject is required to respond to the direction of motion of the coloured stimulus by pressing one of four corresponding buttons on a response pad. A four-alternative, forced-choice procedure in which staircases for each of the 16 colour directions are randomly interleaved is used to determine the minimum CD that a subject requires in order to reliably discriminate stimuli in each of the colour directions. The staircase employed requires two correct responses in order to decrease the saturation of the target upon the next presentation, whereas one incorrect response increases the saturation. This ensures that a subject's threshold for the detection of each colour direction is determined, and so often a subject will not be able to detect any stimulus. In this case, the subject is asked to press any button; as two correct responses are required in order to decrease the saturation, the chance of this occurring randomly is 1 in 16. The staircase requires 11 reversals; hence it is highly unlikely that a subject's resulting threshold will be affected by this aspect of the test. The thresholds for the 16 colour directions are then automatically plotted superimposed on the CIE 1931 chromaticity diagram (similar to MacAdam ellipses) – the lower a subject's threshold, the closer the points will be to the background chromaticity coordinates. This provides a useful tool for the diagnosis of subjects with colour vision deficiency, as the ellipse will be enlarged compared with those of normal subjects and will be orientated along the protan, deutan or tritan confusion lines. These chromatic discrimination thresholds correspond almost linearly to the cone contrasts (i.e. the difference in cone signal between the stimulus and the background) generated by these stimuli, and hence are a good measure of a subject's level of chromatic sensitivity (Barbur & Rodriguez-Carmona, 2012).

In addition to the chromatic discrimination ellipses plotted, the CAD test also provides a numerical indication of a subject's chromatic sensitivity compared to the average normal, which is expressed in Standard Normal Units (SNUs). One SNU relates to the median CD required for threshold discrimination of the red-green (RG) and yellow-blue (YB) colours for a population of 330 normal

trichromats (Rodriguez-Carmona, 2006). Therefore a subject with a RG threshold of 2 will require twice the coloured signal for detection as the average normal, and so on. This allows a quantification of a subject's level of colour vision that is more systematic than most traditional tests of colour vision, which rely on numbers of errors made as a measure of chromatic sensitivity. The upper limit of the normal RG range is set at 1.815 SNU, therefore anyone with a RG threshold higher than this would be diagnosed as colour deficient.

The CAD test is currently in use by the CAA and many other aviation authorities as a secondary test for those subjects that fail the Ishihara, and is also used to test for normal colour vision for UK air traffic controllers. The pass criteria for a commercial pilot licence require a deutan subject to have a RG threshold of 6 or less, whereas protan subjects require a RG threshold of 12 or less. This standard was determined by assessing the most difficult, safety-critical task involving colour vision that pilots are required to carry out (this being the identification of the Precision Approach Pathway Indicator (PAPI) lights that assist pilots in landing), and creating a task analogous to this; performance on a PAPI simulator for colour deficient observers was then related to that of normal trichromats. It was determined that all colour deficient subjects that have thresholds within the aforementioned limits will be able to perform equally as well as normal subjects (Barbur et al, 2009).

2.2 SUBJECTS AND METHODS

Data were obtained through the Colour Vision Assessment Clinic at City University London. This was done in partnership with Dr Marisa Rodriguez-Carmona. In total, 519 subjects (22 female and 497 male) were tested: 141 with normal colour vision, 268 deutans and 110 protans. All subjects carried out the Ishihara 38-plate test, CAD test and Nagel anomaloscope.

Subjects from this group were also examined with the AO-HRR plates (128 normal trichromats, 267 deutans, 109 protans), the D15 test (84 normal trichromats, 232 deutans, 93 protans), the City University test (2nd Ed.) (128 normal trichromats, 267 deutans, 109 protans), the Holmes-Wright type A lantern (41 normal trichromats, 171 deutans, 80 protans) and the Holmes-Wright type B

lantern (41 normal trichromats, 67 deutans, 30 protans). All tests used were approved by the City University Research and Ethics Committee. Subjects were aged between 16 and 64; results from those with known retinal disease or other conditions that affect visual performance were not included. Subjects were not screened for refractive error and visual acuity was not measured, and so this should be noted as a potential source of variability in results between subjects of similar colour sensitivity.

All tests were carried out in a dark room. The Ishihara, AO-HRR and CU test were illuminated with a Macbeth Easel lamp (Kollmorgan Corporation, Waltham, Massachusetts), such that the plates of each test were positioned at a 45° angle relative to the light source, with the subject seated directly facing the plates at a distance of approximately 0.75 metres. The Macbeth Easel lamp provides a spectral power distribution approximating CIE standard illuminant C, produced an illuminance of ~280 lux at the plates. Responses for each plate were recorded; when the subject gave a response that was not correct, the response given was recorded. The Farnsworth D15 was carried out under the same lamp, with the test caps being placed directly beneath; the order in which the subject ordered the caps was recorded.

The Nagel anomaloscope (type 1) was used (Schmidt & Haensch GmbH & Co., Berlin, Germany); the room was lit using a tungsten-halogen lamp to provide low-level ambient light conditions. The subject's matching range was determined for the dominant eye, with the other eye being tested subsequently in order to ensure a similar matching range for both.

The CAD test was displayed on a NEC Multisync P241W LCD monitor (NEC Display Solutions, Tokyo, Japan), which was automatically calibrated using the LUMCAL program provided with the CAD, and was viewed from a distance of 1.4 metres, with indirect low-level ambient light provided by a 7 watt halogen lamp. The subject was positioned on a head rest to ensure the correct viewing distance, and made responses via a Microsoft Bluetooth Number Pad (model 1391). The background adaptation field of chromaticity x= 0.305, y= 0.323 CIE 1931 had a luminance of 24 cd m^{-2}.

Initially, the subject was requested to carry out a 'learning mode' version of the CAD test, in which the target stimuli can be distinguished from the dynamic luminance contrast noise by having a greater luminance as well as a chromatic displacement, and hence can be seen by all subjects regardless of colour deficiency. This step was taken to ensure that a subject is capable of using the response pad and understands the test procedure. Following this, the full version of the CAD test was carried out using staircases for targets with CDs in the following red-green directions: 140°, 145°, 150°, 165°, 170°, 175°, 320°, 325°, 330°, 345°, 350°, 355°, and the following yellow-blue directions: 60°, 64°, 240°, 244°. Staircases had 11 reversals with an initial step size of 0.025 SNU, reducing throughout to a minimum of 0.001 SNU. The average CD of the last 6 reversals in the staircase was used to calculate the subject's threshold. The amplitude of dynamic luminance contrast noise for each cheque was set at ±45% of the background luminance.

In order to determine the efficiency with which the various colour vision tests separate subjects into either the pass or the fail category compared to the relative severity of their deficiency, the CAD test was used to provide a measure of the subjects' chromatic sensitivities.

The advantage of the CAD test is that, as mentioned in 2.1.8, it has been shown to be a highly accurate test which also matches the colour class classification of deutan- and protan-like deficiencies that can be obtained on the Nagel anomaloscope. The CAD test also quantifies the severity of colour vision loss on a scale that is directly proportional to the cone contrasts generated by the coloured stimulus at threshold (Rodriguez-Carmona et al, 2012). The performance of subjects with congenital colour deficiency on conventional colour screening tests can therefore be compared against the subject's loss of chromatic sensitivity as measured on the CAD test.

2.3 STATISTICAL ANALYSIS FOR DIAGNOSTIC TESTS

As discussed in 2.1, some colour vision tests were designed to have a certain level of difficulty such that a colour deficient subject with a certain level of residual chromatic sensitivity could pass and hence be trusted to work in a certain occupational role. Other tests, on the other hand are

concerned with the detection and/or diagnosis of a colour vision deficiency with the highest level of accuracy possible. With either goal in mind, there is variation in the efficiencies of the different tests available. The level of efficiency can be described using two parameters: the sensitivity of the test (the proportion of 'positives' – in this case colour deficient subjects – that are correctly identified by the test) and the specificity (the proportion of negatives – i.e. subjects with normal colour vision – that are correctly identified by the test). For screening tests the sensitivity should be as high as possible, however for occupational roles where the colour vision requirements are not too demanding it can be lower thereby allowing mild colour deficient subjects, which could carry out the role adequately, to pass.

These parameters alone are not enough to describe a test's ability to give the correct diagnosis. The expected rates of correct or incorrect diagnoses can also be calculated, and are described by two factors: the Positive Predictive Value (PPV) which is the proportion of subjects with positive test results that are correctly diagnosed, and the Negative Predictive Value (NPV) which is the proportion of subjects with negative test results that are correctly diagnosed.

In order to determine the sensitivity, specificity, PPV and NPV for a given test one would need to know the true condition of a subject; in the absence of a perfect test (something with 100% sensitivity and specificity) that allows this to be known, the test being evaluated is versus the current 'gold standard' (Altman, 1991). This can be carried out by direct comparison of diagnoses of the two tests for the same population of subjects as follows:

		Reference Test		
		Pass	**Fail**	**Total**
Test being evaluated	**Pass**	a	b	a+b
	Fail	c	d	c+d
	Total	a+c	b+d	n

Table 2-1: Schematic table for the comparison of two diagnostic tests. The diagnostic efficiency of the test being evaluated is derived from the pass/fail rates for the same population of subjects (n) compared with the reference test.

Based on the comparison in Table 2-1, the proportion of correct test results for the new test is (a+d) divided by n. It is now possible to calculate the efficiency of the test with the following formulae:

-Sensitivity = d /(b + d)

-Specificity = a /(a + c)

-PPV = d /(c + d)

-NPV = a /(a + b)

Although PPV and NPV in this case describe the predictive qualities of the test in this situation, these statistics would vary if the test is carried out in a different situation where the prevalence of the condition is different. These values can be recalculated for a different prevalence of the condition using the following formulae, denoted as PPV_2 and NPV_2:

$$PPV = \frac{\text{sensitivity x prevalence}}{\text{sensitivity x prevalence} + (1 - \text{specificity}) \text{ x } (1 - \text{prevalence})}$$

$$NPV = \frac{\text{specificity x } (1 - \text{prevalence})}{(1 - \text{sensitivity}) \text{ x prevalence} + \text{specificity x } (1 - \text{prevalence})}$$

The overall agreement between the two tests can also be calculated from this comparison and is described by kappa ($\varkappa$) on a scale of 0 – 1.0, with 1.0 being total agreement and 0 being agreement equivalent to chance (Viera & Garrett, 2005). Kappa is defined as:

$$\varkappa = \frac{P_o - P_e}{1 - P_e}$$

where P_o is the observed proportional agreement and P_e is the expected proportional agreement, and are defined as:

$$P_o = \frac{a + d}{n}$$

$$P_e = \frac{(c + d)(b + d)}{n^2} + \frac{(a + b)(a + c)}{n^2}$$

2.4 RESULTS

2.4.1 The Nagel normal range

In order to make an assessment of the clinical efficiency of a diagnostic test, it is necessary to compare that test to the current 'gold standard', and in the case of colour vision testing this is generally accepted to be the Nagel anomaloscope (Birch, 2001; Squire et al, 2005). The Nagel has been shown to be effective at classifying subjects as normal trichromats, anomalous trichromats or dichromats.

There is considerable variation in the chromatic sensitivities of normal subjects as well as colour deficient subjects; variations in photopigment genes, cone outer segments, cone population ratio, macular pigment density and cone spatial distribution all contribute to this (discussed in section 1.2.3). The performance of a normal subject on the Nagel will therefore also vary both in the midpoint and matching range, and establishing the parameters of what qualifies as a normal match is further complicated by slight differences between individual anomaloscopes; this range is usually determined by testing many normal trichromats (Birch, 2001). Therefore it was necessary to examine the variability of subjects classified as normal using the anomaloscope and find the statistical limits of the normal range. 141 normal trichromats were tested on the Nagel anomaloscope used in this study; the parameters to be examined were the midpoint of the match as well as the matching range. Results for these data are plotted in Figures 2-7 and 2-8 respectively.

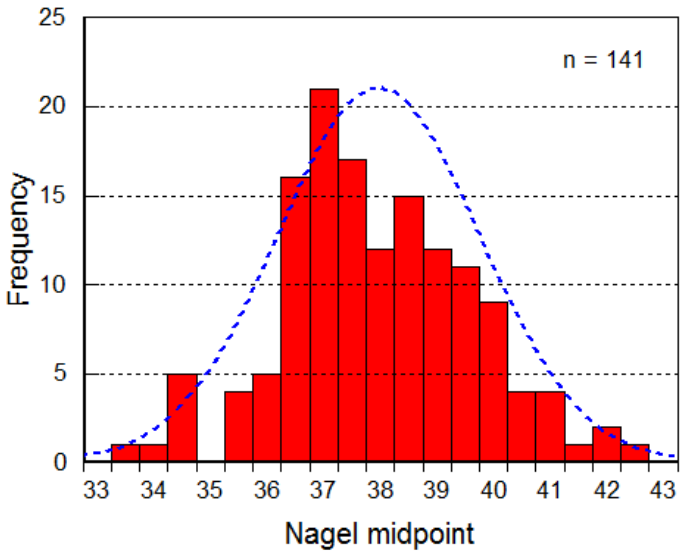


*Figure 2-7: The distribution of the midpoints of the matching ranges of 141 normal subjects on the Nagel anomaloscope. The Gaussian distribution of the data is denoted by the dotted line, the parameters of which were mean (*μ) = 37.95 and standard deviation (σ) = 1.70.

The data for the normal subject's midpoints produces a Gaussian distribution according to the Shapiro-Wilk W test; the null hypothesis that the data does form a Gaussian distribution could not be rejected with a W-value of 0.984 (p = 1.01).

Therefore, the mean (37.9) ±1.96 standard deviations will be used as the cut-off points for the normal midpoint. In this case the lower 2.5% limit is at 34.54, and the upper 97.5% limit is at 41.35; as it is not possible to have a midpoint value that is not divisible by 0.5, this range of midpoints is adjusted to 34.5 – 41.0. There were 6 subjects from the original group of 141 normal subjects that failed the Nagel under these criteria. Using the median for the midpoint would have allowed 4 more subjects to be considered within the normal range than this, and so this was noted and analysis included in the appendix. The mean was 37.9 whereas the median was 38 for this sample, and so using either as a measure of central tendency could be considered appropriate; the mean was chosen in this case as previous work examining the normal range of midpoints for the Nagel had used this measure (see Appendix 6.1 for analysis using the median).

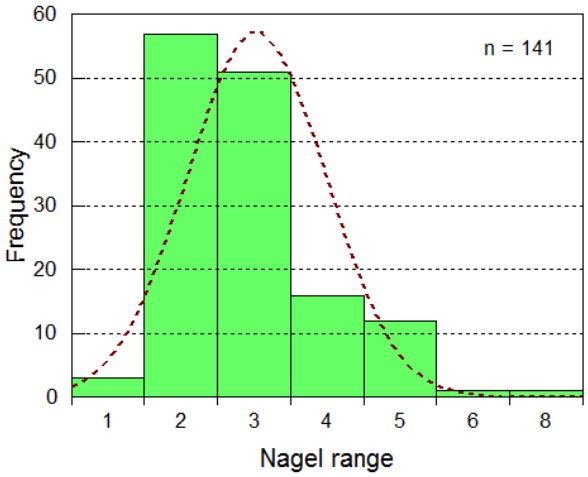


Figure 2-8: The distribution of the matching ranges of 141 normal subjects on the Nagel anomaloscope. The plot does not form a Gaussian distribution.

The matching range data did not, however, form a normal distribution and therefore without any assumed distribution against which outliers could be determined, it was not possible to say that any data in this sample was an outlier (there was no evidence that any of the data points were due to error in collection, and so are assumed to be valid). The data for the normal subject's matching ranges does not produce a Gaussian distribution according to the Shapiro-Wilk W test; the null hypothesis was rejected with a W-value of 0.827 ($p < 0.05$).

Based on this analysis of data from 141 normal subjects, the pass criteria for the Nagel anomaloscope used in this study is defined as:

-The midpoint of the matching range must be between 34.5 and 41 units

2.4.2 Comparison of the CAD and Nagel anomaloscope

With the pass criteria for the Nagel established, it is now possible to assess the clinical efficiency of the CAD test, using the population of subjects that were tested with both. Table 2-2 compares the pass / fail rates of the two tests for a population of 519 subjects:

		Nagel **Midpoint 34.5 – 41, Range 1 - 5**		
CAD **RG threshold ≤1.815**		Pass	Fail	**Total**
	Pass	130	6	136
	Fail	5	378	383
	Total	135	384	Subjects = 519

Table 2-2: the pass and fail rates for subjects tested on the CAD test (where a pass requires a red-green colour threshold of 1.815 or less) compared with the performance of the same population of subjects on the Nagel, where a pass requires a matching-range midpoint of 34.5-41.

	CAD
Sensitivity	0.98
Specificity	0.96
PPV	0.99
NPV	0.96
P_o	0.98
P_e	0.62
$\varkappa$	0.94
PPV_2	0.68
NPV_2	0.99

Table 2-3: The set of predictive values for the CAD test, calculated for the prevalence of colour vision deficiency in the general male population (approximated as 8%); due to the data being collected at a colour vision assessment clinic, the prevalence of colour vision deficiency in this population was significantly higher (72.83%).

This comparison shows that there is a very high agreement ($\varkappa$ = 0.94) between the CAD and the Nagel Anomaloscope. The CAD has more than 98% sensitivity, and hence will be able to correctly diagnose the same number normal subjects in the clinical setting as the Nagel, with the PPV indicating a less-than-two-percent chance of the CAD failing to correctly diagnose a colour deficient subject. While there were 3 % of the colour deficient subjects in this population that were identified

as normal on the CAD but with Nagel or midpoints that fell outside of the established normal range, the NPV indicates that the CAD should be able to identify ~95% of normal subjects in the clinical setting at City University London.

The PPV for the general population (PPV_2) shows that some subjects that would be classified as normal on the Nagel would be colour deficient on the CAD (approximately 32% could fall outside the upper limit of chromatic sensitivity), and NPV_2 values show that only less than 1 % (actual value: 0.0003%) of the population who are colour deficient would be classified as being normal. Although the percentage outside of the upper limit may initially seem high, the upper limit of normal RG in this comparison was 1.85. This figure was established as the mean of 330 normal trichromats with a median age of 26, and therefore this limit represents a relatively young population. As mentioned in section 1.2.5, RG thresholds increase in a linear fashion from the age of 20, and therefore it would be likely that a substantial portion of the general population would fall outside of this limit based on the effects of ageing. Of the 5 subjects that passed the Nagel but failed the CAD, one subject was aged 61, and would be expected to have slight deterioration in chromatic sensitivity that may have been enough to place them outside the normal range (Knoblauch et al, 2001). Furthermore there were three female subjects with histories of colour vision deficiency in their family and hence could show reduced chromatic sensitivity outside of the normal range; heterozygote carriers may partially display the colour deficiency in some L and M cones (Pickford, 1947). With these subjects accounted for, the PPV2 value improves to 0.92 indicating that 8% of the general population could fall outside the upper limit of chromatic sensitivity on the CAD if these factors are accounted for.

The one subject that passed the Nagel but failed the CAD had a relatively high CAD threshold of 9.84, and failed the Ishihara test with only 5 of the first 25 plates correct, as well as the AO-HRR test with 8 errors on the red/green plates. This subject could potentially be using both a hybrid L and M cone in order to make 'normal' Rayleigh matches as described in section 2.1.6; for subjects of this type the CAD has the advantage of being able to diagnose them. As the Nagel is an 'imperfect gold standard'

test, it is important to note that the results will be subject to 'imperfect gold standard bias', in which the accuracy of the test under evaluation is underestimated where there is no tendency for the two tests to make the same errors (Zhou et al, 2011).

2.4.3 The Ishihara test 38-plate edition

The pass/fail results for colour deficient subjects tested on the first 25 plates of the Ishihara test (38-plate edition), where a pass requires a subject to make 0 errors on the first 25 plates, are compared with the threshold for normal RG performance on the CAD test in Table 2-4.

		CAD **RG threshold ≤1.815**		
		Pass	Fail	**Total**
Ishihara **0 errors on plates 1-25**	Pass	128	4	132
	Fail	9	378	387
	Total	137	382	Subjects = 519

Table2-4: The pass and fail rates for subjects tested on the Ishihara 38-plate edition (where a pass requires 0 errors on the first 25 plates) compared with the performance of the same population of subjects on the CAD test.

The pass/fail results for colour deficient subjects tested according to CAA criteria, that a pass requires a subject to make 0 errors on the first 15 plates, are compared with the threshold for normal RG performance on the CAD test in Table 2-5.

		CAD RG threshold ≤1.815		
		Pass	Fail	**Total**
Ishihara 0 errors on plates 1-15	Pass	131	6	137
	Fail	6	376	382
	Total	137	382	Subjects = 519

Table2-5: The pass and fail rates for subjects tested on the Ishihara 38-plate edition (where a pass requires 0 errors on the first 15 plates as per the CAA criteria) compared with the performance of the same population of subjects on the CAD test.

	Ishihara 0 errors	
	First 25 Plates	**First 15 plates**
Sensitivity	**0.99**	**0.98**
Specificity	**0.93**	**0.96**
PPV	**0.98**	**0.98**
NPV	**0.97**	**0.96**
P_o	**0.98**	**0.98**
P_e	**0.62**	**0.61**
κ	**0.94**	**0.94**
PPV_2	**0.57**	**0.66**
NPV_2	**0.99**	**0.99**

Table 2-6: Measures of diagnostic efficiency for the Ishihara 38-plate test with the CAD test as a reference test, where a pass is set as 0 errors on the first 25 or first 15 plates.

The comparison of the Ishihara test with the CAD indicates, as expected, that it is a very sensitive test with 99% or 98% of colour deficient subjects identified using the first 25 plates or first 15 plates respectively, and hence performs well as a screening test. This sensitivity appears to come at the cost of also diagnosing some normal subjects as colour defective; where one error constitutes a fail results show that 7.0% of normal subjects as per the CAD would not pass the Ishihara. This number is reduced when the CAA criteria of allowing no errors only on the first 15 plates to 4.6%, however the sensitivity is also reduced to 98.4%. Of the 9 normal subjects that passed the CAD test but failed the Ishihara test, two made one error plus one common misreading, and the remaining subjects made

common misreadings on plates 7, 12, 13 and 17. The JAR criteria to only consider errors and misreadings made in the first 15 plates therefore resulted in 2 normal subjects that made misreadings on plate 17 would have passed.

The NPV_2 values of the Ishihara test under either criterion are high and indicate that almost anyone who passes will have normal colour vision; however the fact that some normal trichromats will also fail and hence require secondary testing is reflected in the comparatively lower PPV_2 values.

2.4.4 The American Optical (Hardy, Rand and Rittler) plates (AO-HRR)

The pass/fail results for colour deficient subjects tested on the AO-HRR test, where a pass requires a subject to make 0 errors on all plates, are compared with the threshold for normal RG performance on the CAD test in Table 2-7; diagnostic efficiency values for the AO-HRR, calculated with the CAD test as the reference test, are shown in Table 2-8.

		CAD **RG threshold ≤1.815**		
		Pass	Fail	**Total**
AO-HRR **0 errors total**	Pass	121	21	142
	Fail	1	356	357
	Total	122	377	Subjects n=499

Table2-7: The pass and fail rates for subjects tested on the AO-HRR test (where a pass requires 0 errors) compared with the performance of the same population of subjects on the CAD test

AO-HRR 0 errors	
Sensitivity	**0.94**
Specificity	**0.99**
PPV	**0.99**
NPV	**0.85**
P_o	**0.96**
P_e	**0.61**
$\varkappa$	**0.889**
PPV_2	**0.91**
NPV_2	**0.99**

Table 2-8: Measures of diagnostic efficiency for the AO-HRR test with the CAD test (with an upper limit of normality set as 'RG threshold ≤1.815') as a reference test, where a pass is set as 0 errors from all plates.

There were no tritan subjects in this sample and so it is not possible to comment on the YB diagnostic ability of the test. In comparison to the Ishihara, the AO-HRR test was less sensitive, allowing 17 more colour deficient subjects to pass, which translates to the prediction that an extra 0.4% of the population who are colour deficient to be able to pass compared with the Ishihara. However, only one normal subject failed the AO-HRR and so there is a significantly higher probability that a subject who fails will be colour deficient.

Only one protan was able to pass. Previous work has indicated that the AO-HRR can be passed by subjects with minimal colour vision deficiencies (Birch, 1997); to examine this, the CAD thresholds of deutan subjects that carried out the AO-HRR test are plotted in rank order in Figure 2-9. As indicated, there are no deutans with a RG threshold of over 5 (the highest being 4.87) that are able to pass without error. As a consequence of this, minimal deuteranomalous subjects would be expected to pass the AO-HRR and be confused with normal trichromats without further testing.

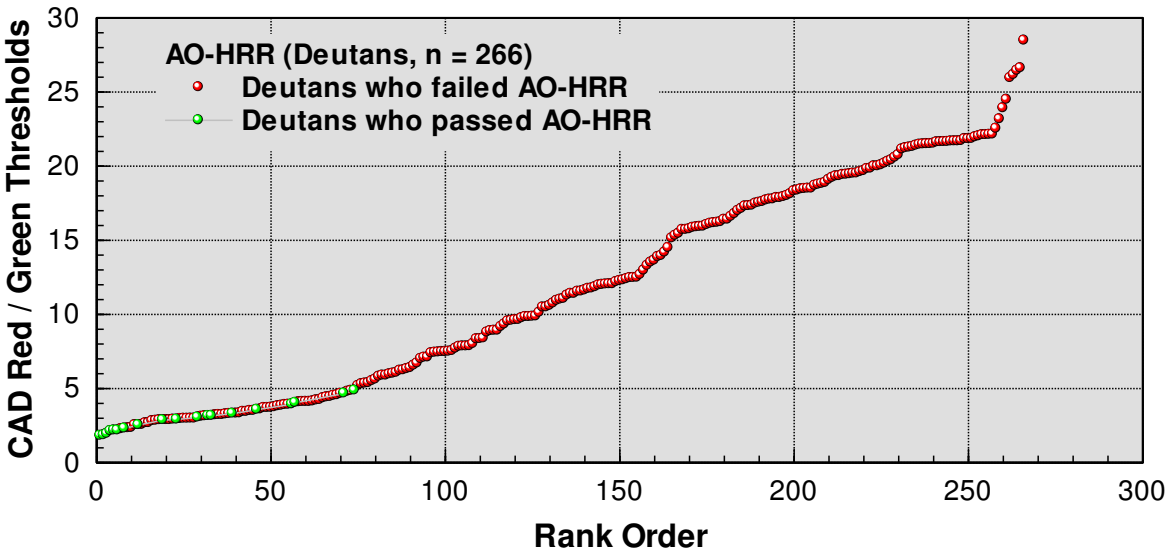


Figure 2-9: CAD thresholds of all deutan subjects that were tested on the AO-HRR test in rank order. The green circles indicate where the subject was able to pass without error, and the closed red circles indicate those that failed.

2.4.5 The City University Test (2nd edition)

The pass/fail results for colour deficient subjects tested on the City University test (2nd edition), where a pass requires a subject to make normal responses on all pages, are compared with the threshold for normal RG performance on the CAD test in Table 2-9; diagnostic efficiency values, calculated with the CAD test as the reference test, are shown in Table 2-10.

		CAD RG threshold ≤1.815		
CU test (2nd Edition) 0 errors total		Pass	Fail	**Total**
	Pass	122	174	296
	Fail	0	203	203
	Total	122	377	Subjects n=499

Table2-9: The pass and fail rates for subjects tested on the CU test (where a pass requires 0 errors) compared with the performance of the same population of subjects on the CAD test.

CU test (2nd Edition) 0 errors	
Sensitivity	**0.54**
Specificity	**1.00**
PPV	**1.00**
NPV	**0.41**
P_o	**0.65**
P_e	**0.45**
$\varkappa$	**0.36**
PPV_2	**1.00**
NPV_2	**0.96**

Table 2-10: Measures of diagnostic efficiency for the CU test with the CAD test as a reference test, where a pass is set as 0 errors.

All normal trichromats can be expected to pass this test, which has specificity, PPV and PPV_2 of 100%, however a relatively large number of colour deficient subjects can pass this test as well; 46.2% of colour deficient tested passed without error. One protanope was also able to pass without error. In the general population, the PPV_2 shows that all subjects that fail this test will indeed be colour deficient, while the NPV_2 shows that out of the general population 3.9% would be classified as normal where they are colour deficient. The CU test shows a relatively weak agreement with the CAD test, with the kappa value indicating a slightly above-chance agreement.

Pass/fail results for the same subject population were then compared with the CAD as a reference test, where the police RRD criterion of 3 or less incorrect responses over all pages, shown in Table 2-11 with updated diagnostic efficiency values shown in Table 2-12.

		CAD RG threshold ≤1.815		
		Pass	Fail	**Total**
CU test (2nd Edition) ≤ 3 errors total	Pass	122	248	370
	Fail	0	129	129
	Total	122	377	Subjects n=499

Table2-11: The pass and fail rates for subjects tested on the CU test (where a pass requires 3 or less errors) compared with the performance of the same population of subjects on the CAD test.

CU test (2nd Edition) ≤ 3 errors	
Sensitivity	**0.34**
Specificity	**1.00**
PPV	**1.00**
NPV	**0.33**
P_o	**0.50**
P_e	**0.38**
$\varkappa$	**0.20**
PPV_2	**1.00**
NPV_2	**0.95**

Table 2-12: Measures of diagnostic efficiency for the CU test with the CAD test as a reference test, where a pass is set as 3 errors or fewer.

When the police RRD criterion of a pass consisting of 3 or less errors is considered the results show that, as with a pass criterion of 0 errors, all normal trichromats will be correctly identified with these criteria however the accuracy of this test is further diminished. There were 7 dichromats that were able to pass with 3 or fewer errors: 1 deuteranope and 6 protanopes. As stated in section 2.1, this test was designed not as a screening test but to assess a subject's ability to distinguish between surface colours and hence mild and moderate subjects are expected to pass whilst more severely deficient subjects should fail, and so it is therefore useful to analyse the CAD thresholds of those colour deficient subjects that took both tests. Results for deutan and protan subjects are shown in Figures 2-10 and 2-11 respectively.

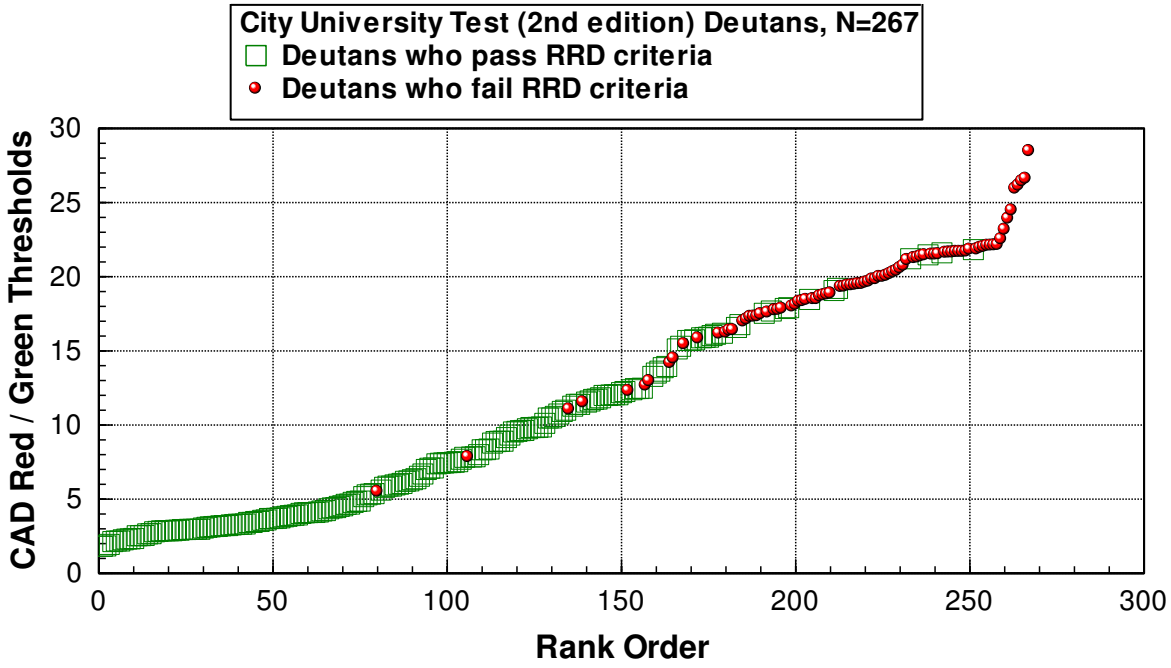


Figure 2-10: CAD thresholds of all deutan subjects that were tested on the CU test in rank order. Open green squares indicate where the subject was able to pass the RRD criteria, and the closed red circles indicate those that failed.

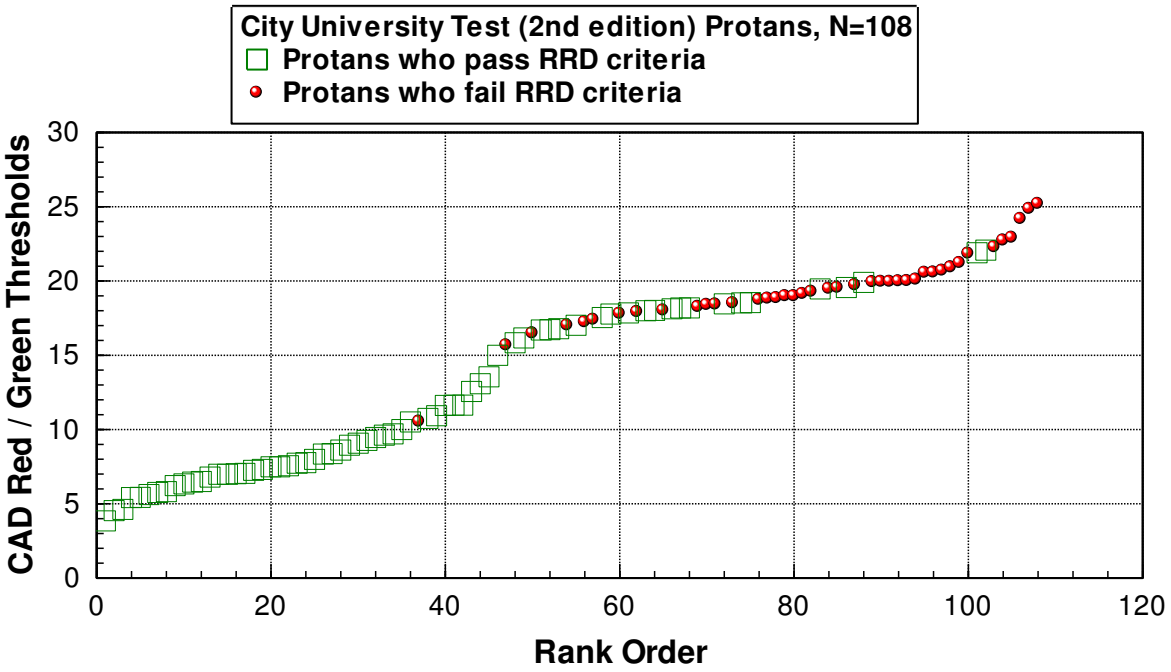


Figure 2-11: CAD thresholds of all protan subjects that were tested on the CU test in rank order. Open green squares indicate where the subject was able to pass the RRD criteria, and the closed red circles indicate those that failed.

From Figures 2-10 and 2-11, there is a clear overlap in severity between those that pass and fail the test based on the RRD criteria, and even severe colour deficient subjects can pass the test while less

severe subjects can fail. This was true for both deutan (Fig. 2-10) and protan (Fig. 2-11) subjects. Three protanopes (as assessed by the Nagel anomaloscope) were also able to pass with 3 or less errors.

In addition, the diagnostic element of this test is not consistent; 8 of 267 deutans were classified as either protan or had equal deutan and protan/tritan responses, and 37 of 108 protans were similarly classified. In addition there were 58 more deutans making at least 1 protan response and 21 more protans making at least 1 deutan response. There were no cases where a subject made all-deutan responses where this was not the correct diagnosis, which only occurred in 5 deuteranopes and 2 severe deuteranomalous subjects. On the other hand, there were no protans that made only protan responses.

2.4.6 The Farnsworth D15

The pass/fail results for colour deficient subjects tested on the Farnsworth D15 test, where a pass requires a subject to make no major crossings on the cap sequence plot, are compared with the threshold for normal RG performance on the CAD test in Table 2-13; diagnostic efficiency values, calculated with the CAD test as the reference test, are shown in Table 2-14.

		CAD **RG threshold ≤1.815**		
		Pass	Fail	**Total**
Farnsworth D15 **No major crossings**	Pass	81	184	265
	Fail	0	141	141
	Total	81	325	Subjects = 406

Table 2-13: The pass and fail rates for subjects tested on the D15 (where a pass requires no major crossings on the cap sequence plot) compared with the performance of the same population of subjects on the CAD test.

D15 No major crossings	
Sensitivity	**0.51**
Specificity	**1.00**
PPV	**1.00**
NPV	**0.34**
P_o	**0.61**
P_e	**0.44**
κ	**0.29**
PPV_2	**1.00**
NPV_2	**0.96**

Table 2-14: Measures of diagnostic efficiency for the D15 test with the CAD test as a reference test, where a pass requires no major crossings on the cap sequence plot.

As with the CU test, the Farnsworth D15 has 100% specificity and PPV, and hence all normal subjects will pass without error, whereas all subjects that fail will be colour deficient. Not all colour deficient subjects will fail however, as indicated by the NPV values. This was expected, given that the tests are based on the same Munsell sample colours and hence should have relatively similar difficulty levels. There is a slight difference in sensitivity however, in that the D15 has a sensitivity of ~51% compared with ~54% for the CU test.

The D15 was also designed to assess a subject's ability to distinguish between surface colours and hence separate those mild/moderate colour deficient subjects that can perform these tasks from the more severe subjects that cannot. In order to determine the relationship between a subject's CAD threshold and performance on the D15, CAD thresholds of all subjects were put in rank order for those that passed and failed, shown in Figures 2-12 and 2-13.

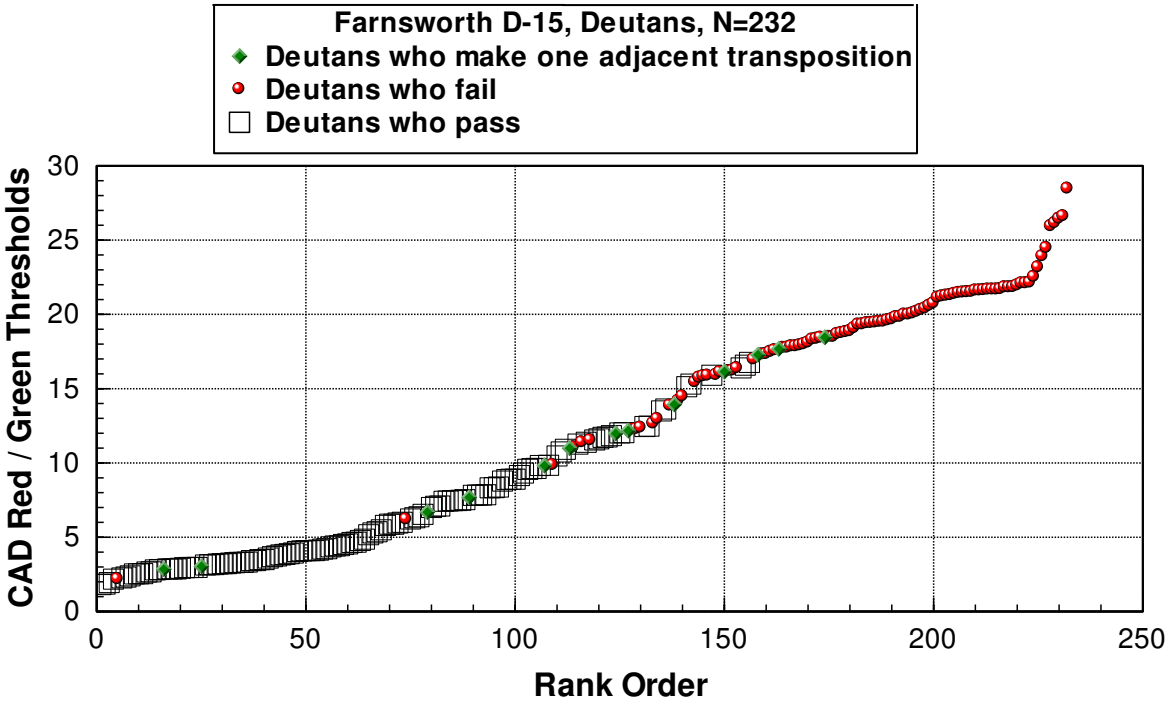


Figure 2-12: CAD thresholds of all deutan subjects that were tested on the D15 in rank order. Open black squares indicate where the subject was able to pass without error, green squares indicate that one adjacent transposition was made, and the closed red circles indicate those that failed.

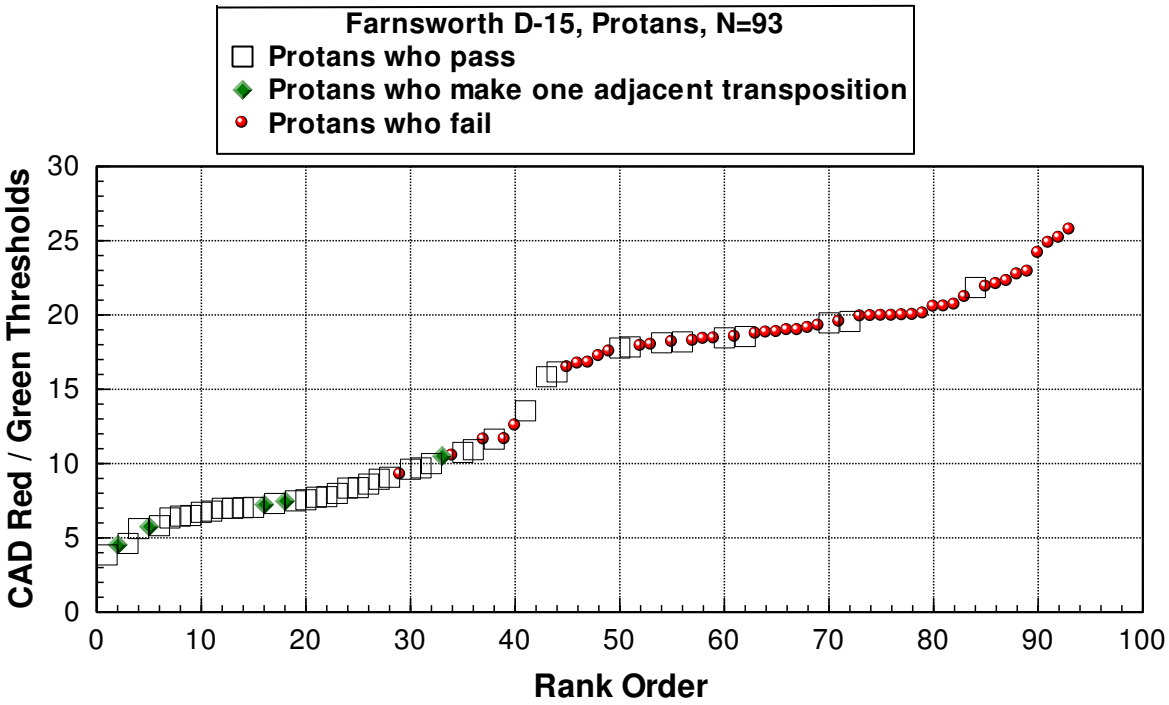


Figure 2-13: Thresholds of all protan subjects that were tested on the D15 in rank order. Open black squares indicate where the subject was able to pass without error, green squares indicate that one adjacent transposition was made, and the closed red circles indicate those that failed.

For both classes of congenital colour deficient it is possible for severe subjects to pass while less severe subjects can fail. Several severe protans appear to be able to pass without error. For deutans, where one major crossing constitutes a fail, this can be made by subjects with milder deficiencies than some which passed. No dichromats passed the D15.

2.4.7 The Holmes - Wright lanterns (types A and B)

The difference in difficulty between the HW-A and the HW-B is illustrated in Table 2-15; all normal subjects can be expected to pass the type A, and furthermore it is possible for a number of deutans to pass. All colour deficient subjects tested fail the type B, and 12.2% of normal subjects also fail.

Percentage that pass	HW-Type A	HW-Type B
Normal	100.0 (n=42)	87.8 (n=41)
Deutan	22.2 (n=171)	0 (n=67)
Protan	0 (n=80)	0 (n=30)

Table 2-15: The percentage of subjects tested that were able to pass the HW-A and the HW-B.

The pass / fail results for all subjects tested on the Holmes – Wright lantern type A, compared with performance on the CAD test, are summarised in Table 2-16, with resulting diagnostic efficiency values shown in Table 2-17:

		CAD **RG threshold ≤1.815**		
		Pass	Fail	**Total**
HW - A standard criteria	Pass	41	38	79
	Fail	0	212	212
	Total	41	250	291

Table 2-16: The pass and fail rates for subjects tested on the HW-A (where a pass requires 0 in the first run of either lighting condition, or no errors in the second and third runs of either lighting condition) compared with the performance of the same population of subjects on the CAD test.

HW-A standard criteria	
Sensitivity	**0.85**
Specificity	**1.00**
PPV	**1.00**
NPV	**0.52**
P_o	**0.87**
P_e	**0.66**
$\varkappa$	**0.61**
PPV_2	**1.00**
NPV_2	**0.99**

Table 2-17: Measures of diagnostic efficiency for the HW-A with the CAD test as a reference test, where a pass requires 0 in the first run of either lighting condition, or no errors in the second and third runs of either lighting condition.

All subjects in the general population that fail the HW-A will be colour deficient, as indicated by a PPV_2 value of 1, and 1.3% of the population who have congenital colour deficiency (in this case, all would be deutan) are also predicted to pass as per the NPV_2 value of 0.987. Figure 2-14 compares the CAD thresholds of the 171 deutans tested with their performance on the HW-A. It is clear that while in general the subjects with lower CAD thresholds are more likely to be able to pass, there is not a complete separation of those that pass and those that fail. The ability to pass the HW-A is therefore not linked solely to a subject's chromatic sensitivity and may depend on a variety of factors affecting individual difference in performance when viewing small light sources.

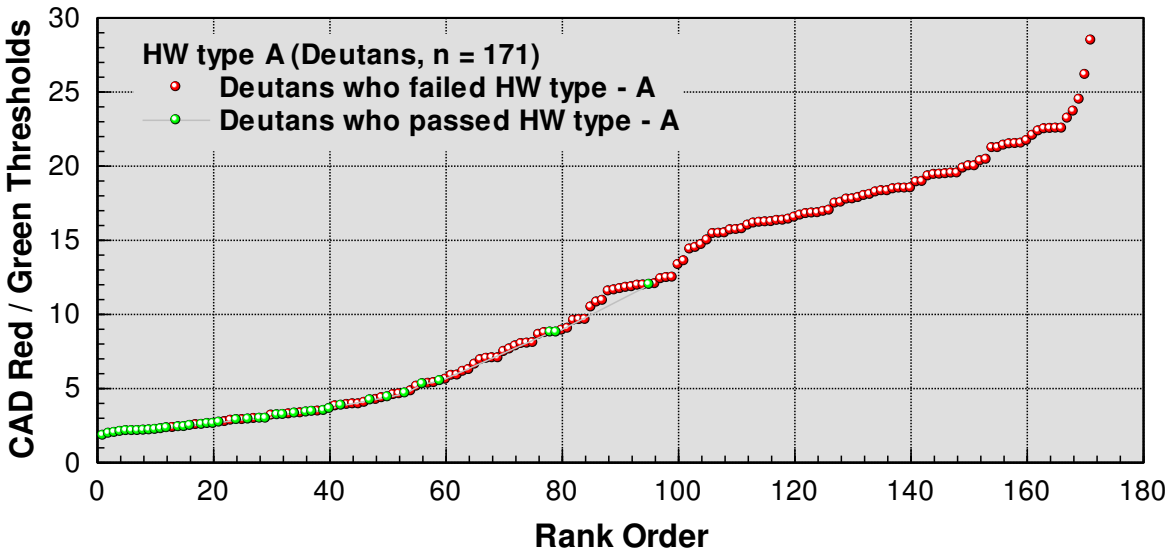


Figure 2-14: The ranked chromatic sensitivities, as measured by the CAD test, of 171 deutan subjects that carried out the HW-A. Those that pass are indicated with green symbols, those that fail with red.

Figure 2 -14 shows the performance of 171 deutan subjects on the HW-A. From this it is clear that there is significant overlap between those that pass and those that fail for this sample. Subjects with a CAD RG threshold under 2.35 always pass.

The pass / fail results for all subjects tested on the Holmes – Wright lantern type B are shown in table 2-18.

		CAD RG threshold ≤1.815		
		Pass	Fail	**Total**
HW - B MCA Criteria	Pass	36	0	36
	Fail	5	97	102
	Total	41	97	138

Table 2-18: The pass and fail rates for subjects tested on the HW-B (where a pass requires 0 errors in the introduction followed by 0 errors in all runs) compared with the performance of the same population of subjects on the CAD test.

HW-B MCA criteria	
Sensitivity	1.00
Specificity	0.88
PPV	0.95
NPV	1.00
P_o	0.96
P_e	0.60
$\varkappa$	0.91
PPV_2	0.42
NPV_2	1.00

Table 2-19: Measures of diagnostic efficiency for the HW-B with the CAD test as a reference test, where a pass requires 0 errors in the introduction followed by 0 errors in all runs.

In contrast to the HW-A, only 41.6% of subjects in the general population that fail are predicted to be colour deficient, and all colour deficient subjects are expected to fail. As an occupational screening test this therefore ensures that no colour deficient subject will pass but at a cost of also failing some normal subjects. The CAD thresholds of all those subjects that failed the HW-B are shown in figure 2-15

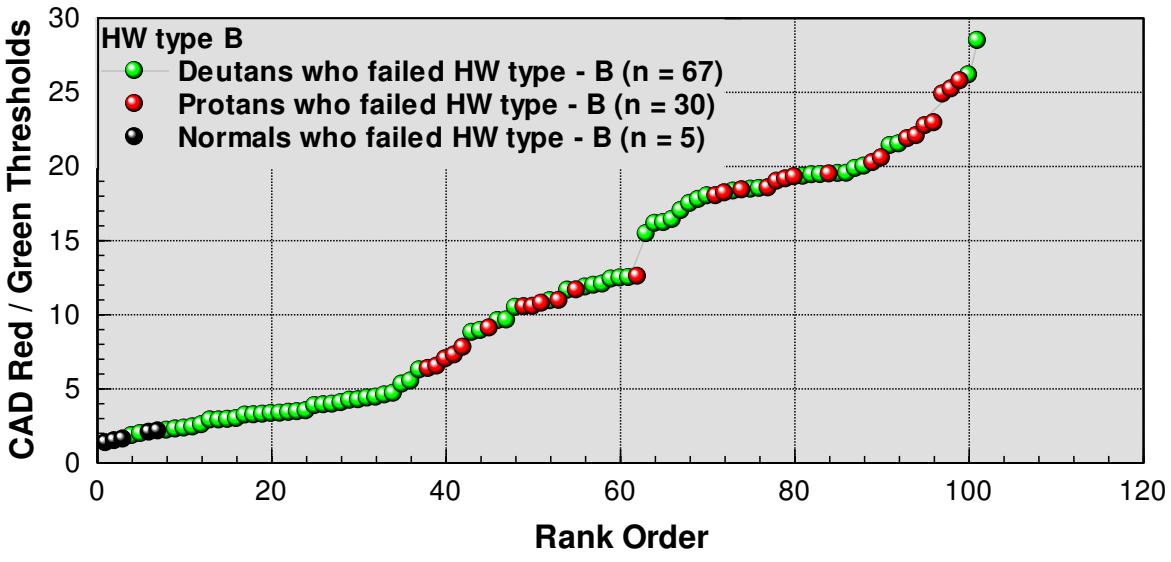


Figure 2-15: The ranked chromatic sensitivities, as measured by the CAD test, of 102 subjects (5 normal, 30 protan and 67 deutan) that failed the HW-B. Even when very mild colour deficiencies are involved no deutan or protan subject passes.

There is a chance for normal subjects to fail the Ishihara test with more than three errors, and even with this criteria there are deutan and protan subjects that would pass. Reducing the number of errors allowed would filter out more colour deficient subjects, but also fail more normals. When secondary testing is carried out using the Holmes-Wright lanterns, the type A passes all normals, however many mild colour deficient subjects can pass, whereas the lantern type B fails all colour deficient subjects as well as some normal subjects.

2.5 CONCLUSIONS

2.5.1 The Ishihara test

The value of the Ishihara is as a quick and highly sensitive screening test; where subjects fail there should be a secondary test available. Negative predictive values calculated for the Ishihara confirm that less than 0.1% of the population that is colour deficient will be able to pass. This comes at a cost of specificity however: 7.0% of normal subjects fail, and as explained in section 2.1.2, increasing the number of errors allowed to ensure that all normal subjects pass would increase the number of colour deficient that are able to pass, and so this is not advisable. In terms of a secondary test to confirm that a subject is normal, there are no tests which pass 100% of normals but fail 100% of colour deficient subjects; the Nagel or the CAD would be the best choice.

The JAR criterion has the effect of increasing the number of normal subjects that can pass by reducing the potential for misreadings. This only reduces the sensitivity of the test by 0.6% and provides an increase in specificity of 2.2%, which appears to be an acceptable trade-off. There is the counter-argument that the purpose of the Ishihara is simply to detect deficiencies with as much sensitivity as possible, and where normals fail they can be subsequently assessed with one or more other tests to clarify the diagnosis. Under these conditions the pass criterion of ‘no errors’ is the most effective.

2.5.2 The American Optical (Hardy, Rand and Rittler) plates (AO-HRR)

The AO-HRR is a relatively sensitive pseudoisochromatic plate screening test however, when no errors are permitted on either test, the Ishihara test is more sensitive. Only one normal trichromat made an error out of 122 tested and so the AO-HRR will rarely provide a false positive, however this comes at the cost of allowing colour deficient subjects with a CAD RG threshold of below 5 SNU to also pass. While the AO-HRR avoids the complication of having to be able to read and interpret the font used in the Ishihara test, it would not be possible to say whether a subject who failed the Ishihara test but passed the AO-HRR was able to achieve this based on the lack of misreading, or simply due to the detection of the figures being less demanding. The AO-HRR has the advantage of including screening plates for tritan deficiency, however no tritans were identified in this study and so it is not possible to make any evaluation of how effective this component of the test is, other than to say that no subjects made errors on these plates.

2.5.3 The Nagel anomaloscope

As previously mentioned, effective diagnosis using the Nagel requires an expert examiner, who is capable of interpreting the subject's responses – which may often be ambiguous or inaccurate. While the normal range of the instrument used in this study was established, there were subjects that were assessed as having normal colour vision that fell just outside of this range. In addition one deutan subject with a relatively high CAD threshold of 9.84 and 19 errors on the first 25 plates of the Ishihara 38 plate edition was able to make Rayleigh matches within the normal range established in 2.1.6.

Although the Nagel is a very effective means of diagnosing a subject as normal, protan or deutan, and separating colour deficient subjects into anomalous trichromats or dichromats, it is not without drawbacks. Its increasing rarity means that colour vision standards based on it may not be practical to implement. In addition to this, the matching range and midpoint on the Nagel are contingent on multiple factors other than the spectral responsivity functions of cones: the optical density of

photopigment, the L:M cone ratio and noise of the L/M channel affect the result, accounting for some unusual matches in normal trichromats. Modelling of the Rayleigh match has indicated that in some cases, colour deficient observers who rely on both hybrid M' and L' cones can be classified as normal trichromats (Barbur et al, 2008).

While other anomaloscopes are available, such as the Neitz anomaloscope (Neitz Instruments Co., Tokyo), or the Oculus HMC anomaloscope (Oculus GmbH, Wetzlar) that requires subjects to make Moreland matches (blue-green matches as opposed to the Nagel's red-green), these instruments are less popular and the blue-green matches are more difficult to interpret.

2.5.4 The City University test (2nd edition)

The results for the CU test are similar to those of the D15: all normal subjects will pass without error as well as many colour deficient subjects. This is expected, as the test was designed to test a subject's ability to recognise surface colours rather than to identify all subjects with a deficiency. For both classes of congenital colour deficient, there is not a clear separation in the chromatic sensitivities of those that pass and those that fail. From Figures 2-10 and 2-11, it is clear that there are several occasions where significantly less sensitive subjects pass without error while more sensitive subjects can make an error. There was also one protanope that was able to pass without error.

The extent of the usefulness of the CU test is therefore limited to when the arrangement aspect of the D15 presents too much of a challenge, or the D15 is not available.

It has been previously noted that the diagnostic element of this test is not reliable, and that many colour deficient subjects will make mixed deutan, protan and normal responses in the same run (Birch, 1984). The findings here are in agreement with this; 8 deutans (out of 267) and 37 protans (out of 108) had incorrect or equally-mixed responses, with 58 more deutans making at least 1 protan response and 21 more protans making at least 1 deutan response. There were no cases

where a subject made all-deutan responses where this was not the correct diagnosis, whereas there were no protans that made only protan responses. This emphasises that the CU test is only reliable where severe deficiencies are present, but also that this test appears to favour protan subjects – a finding that has been previously reported (Birch, 1997; Oliphant et al, 1998).

The current standard for police rapid response drivers appears to be completely ineffective in excluding any particular category of colour-deficient save for deuteranopes, and therefore should be reconsidered.

2.5.5 The Farnsworth D - 15 test

It is assumed that the D15 is calibrated to present a colour-matching task that is of sufficient difficulty to allow more mild / moderate colour deficient subjects to pass, while severe colour deficient subjects will fail, however the result shown here demonstrates that this is not always the case. Although no dichromats have passed this test, there are protan subjects with high CAD thresholds that pass.

For both classes of congenital colour deficient, there is not a clear separation in the chromatic sensitivities of those that pass and those that fail. From Figures 2-12 and 2-13, there are clearly several occasions where significantly less sensitive subjects pass without error while more sensitive subjects can make an error – for example a deutan with a CAD threshold of 21.85 was able to pass, where another deutan with a threshold of 9.27 failed.

The current testing procedure used by the fire service is only effective for excluding protan subjects when a Nagel anomaloscope is available – however considering that this piece of equipment is relatively rare and requires an experienced user in order to administer, this will not always be used in conjunction with the D15, and therefore those protans that pass the D15 will be accepted for employment. As the current criteria suggest that one major crossing should be classed as a fail, there is an overlap between moderate deutans: some more mild subjects fail where more severe subjects

sometimes pass. It is therefore doubtful that the D15 test will be a good predictor of who can correctly identify surface colours in general.

2.5.6 The Holmes Wright lanterns (type A and B)

The HW-A allows some mild deutans to pass along with all normals, however no protans pass. The deficiencies of those deutan subjects that are able to pass the HW-A are generally quite minimal, with CAD thresholds of 5 or lower, however there are a few subjects with higher thresholds that have also been able to obtain a pass. The pass criteria used here – no errors in the first run under either lighting condition, or no errors in the subsequent two runs under either lighting condition – could be altered to 'no errors on the three runs of either lighting condition', however this would still not fail all deutans and some normals would also fail.

The HW-A is therefore not a perfect screening test as minimal colour deficient subjects can pass, and when it is used as a secondary test following the Ishihara, there is a chance that minimal deutan subjects will be confused with normal subjects. While this lantern has been superseded by the CAD test for aviation in the UK, it is still in use by the armed forces. As it is no longer in production, it would be advisable for those occupations still relying on it as a secondary test to determine a suitable replacement test.

It is interesting to note that there was not a complete segregation between those subjects that failed the HW-A and those that passed, based on their CAD thresholds. Therefore some subjects are capable of passing that have less chromatic sensitivity than some who fail. This indicates that the lantern test does not isolate the chromatic channels as effectively as the CAD test, potentially because of the high luminance contrast that exists between the target light of the lantern and the surrounding background. This effect is further investigated in chapter 3. It should also be considered that as refractive error was not measured in this cohort, and the visual angle of the lantern signal lights is relatively small, this could be a potential source of some of this variation. There is, however,

no resolution task involved and hence the principal effect of any uncorrected refractive error must be through a change in retinal illuminance.

All subjects with CAD RG thresholds below 2.35 were able to pass the HW-A, and so this threshold could be used as an alternative where the lantern is not available. However the variability in performance on this lantern was such that many deutan subjects with RG thresholds higher than this were also able to pass, and therefore this approach should only be considered as a temporary alternative in place of a thorough study to determine the specific requirements of either the lantern test, or the working conditions that it aims to replicate.

The HW-B will fail all colour deficient subjects but also can be expected to fail some normal subjects. As the Ishihara test is also capable of failing some normals, this means that the current MCA testing protocol has the potential to incorrectly fail some normal subjects.

The difficulty of the HW-B compared with the HW-A arises from the smaller aperture through which the lights are viewed. Of the normal subjects that failed the HW-B, the majority were over the age of 48. It has previously been reported that subjects over the age of 45 show an increase in forward light scatter within the eye caused by a decrease in average pupil diameter and increase in the optical density of the crystalline lens (Hennelly et al, 1998). There is also a reduction in cone photopigment density and morphological changes occur in the cones. These factors which further contribute to reduced retinal performance and so the relatively low intensity of light from the HW-B will therefore be scattered more with increasing age of subject, reducing the light flux per area of the retina and hence overall signal strength. It could therefore be the case that a subject who is capable of passing the HW-B at the start of their career could fail it at a later time. These findings have implications for determining a suitable supplementary test when replacing the lantern, which is no longer manufactured.

2.5.7 The Colour Assessment and Diagnosis test

As detailed in section 2.4.2, the CAD has high agreement with the Nagel ($\varkappa$ = 0.975) and is comparable in terms of both diagnosing colour deficient subjects and allowing normal subjects to pass. It is worth considering that, as with the Holmes Wright lanterns, the Nagel (type 1) is no longer in production and therefore a new gold standard for colour vision diagnosis will be required in the near future. In terms of considering the CAD as a new gold standard test, it is worth taking into account that not only does it have diagnostic efficiency comparable to the Nagel, but it is capable of diagnosing the extent of a subject's chromatic sensitivity and placing that value on a simple numerical scale. This provides the opportunity for occupational standards to be set based purely on a subject's level of colour vision.

In addition the CAD does not require interpretation of a subject's responses or expert examiners in order to be administered, and can detect tritan deficiencies. Each of these factors, combined with the fact that the Nagel is relatively scarce and, as mentioned in 2.5.3, can produce unusual results, leads to the conclusion that the CAD is a suitable candidate as a new gold standard test for colour vision assessment.

2.6 DISCUSSION

Traditional tests of colour vision are often quick to administer, however they are rarely suitable for determining the ability of a subject to carry out a particular occupational task except in the case of either normal trichromatic colour vision or the significant absence of RG colour vision. Although other colour vision tests such as the D15 or the CU test are calibrated to allow those to pass who are mild enough to recognise surface colours, this in-built insensitivity appears to allow some subjects to pass where more mild subjects will fail, and in addition these colours are not necessary analogous to those used in a given occupation. The results from this chapter highlight the different difficulties, and the levels of variability involved for various colour vision tests, and indicate that each of them

may be testing different aspects of colour vision, or otherwise be co-dependent on other factors affecting visual performance, such as age or uncorrected refractive error.

It is important to consider that for suprathreshold coloured targets used in occupational environments, where the colour will often not be monochromatic, it is quite possible that a colour deficient could perform a task within the normal range of time and accuracy. A more reasoned approach to occupational colour vision testing would therefore be to attempt to quantify the visual requirements of any tasks that involve the use of colour and determine the level of colour deficiency that would impede operational performance.

However, as mentioned in section 1.2.5, ageing has a significant effect on colour sensitivity. Therefore it is important to consider that if a subject is deemed to have sufficient colour vision to safely carry out a particular role on initial application, this may not be the case throughout their employment. In the interests of safety it would be advisable to continue testing the colour vision of those working in roles where the detection and / or interpretation of coloured signals is critical at regular intervals. Where a subject is deemed to have passed existing occupational criteria, however they were close to the acceptable limit, they should be advised that this may cause potential problems in the future, so that they can plan their career accordingly.

As mentioned in 2.1.8, this process was effectively demonstrated by the CAA in setting new colour vision standards for pilots based on the most difficult colour-related safety critical task. Determining the minimum level of chromatic sensitivity, as assessed by the CAD test, that allows all subjects to carry out the task as well as normal trichromats is not only an effective way of ensuring occupational capability, but it has the advantage of being directly related to the task at hand. Where a colour vision test is accepted as a suitable standard, but is not in production and becoming increasingly rare – for example the Nagel anomaloscope or the Holmes Wright lanterns – then it is possible to use a similar method and compare the CAD thresholds of subjects to their performance on these tests, and determine a cut-off for RG threshold that represents the same difficulty as the task in question.

3 LUMINANCE AND COLOUR INTERACTION

3.1 LUMINANCE AND COLOUR IN OCCUPATIONAL COLOUR VISION TESTS

Coloured signal lights are used within occupations as a means of coding important information that allows for the safe operation of various tasks, and so it is necessary to ensure that those working in a role utilizing signal lights are able to detect and correctly interpret them. For example, as detailed in (2.1.7), the Holmes-Wright lantern type B was designed to simulate navigation lights that indicate the orientation of a ship, when viewed at night from a distance of two miles. Lantern tests and the signal lights that they aim to replicate essentially require detection of a relatively small coloured stimulus combined with a high luminance contrast relative to the surround.

As the Holmes Wright lanterns are out of production, but still used by the UK armed forces and the Marine Coastguard Agency, a suitable replacement will be required in the near future. It is therefore of interest to determine the factors affecting visual performance for the detection of signal lights.

Approximately 80% of retinal ganglion cells respond to both chromatic and achromatic spatial modulations in the retinal image; parvocellular retinal ganglion cells can exhibit both spatial and chromatic opponency and in general respond less well to rapidly changing stimuli (Barbur et al, 1994). Magnocellular ganglion cells, on the other hand, do not in general exhibit chromatic opponency and respond best to temporarily modulated stimuli. As a consequence, psychophysical experiments relating to colour vision are often designed to mask luminance contrast cues in order to isolate the chromatic response from the composite signal.

Attempting to create a coloured target that is isoluminant with the background and presenting it in isolation is problematic, as the luminous efficacy function V(λ) varies between subjects, and furthermore will vary across the visual field of each subject, and hence the equiluminant point between target and background is difficult to achieve.

Pedestal experiments are psychophysical procedures that allow for the measurement of a subject's level of sensitivity to a stimulus parameter under varying levels of chromatic and/or achromatic luminance contrast (Stockman, 2009). For measurement of chromatic sensitivity, pedestal techniques isolate the chromatic response by adding coloured stimuli to high luminance contrast targets with respect to the background adaptation field. In addition, two or more possible targets may be used that have random, static luminance variation within a specified range; the subject's task is to identify the pedestal containing the test stimulus. These conditions ensure that small changes in luminance that can be caused by the addition of the colour signal are not a viable cue for detection, and hence the identification of the target is based on the strength of the coloured signal generated. Although luminance pedestals are effective in isolating chromatic stimuli, there is no consensus on whether they have any effect of facilitating or reducing chromatic detection thresholds, and observed differences between studies likely result from procedural differences between studies (De Marco et al, 1993).

Signal lights can be thought of as luminance pedestals, with small coloured targets that have a high luminance contrast compared to the background, as can the lanterns that are used to predict operational performance. Often multiple lights are used with multiple possible colours, the combination or presence of which is used to convey information to the observer.

Luminance noise masking techniques employ a spatially-structured chromatic stimulus that is embedded in a field of achromatic luminance patches that vary randomly in luminance contrast. This noise can be static, as per the pseudoisochromatic plates described in 2.1.1, or it can be dynamic as per the CAD test described in 2.1.8. For dynamic luminance contrast procedures, the array of checks have a spatially averaged luminance level equal to the background adaptation field, and each changes luminance randomly within a specified amplitude at intervals during the stimulus presentation. Increasing the amplitude of random luminance modulation increases detection thresholds for targets defined by achromatic luminance contrast, whereas chromatic detection

thresholds are unaffected in normal subjects, and hence the chromatic response is isolated (Barbur et al, 1994).

In this chapter pedestal data will be compared with CAD test data to investigate if there are differences in the underlying mechanisms for the processing of chromatic signals in these two conditions. In aviation and seafaring conventionally red, green and white lights are employed for signals. The prevalence of colour vision deficiency leads to the question of why yellow and blue signal lights have not been employed, as the incidence of tritan deficiency is much lower. The experiments in this chapter will examine the sensitivity of S-cone as well as L and M cone stimuli.

3.2 METHODS

To investigate the use of colour for conditions that simulate the use of signal lights, a luminance pedestal technique was used that incorporated a four alternative, forced choice staircase procedure to measure chromatic detection thresholds (figure 3.1).

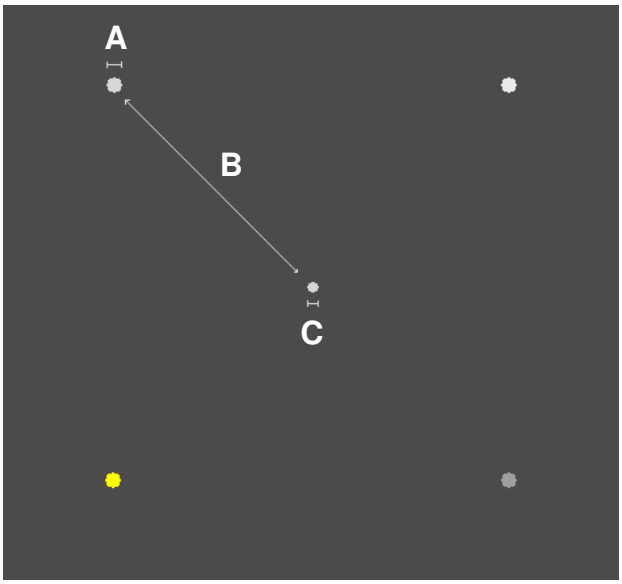


Figure 3-1: Example of the stimuli used in the luminance pedestal procedure Four pedestals (e.g. A) of equal size and chromaticity, with varying luminance contrast, were presented in a square formation a set distance (B) from central fixation (C). One of these pedestals is presented in combination with a colour and the subject is required to indicate which with using a keypad.

Jennings & Barbur (2010) showed that background luminance level affects threshold discrimination of coloured stimuli. In other words, a greater L and M cone excitation is required to produce

detection at lower background luminance which decreases linearly with luminance. Stimuli were presented against a background with the lowest luminance possible for the CRT (less than 0.05cd/m^2) in order to replicate the most difficult condition.

Stimuli were presented on a LaCie 19" Electronblue CRT monitor (LaCie Ltd, Paris, France). The Colour Naming (luminance pedestal) test was programmed by Mr Alistair Harlow (City University London). The display consisted of a dark background (less than 0.05 cd/m^2) and four disc-shaped luminance pedestals of 24cd/m^2 and chromaticity of x= 0.305, y= 0.323, positioned in a square formation at equal distances from a central fixation point. Dark adaptation was carried out for 15 minutes before each staircase. Luminance and chromatic output of CRTs fluctuate from the time they are switched on, due to the time taken to reach a stable temperature in the high-voltage cathodes and control grid accelerators (Metha et al, 1993). Therefore the CRT monitor used in this experiment was turned on for at least 45 minutes before use.

Monitor calibration is essential in ensuring that stimuli presented on the screen are as specified in the controlling software. In order to achieve this, it is necessary to know the chromaticity produced by each of the phosphors at maximum (e.g. RGB = 1023, 0, 0 for the red phosphor, where the three values correspond to the red, green and blue phosphor outputs that can be adjusted in steps of 1, between 0 and 1023), and the relationship between the voltage of each gun and the luminance produced, compared with the values set on the driver card. When this relationship is known then stimuli can be accurately defined by modifying input from the driver. Calibration was carried out by Prof. John Barbur (City University London).

A Gamma Scientific telespectralradiometer (Model 1980B) was used to measure the spectral radiance for each of the phosphors at maximum output. A LMT photometer (L1003, LMT) was then used to measure the luminance (in cd/m^2) of each of the three primary colours of the display. Luminance was measured in steps of 8 for each of the phosphors (i.e. 0 to 1023 while the other two phosphors were kept at 0). The LUMCAL program automatically calibrates the monitor based on the

relationship between inputs from the driving program and measured spectral and luminance output. All experiments were carried out within two months of calibrating the monitor.

One of the four pedestals had a colour superimposed upon it at random on each presentation, with the others remaining achromatic. The subject's task was to indicate the location of the coloured luminance pedestal using a four-button response box. Staircases had 11 reversals with an initial step size of 0.05 CAD SNU, reducing throughout to a minimum of 0.002 CAD SNU. The average CD of the last 6 reversals in the staircase was used to calculate the subject's threshold. Two correct responses decreased the saturation of the target for the next presentation, whereas one incorrect response increased the saturation. A central fixation of chromaticity x= 0.305, y = 0.323 (CIE 1931) and a luminance of 12 cd/m^2 was employed, subjects were asked to fixate on this throughout each presentation.

All subjects had normal colour vision as determined by the Ishihara Test (38 plate edition) and the Nagel anomaloscope. Additionally, all subjects carried out the CAD test (see section 2.2) to confirm normal trichromacy and to provide a base-line measurement against which performance on the luminance pedestal test could be compared. A table containing the CAD RG and YB detection thresholds for each subject in this chapter can be found in Appendix A.

Chromatic discrimination thresholds were obtained using the luminance pedestal test, for the same colour directions used in the CAD test; thresholds obtained from the luminance pedestal test were converted into CIE 1931 x, y coordinates by the following formulae:

x = 0.305+CD*COS(angle*π)/180

y = 0.323+CD*SIN(angle*π)/180

3.2.1 Parameters for preliminary tests

The purpose of the luminance pedestal technique is to ensure subjects are insensitive to any difference in luminance that would be caused by the addition of colour onto a given target. The

target, however, still generates a strong luminance contrast signal. Therefore chromatic detection is measured on the basis of the observer's ability to select one of four pedestals that have high luminance contrasts as well as a colour. Although the chromatic component is the only available cue in making a correct choice, the detection threshold could still be affected by the luminance contrast of the pedestal. It is therefore of interest to establish how chromatic detection thresholds for isolated stimuli vary with background adaptation level and luminance contrast. It is also of interest to examine if the polarity of the luminance contrast, whether positive or negative with respect to the background field, affects detection thresholds.

Chromatic detection thresholds were obtained using staircases for four colour directions (157°, 337°, 62° and 242° in CIE 1931 colour space, with a background chromaticity of x = 0.305, y = 0.323) over a range of pedestal and background luminance levels. The following light levels were used for the background adaptation field: *0 (less than 0.05)*, 1.5, 3, 6, 12, 24 and 48 cd/m^2; at each of these adaptation levels thresholds were obtained for coloured targets of the following light levels: 1.5, 3, 6, 12, 24 and 48 cd/m^2. The pedestals subtended 12' visual angle and were positioned 15' from central fixation.

Following this the procedure was refined: the luminance pedestals were set to a luminance of 3cd/m^2, allowing for a range of negative pedestal luminance contrasts. Thresholds were measured for background adaptation field light levels of 1.5, 3, 6, 12, 24 and 48 cd/m^2.

3.2.2 Preliminary results

Chromatic detection thresholds were measured in a normal trichromat subject for colour directions 157°, 337°, 62° and 242° in CIE 1931 colour space over a range of pedestal and background luminance levels. Thresholds obtained for each colour direction at each combination of luminance contrasts are shown in Figure 3-1.

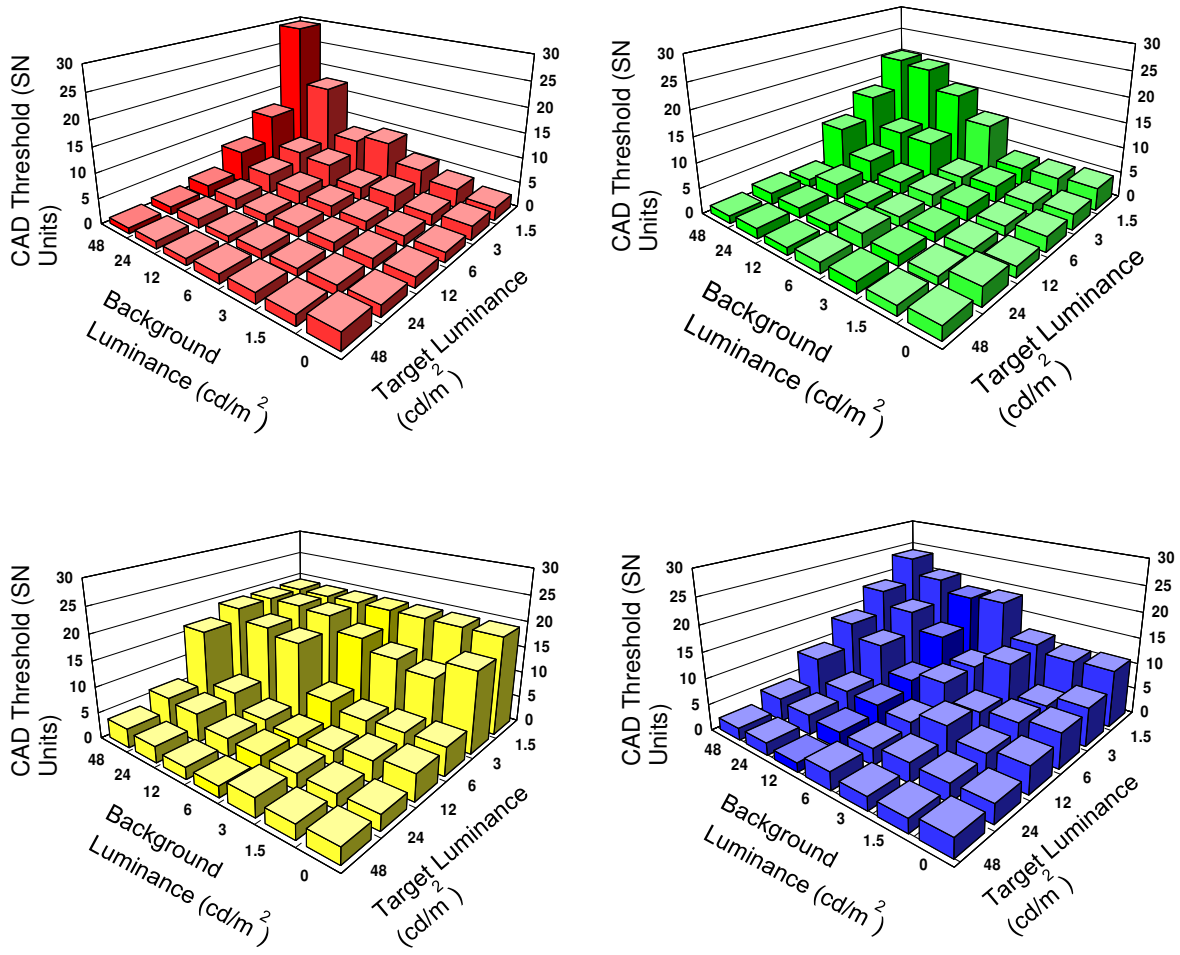


Figure 3-2: Thresholds for detection of a colour difference in a normal trichromat observer for cardinal red, green, yellow and blue luminance pedestals over a range of background and target luminance contrasts.

Preliminary data indicated that while increasing the luminance contrast such that the target has a higher luminance than the background has no effect of increasing performance over equiluminance, when chromatic signals are added to objects defined by negative luminance contrast, the corresponding colour thresholds are no longer processed independently and increase monotonically with luminance contrast. Following this, the effect of negative luminance contrast on threshold detection was further examined in three normal trichromats, as shown in Figure 3-2.

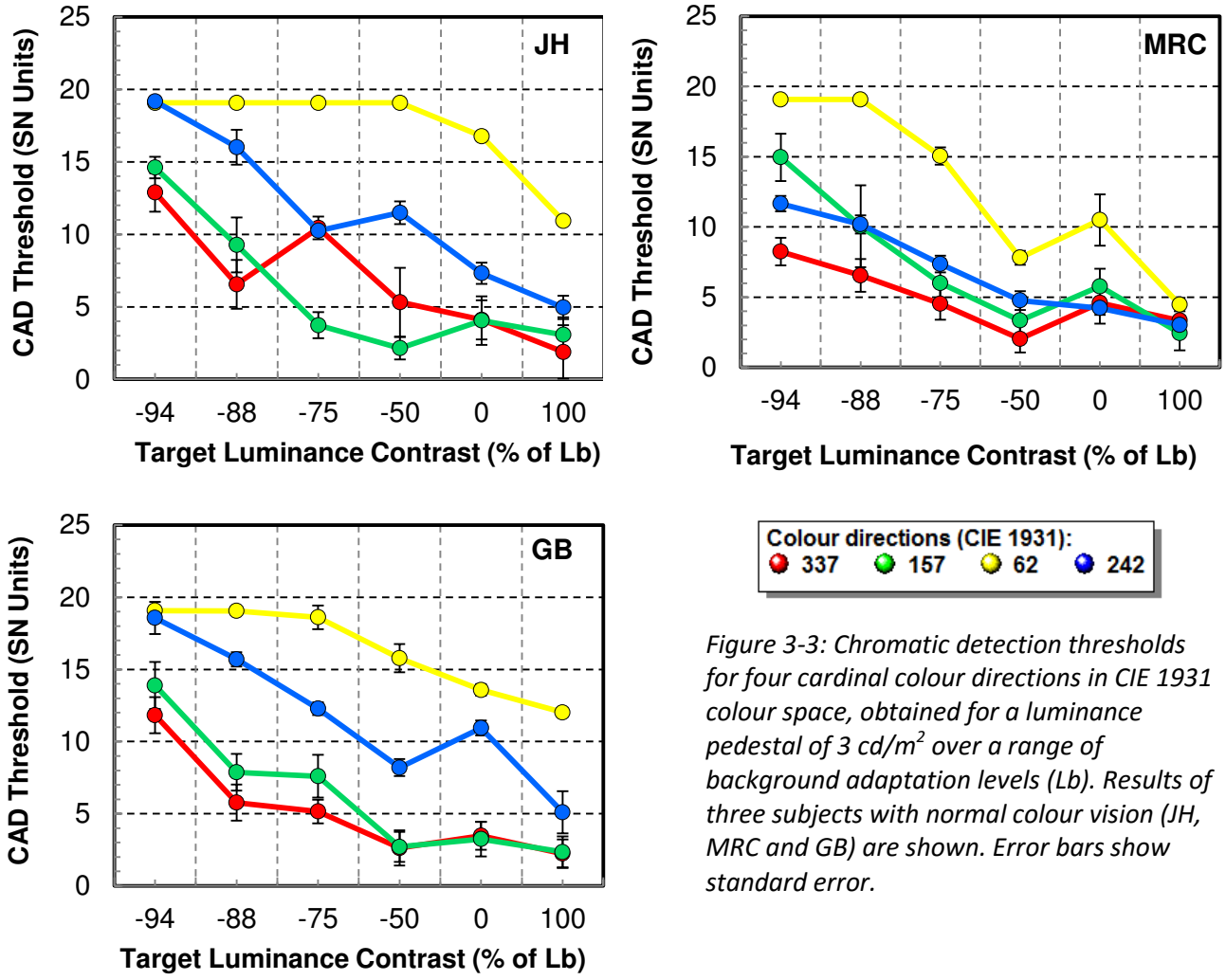


Figure 3-3: Chromatic detection thresholds for four cardinal colour directions in CIE 1931 colour space, obtained for a luminance pedestal of 3 cd/m^2 over a range of background adaptation levels (Lb). Results of three subjects with normal colour vision (JH, MRC and GB) are shown. Error bars show standard error.

As per Figure 3-2, as the luminance contrast of the target becomes more negative compared with the background, thresholds for detection increase for all colour directions. Yellow consistently yields the highest detection thresholds at each contrast measured. This indicates that in order to achieve the most accurate thresholds, it is necessary for the luminance pedestals to have a positive luminance contrast in order to avoid this interaction with the luminance of the background.

3.3 EXPERIMENT 3.1: SIGNAL LIGHT DETECTION THRESHOLDS

3.3.1 Parameters for Experiment 3.1

Experiment 3.1 was designed to allow for comparison between a subject's chromatic detection thresholds, as measured by the CAD test, and their ability to detect coloured stimuli under conditions that replicate signal lights.

The colour directions used for the pedestal stimuli were the same as those used in the CAD test to allow for a more direct comparison. Colours were expressed as a displacement away from the background chromaticity of x= 0.305, y= 0.323 in CIE 1931 colour space, along the following red-green directions: 140°, 145°, 150°, 165°, 170°, 175°, 320°, 325°, 330°, 345°, 350°, 355°, and the following yellow-blue directions: 60°, 64°, 240°, 244°. The pedestals subtended 2' visual angle and were positioned 5' from central fixation.

In each run of the experiment, there were four staircases interleaved that correspond to red, green, yellow and blue colour direction; although it would be possible to test each colour direction in isolation, this would not be analogous to real-world use of signal lights where multiple possible colours are employed. An experiment was carried out to examine this briefly and results revealed lower thresholds for isolated colours (see Appendix B).

3.3.2 Results for Experiment 3.1

The results of three subjects with normal trichromacy are shown in Figure 3-3; subjects all had colour vision, assessed by the CAD test, within the normal range. Subject JH had a CAD RG threshold of 0.74 and a YB threshold of 0.65; subject HGG had a CAD RG threshold of 1.01 and a YB threshold of 1.02; subject GB had a CAD RG threshold of 0.93 and a YB threshold of 1.22.

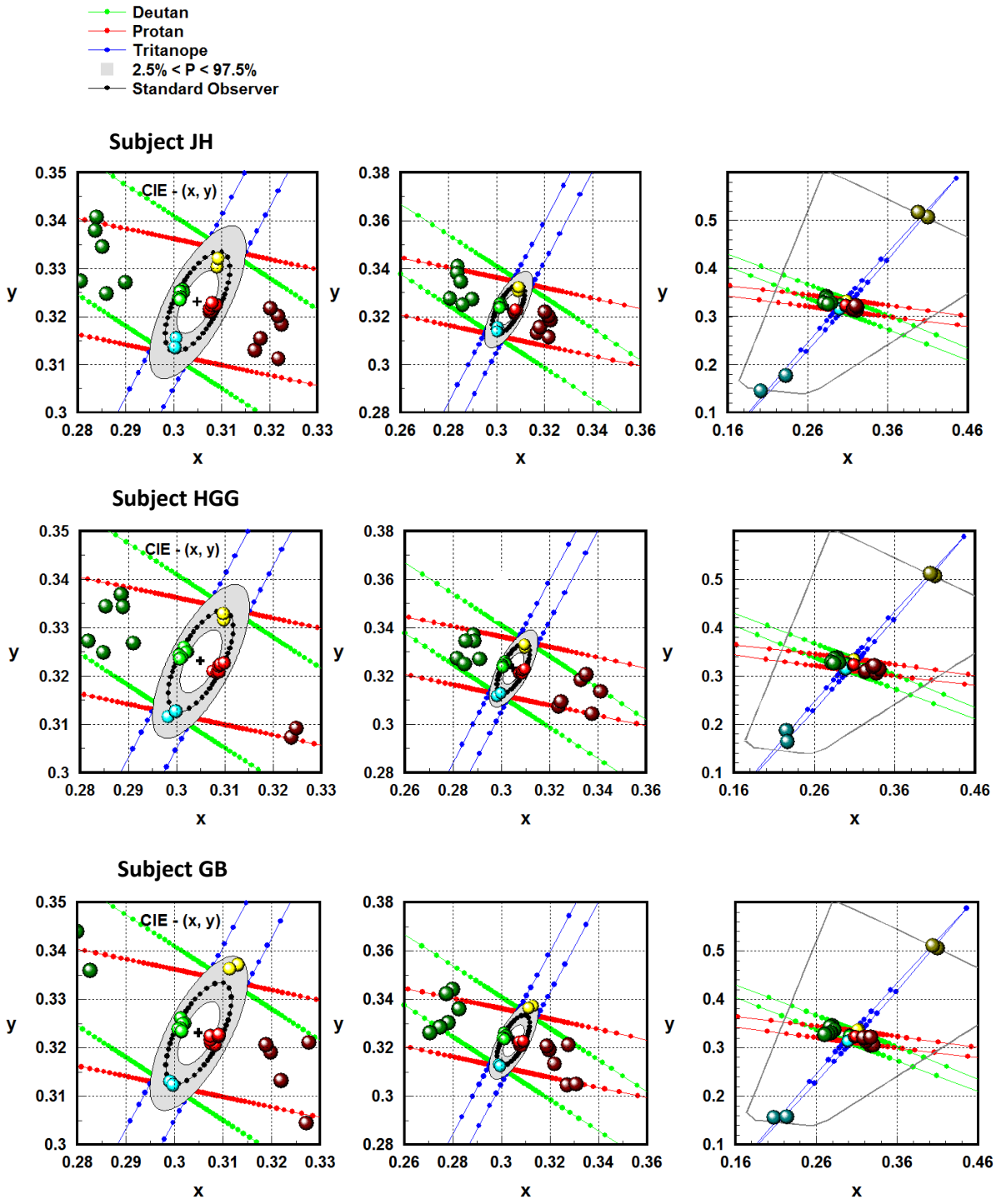


Figure 3-4: Chromatic discrimination thresholds for subjects JH, HGG and GB for the same colour directions in both the CAD and luminance pedestal tests, plotted in CIE 1931 colour space and shown at three levels of magnification. The CAD thresholds are indicated by the lighter discs within the central grey ellipse, and the luminance pedestal thresholds are indicated by the darker circles. The central point indicates the background chromaticity, and the grey ellipse indicates the normal range of colour vision on the CAD test, as described in section 2.1.8. Protan, deutan and tritan confusion axes are indicated by the regions within the corresponding dotted lines; the phosphor limits of the monitor are indicated by the area shown in the third plot. For each subject, discrimination thresholds for colours isolated by the luminance pedestal technique are noticeably higher than those thresholds obtained from the CAD test, particularly in the yellow-blue direction.

As Figure 3-3 indicates, the detection thresholds obtained for the luminance pedestal technique were significantly higher in all colour directions. When these results are converted into CAD thresholds subject JH had a RG threshold of 4.93 and a YB threshold of 17.83, subject HGG had a RG threshold of 6.53 and a YB threshold of 17.05 and subject GB had a RG threshold of 7.01 and a YB threshold of 17.95. A comparison between these thresholds and those obtained with the CAD test are shown in Table 3-1.

Subject	CAD RG threshold	LP RG threshold	CAD YB threshold	LP YB threshold
JH	0.74	4.93	0.65	17.83
HGG	1.01	6.53	1.02	17.05
GB	0.93	7.01	1.22	17.95

Table 3-1: A comparison of chromatic discrimination thresholds for subjects JH, HGG and GB for the CAD test and Luminance Pedestal (LP) technique.

Thresholds obtained were higher for the luminance pedestal test than those of the CAD test, in every colour direction, and therefore this represents a more difficult condition for chromatic detection. Most noticeably, the YB thresholds obtained would indicate tritanopia for normal subjects when viewing signal lights. For some yellow-blue colour directions, stimuli were not detected even at the maximum possible chromatic displacement that the monitor could produce; this is illustrated in the third plots for each subject in Figure 3-3.

3.4 EXPERIMENT 3.2: DETECTION OF YELLOW AND BLUE SIGNAL LIGHTS

3.4.1 Parameters for experiment 3.2

Results from experiment 3.1 indicated that under conditions that replicate the use of signal lights, normal trichromat subjects were effectively unable to detect the yellow or blue colour directions. To further explore this deficit, the luminance pedestal procedure outlined in 3.2 was repeated for the same subjects over a greater range of yellow-blue colour directions. In order to ensure consistency

with the previous experiment, staircases for these colours were interleaved with red and green colour directions.

Colours were expressed as a displacement away from the background chromaticity of x= 0.305, y= 0.323 in CIE 1931 colour space, and staircases were carried out for the following red-green directions: 337°, 157°, and the following yellow-blue directions: 32°, 47°, 55°, 62°, 69°, 77°, 92°, 227°, 235°, 242°, 249°, 257°. Due to the monitor used and the chromaticity coordinates of the background field, it was not possible to produce the same intervals of 'blue' colour directions as 'yellow', and therefore 5 blue and 7 yellow colour directions were used. Thresholds obtained were then converted into CIE 1931 x, y coordinates in order for comparison with results from experiment 3.1.

3.4.2 Results for experiment 3.2

The apparent tritanopia when viewing foveal signal lights was further measured by obtaining detection thresholds for a greater range of colours that contain a yellow-blue component.

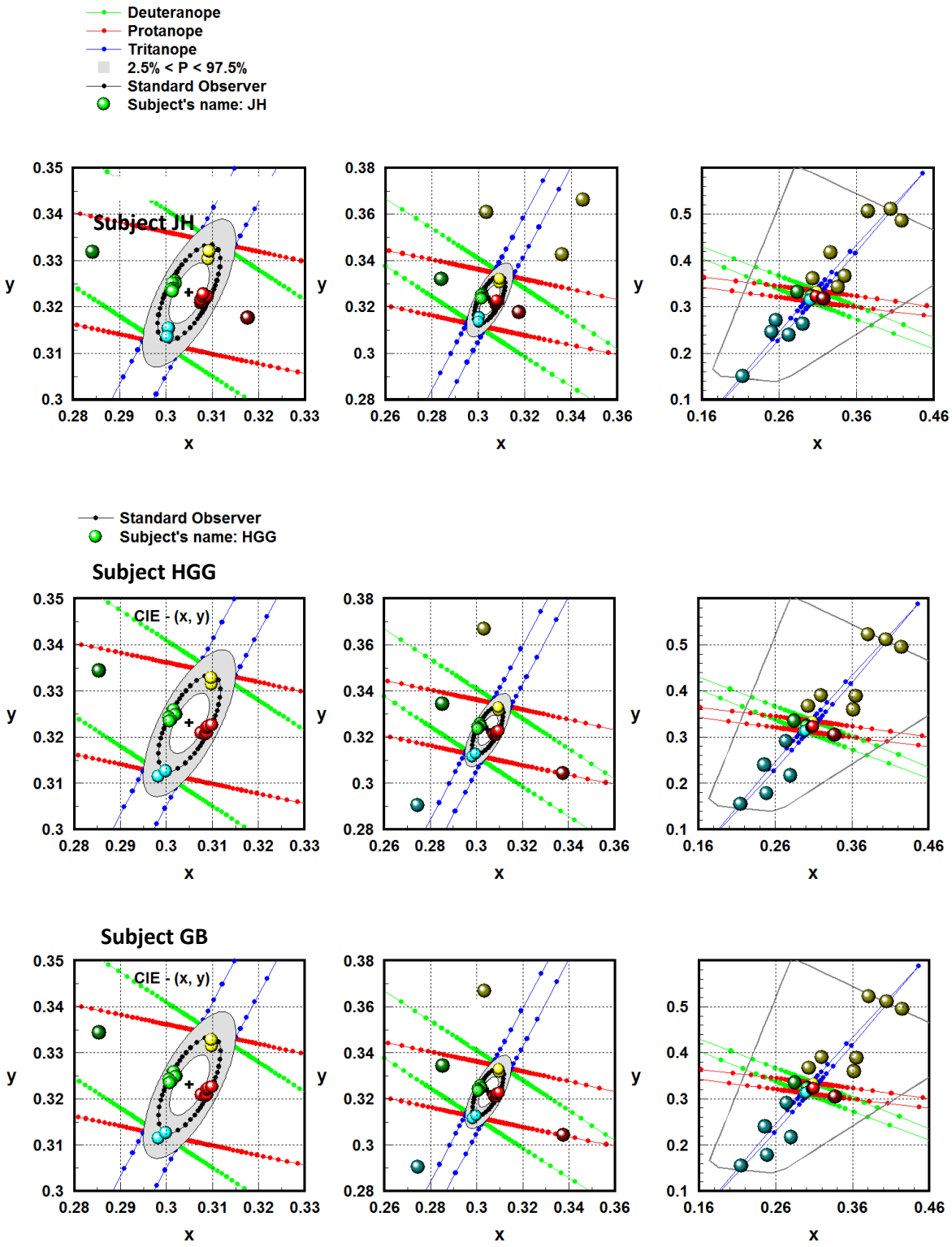


Figure 3-5: Chromatic discrimination thresholds for subject JH, HGG and GB for an extended range of yellow-blue colour directions, plotted in CIE 1931 colour space and shown at three levels of magnification. Thresholds appear to increase with the proportion of yellow or blue in the stimuli and form an ellipse along the tritan confusion axis.

The detection of yellow-blue under conditions simulating those of occupational signal lights is impaired; thresholds measured appear to increase as the colour direction becomes closer to the tritan axis, and when plotted in CIE 1931 colour space, form an ellipse along the tritan confusion axis.

Detection thresholds therefore appear to vary based on the proportion of L or M cone stimulation that the stimulus produces, with S-cones having little contribution to threshold detection.

3.5 EXPERIMENT 3.3: THRESHOLD DETECTION FOR COLOURED LUMINANCE PEDESTALS OVER A RANGE OF ECCENTRICITIES

3.5.1 Parameters for experiment 3.3

Initial measurement of chromatic detection thresholds for luminance pedestals presented within foveal viewing, in experiments 3.1 and 3.2, indicated a significant impairment for yellow-blue stimuli. The lack of S-cones in the central 0.3° - 0.4° of the fovea is a likely explanation for this result given that the stimuli were located 5' of visual angle from the central fixation, and were 2’ in diameter. Colour matching experiments have previously shown effective foveal tritanopia within the central 25’ of the fovea, and have also ruled out this effect being attributed to greater concentrations of macular pigment (Williams et al, 1981).

In order to confirm this result for the stimuli described in 3.2.1, the procedure was carried out for the same coloured stimuli over a range of eccentricities. Thresholds were initially measured for targets of eccentricities of 3’, 5’, 8’, 12’ and 15’ from the central fixation.

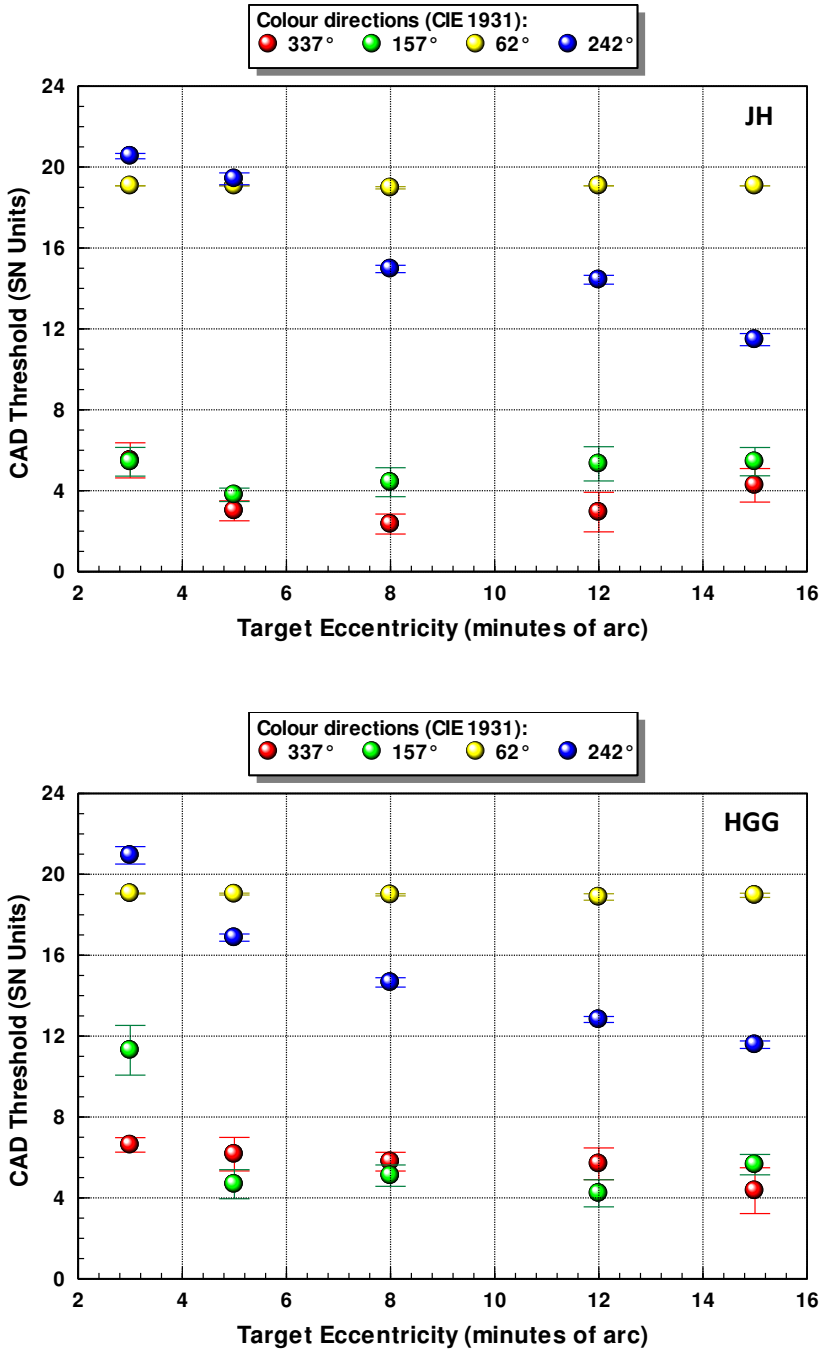
As stated in 3.2.1, the CAD test measures chromatic detection in 16 directions in colour space. Red-green colour sensitivity is measured by two sets of directions: 140° to 170° (the ‘green’ direction) and 320° to 355° (the ‘red’ direction), and yellow-blue sensitivity is measured in two sets of directions 60° – 64° (the ‘yellow’ direction) and 240° – 244° (the ‘blue’ direction). Therefore the red-green and yellow-blue directions selected for this experiment correspond to the central values of

these ranges. In each run, interleaved staircases were presented for four cardinal colour directions in CIE 1931 colour space, corresponding to red, green, yellow and blue (337°, 157°, 62° and 242° respectively). These colour directions were selected as they correspond to the centre of the confusion axes: 337° (red) and 157° (green) degrees are located centrally with respect to the deutan and protan axes and hence produce no S cone signal, and 62° (yellow) and 242° (blue) are located in the centre of the tritan axis and produce no L or M cone signal.

Following this initial procedure, results indicated an asymmetry in the detection of yellow and blue (section 3.3.3); the yellow stimulus was often not detected even at the maximum chromatic displacements that could be produced by the display. To ascertain the level of asymmetry between yellow and blue detection thresholds, and to further profile the effect, the background chromaticity was changed to x = 0.249, y = 0.217 in order to allow for greater chromatic displacements in the yellow direction. Thresholds were obtained for additional eccentricities: 3', 5', 8', 12', 15', 22.5', 30', 45', and 60' for the same four colour directions.

3.5.2 Results for experiment 3.3

Chromatic detection thresholds were measured for targets of eccentricities of 3', 5', 8', 12' and 15' from the central fixation, using the luminance pedestal test. In each run, interleaved staircases were presented for four cardinal colour directions in CIE 1931 colour space, corresponding to red, green, yellow and blue (337°, 157°, 62° and 242° respectively). Figure 3-5 shows the results obtained for 3 normal trichromats.



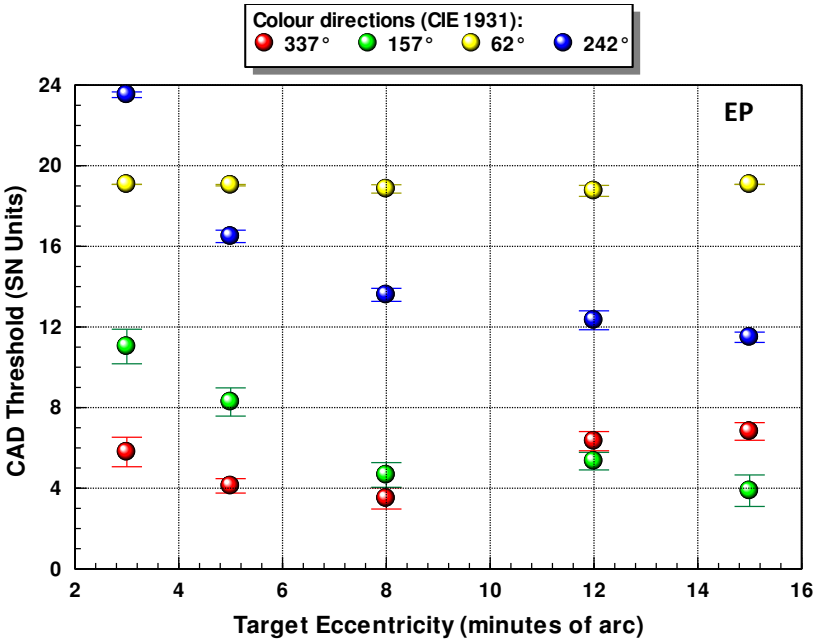


Figure 3-6: Chromatic detection thresholds for luminance pedestal stimuli over a range of eccentricities for subjects JH, EP and HGG, with standard error. Measurements taken at 3' indicate a lower threshold for the detection of the yellow (62°) target, with blue thresholds being higher, however given the gamut of the monitor and background chromaticity coordinates employed, the yellow stimulus reached the maximum possible saturation without being detectable, and hence actual detection thresholds will have been higher.

As can be seen from Figure 3-5, the detection of red and green is not affected by increasing the eccentricity of the luminance pedestals within this range. Yellow and blue thresholds remained higher at all eccentricities tested, however while thresholds for yellow were relatively unaffected by increasing eccentricity, thresholds for blue decreased.

This appears to be an unusual result as thresholds were measured for stimuli with eccentricities that fall within the S cone free region; however the detection thresholds observed were likely due to scattered light from the target spreading over a wider area of the retina. There was an asymmetry observed for the detection of yellow and blue stimuli; yellow thresholds were consistently higher and often were still not detected at the maximum chromatic displacement that could be displayed on this monitor with the given background coordinates. Therefore, the actual detection thresholds for yellow may be even greater than those indicated in Figure 3-5.

In order to examine the extent of this asymmetry, background chromaticity coordinates were changed to x = 0.249, y = 0.217 to allow for greater chromatic displacements in the yellow direction. Furthermore, thresholds were obtained for additional eccentricities: 3', 5', 8', 12', 15', 22.5', 30', 45', and 60'. Results for chromatic detection of the four cardinal colour directions over this range of eccentricities are shown in Figures 3-6 and 3-7.

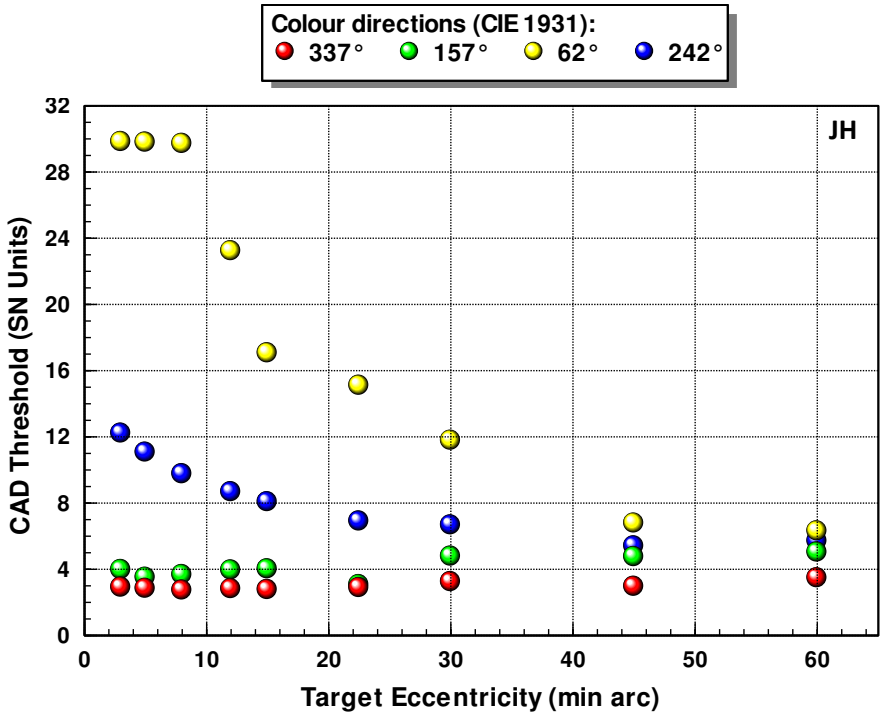


Figure 3-7: Chromatic detection thresholds for luminance pedestal stimuli over an extended range of eccentricities, up to 1°, for subject JH. Background chromaticity coordinates were changed to x = 0.249, y = 0.217 to allow for greater chromatic displacements in the yellow direction.

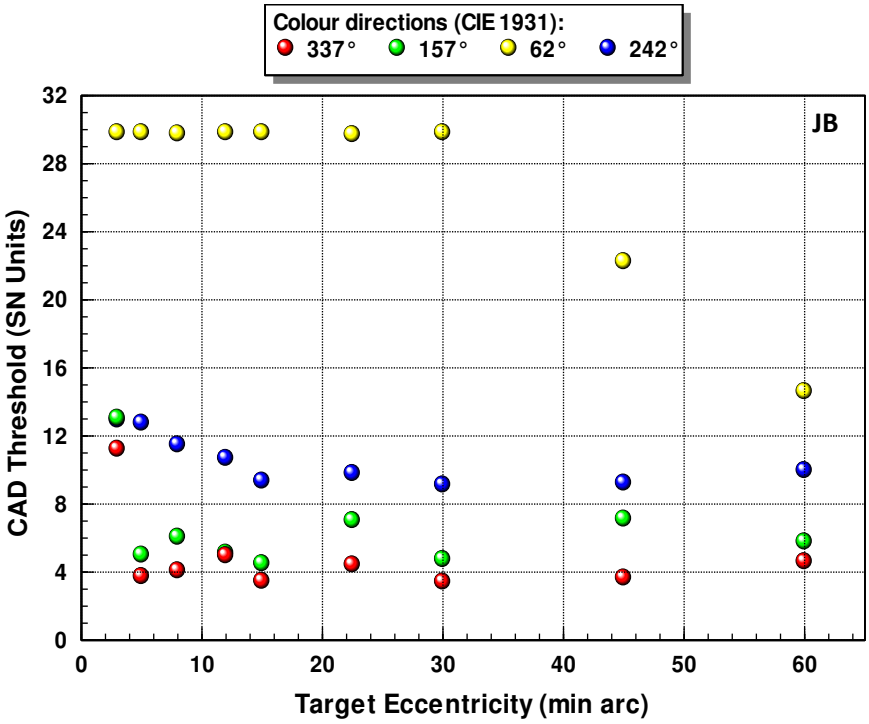


Figure 3-8: Chromatic detection thresholds for luminance pedestal stimuli over an extended range of eccentricities, up to 1°, for subject JB. Background chromaticity coordinates were changed to x = 0.249, y = 0.217 to allow for greater chromatic displacements in the yellow direction.

Over the increased range of stimulus eccentricity, thresholds for the detection of yellow and blue became progressively lower. This is consistent with light scattering from the source over a greater region of the S cone populated retina with increasing eccentricity.

Yellow stimuli up to 8' for subject JH and 30' for subject JB were not detected even at the maximum chromatic displacement possible on this display at the new background chromaticity coordinates, whereas blue stimuli were always detected. Subject JB had higher thresholds than JH for the detection yellow stimuli, however so this reduced performance is likely due to inter-subject variation in chromatic sensitivity (subject JB had a CAD YB threshold of 1.02 whereas subject JH had a YB threshold of 0.65).

3.6 EXPERIMENT 3.4: COMPARISON WITH CAD THRESHOLDS

3.6.1 Parameters for experiment 3.4

Thresholds for the detection of luminance pedestal stimuli in section 3.1 were higher than those for the same coloured stimuli on the CAD test in every case. Basic differences between the stimulus parameters of the tests account for this disparity in performance.

The CAD test employed larger stimuli than the relatively small 2' luminance pedestals, and so a likely explanation would be that reduced spatial summation for coloured stimuli in the latter test resulted in higher detection thresholds. Within the central 10°, the detection of chromatic stimuli has been shown to improve as the area of the retina over which the stimulus spreads increases (Brown, 1952; Yebra et al, 1994).

Additionally, the CAD test used a background adaptation field chromaticity x= 0.305, y= 0.323 CIE 1931 with a luminance of 24 cd/m^2 while the luminance pedestals (also with a luminance of 24 cd/m^2) were presented against a dark background set at 0 cd/m^2. When chromatic detection thresholds are measured, the performance of an observer will vary based on the luminance of the background as well as its spectral composition (Yebra et al, 2001; Jennings & Barbur, 2010).

A key aspect of the luminance pedestal procedure is that it employs a luminance contrast between the stimuli and background in order to negate the additional cue that would be provided by the change in luminance caused by the addition of colour to a target.

The luminance pedestal procedure, used in this case to simulate chromatic detection for occupational signal lights, was compared in the previous experiments with the CAD test that employs dynamic luminance noise masking to isolate chromatic detection. If the differences in spatial summation and light adaptation are accounted for, is threshold detection using this procedure equivalent to that of the CAD or are there fundamental differences in the sensitivities of the two paradigms?

In order to answer this, the same staircase procedure outlined in section 3.1 was used for the CAD and luminance pedestal tests. In each run of the experiment, there were four staircases interleaved that correspond to red, green, yellow and blue colour directions, which were expressed as a displacement away from the background chromaticity of x= 0.305, y= 0.323 in CIE 1931 colour space. Thresholds were obtained for the two cardinal red-green (157°, 337°) and two yellow-blue (62°, 242°) colour directions.

In order to determine the effect of increased spatial summation, the luminance pedestal test was modified to have a target size of 9.6', with the four luminance pedestals displayed 12' from central fixation; the CAD test was set to present stimuli of equivalent size (0.16 square degrees) within an array of dynamic luminance contrast noise checks subtending the same visual angle.

To test the effect on threshold detection of increasing the light adaptation level, the background was set at 0cd/m^2 and 18cd/m^2 for the luminance pedestal test for target sizes of 2' and for 9.6' and to 18cd/m^2 for the CAD test. The CAD test necessarily has a background light level, and so testing at 0cd/m^2 was not possible.

3.6.2 Results for experiment 3.4

In order to determine the extent/weights of factors causing the reduction of performance when using signal lights as opposed to the CAD test, parameters of both tests were changed and repeat measurements taken. The size of stimuli and the luminance of the background were altered in for the luminance pedestal test, and the size of the targets used were altered for the CAD test. Subjects' discrimination thresholds for modified luminance pedestal procedures are shown in Figures 3-8, 3-9 and 3-10, compared with thresholds for the CAD test with smaller stimuli and an equal background luminance level.

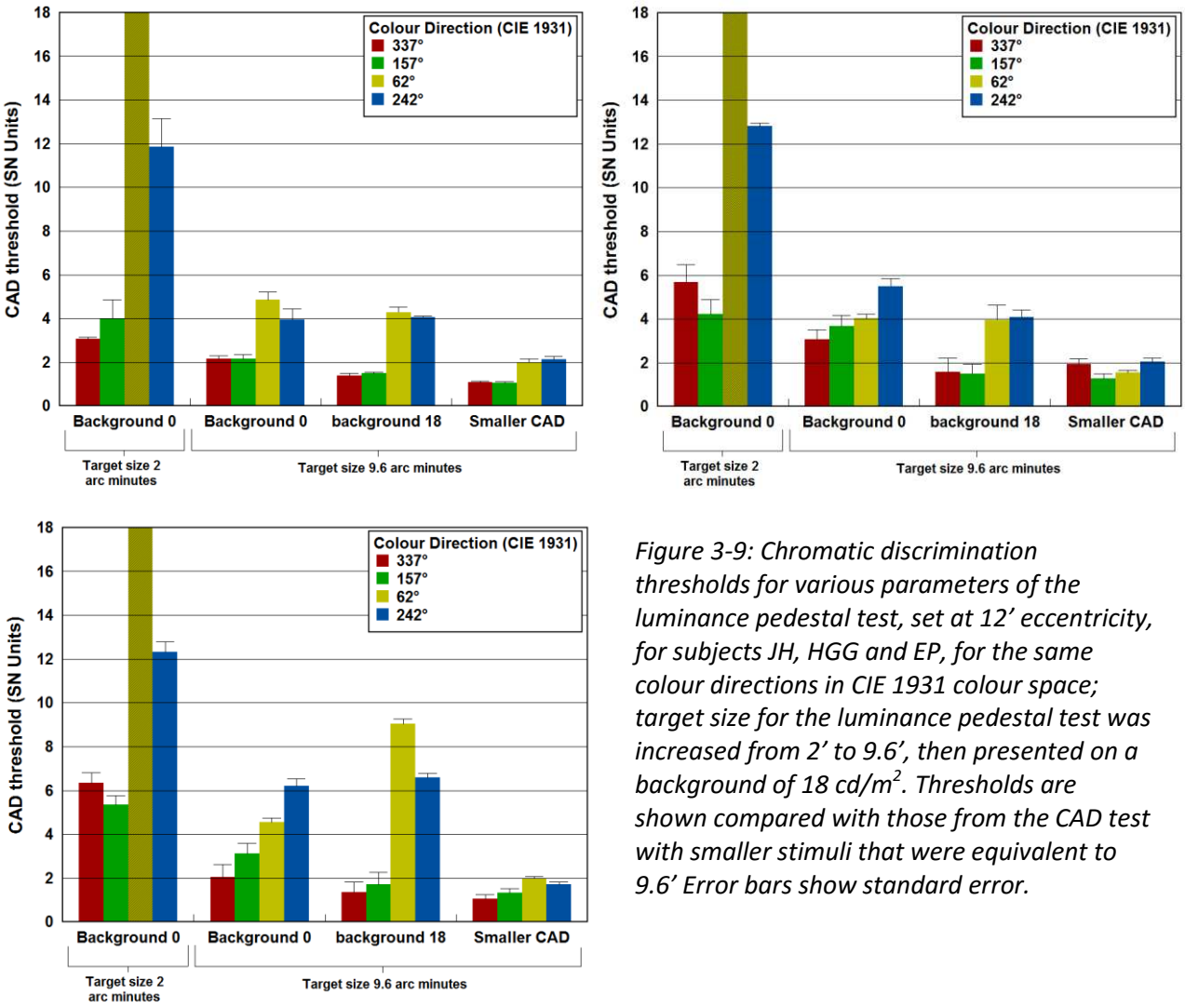


Figure 3-9: Chromatic discrimination thresholds for various parameters of the luminance pedestal test, set at 12' eccentricity, for subjects JH, HGG and EP, for the same colour directions in CIE 1931 colour space; target size for the luminance pedestal test was increased from 2' to 9.6', then presented on a background of 18 cd/m^2. Thresholds are shown compared with those from the CAD test with smaller stimuli that were equivalent to 9.6' Error bars show standard error.

As expected, increasing the size of the stimuli produced a substantial reduction in chromatic detection thresholds for all colours and for each subject. Increasing the background light level improved the detection of red and green, however there was no obvious effect of improving detection of yellow or blue. When compared with the modified CAD test, a luminance pedestal of equal size to the CAD stimulus and with an equivalent background luminance could allow for similar detection of red and green. However, for yellow and blue the CAD test still yielded much lower thresholds.

When stimulus size and background light level were equivalent, thresholds for the detection of red and green were similar for both tests, however thresholds obtained for yellow and blue were still

significantly higher from the luminance pedestal test. This indicates that there is a difference in the processing of S cone stimuli under the two conditions, which L and M cone signals are not subject to.

Procedural differences may also compound the difference in performance - specifically the required judgement of the relative colour difference for four targets with the luminance pedestal technique, where the CAD simply required the detection of motion based on colour perception.

It is also possible that when at or near threshold, colour differences between the four pedestals could be affected by afterimages from the previous presentation, resulting in multiple targets appearing to have some slight chromatic difference relative to the background.

The failure to reconcile blue and yellow luminance pedestal thresholds with CAD thresholds, when spatial summation of stimuli and background light adaptation level were accounted for, indicate an inherent lack of sensitivity to S cone stimuli due to the presence of the high luminance contrast employed.

3.7 DISCUSSION

Using luminance pedestals to simulate signal lights provided some insight into the factors that affect this visually demanding task. Colour thresholds measured with the luminance pedestal technique were higher than for those where the achromatic component of a target was masked by dynamic luminance contrast noise. In addition, differences in detection threshold based on the colour of the target were also observed.

Although RG congenital colour vision deficiencies are the most common type, safety critical occupational colour coding is traditionally based on the discrimination of red, green and white lights (e.g. see chapter 2 on seafaring and aviation). One way of reducing the risk of red / green colour confusions in congenital deficiency would be to make greater use of yellow or blue lights that colour deficient subjects have no difficulty with. From the results of experiment 3.2 it is however apparent that when small, foveal signal lights are involved, visual performance is significantly worse and for

monochromatic blue or yellow lights. When the chromaticity of the lights is restricted to the tritanopic colour confusion axis, a normal trichromat could be effectively unable to discriminate yellow / blue colour differences for small stimuli. Chromaticities that produce both RG and YB colour differences and fall outside of the deutan and protan confusion would be more acceptable but still inadvisable for use in normal trichromats; as per Figures 3-3 and 3-4, higher thresholds are involved in proportion to the YB signal. Therefore for occupational use in safety critical tasks involving signal lights, monochromatic reds and greens would be optimal for use in normal trichromats.

The fact that luminance pedestal detection thresholds measured in colour normal trichromats were between 4 and 5 times higher than their CAD threshold illustrates the difficulty of chromatic discrimination under these conditions, and corresponds to results from 2.4.7 that showed that only mildly-deficient deuteranomalous trichromats could pass the HW-A lantern, and that no colour deficient subjects could pass the HW-B lantern which employs significantly smaller stimuli.

Thresholds measured at eccentricities up to 1 degree from central fixation are consistent with the lack of S cones in the central 100 µm (0.35°) of the fovea (Curcio et al, 1991); any thresholds measured from targets of eccentricities within this region may have resulted from light scattering further over the retina.

A consistent result in experiments 3.3 and 3.4 was the asymmetry between the detection thresholds of yellow and blue where chromatic detection was measured using luminance pedestals. In many cases (Figures 3-5 – 3-7) the yellow stimulus could not be detected at the maximum chromatic displacement possible for the display equipment and background chromaticity coordinates, under conditions where blue could be detected (along with red and green). When all colours could be detected, thresholds obtained for yellow were consistently higher than those for blue. This result initially appears unusual for two reasons: thresholds for the same stimuli measured with the CAD test do not show this asymmetry, and that detection of yellow and blue is based on the same (S - (L + M)) opponent visual pathway. These asymmetries shown in the thresholds for yellow and blue

detection described in 3.5.2 could, however, be explained by differences in the underlying neural circuitry that corresponds to S cone increments and decrements.

Although S cone increment and decrement stimuli both result in responses from the S- (L+M) opponent system, there is substantial evidence that these signals do not share a common visual pathway. Initially, the S cone receptive field is established by feedback from H2 horizontal cells; L and M cones provide inhibitory input to the S cones, creating a centre/surround organisation in which the S cone signal is subtracted from the combined L+M signal, creating two outputs: the S-ON signal where the S cone signal is greater than L+M (signalling 'blue') and the S-OFF signal where the combined L+M signal outweighs that of the S cone (signalling 'yellow'). S-ON responses have been established as arising from blue-cone selective bipolar cells, which proceed to contact the small bistratified ganglion cells, whereas the S-OFF response is thought to be carried by midget bipolar cells, however not exclusively (Dacey et al, 2014).

Psychophysically observed differences in S-ON and S-OFF responses are thought to arise from physiological differences between the two pathways. The midget bipolar cells of the S-OFF pathway have a small receptive field when compared with the blue-cone bipolar cells of the S-ON pathway; however there have also been reported interactions of S-OFF stimuli with IPRGCs and other ganglion cell types with a much larger receptive field (Smithson, 2014). The ratio of L and M cone input to the two pathways is also thought to differ; in a study by McLellan and Eskew (2000), thresholds for the detection of S cone decrement stimuli (transmitted via the S-OFF pathway) decreased when the proportion of long wavelength light in the surround was increased – implying that the OFF pathway receives proportionally more M than L cone input – an effect not shown for increment stimuli (McLellan & Eskew, 2000). Aside from this difference in threshold detection the two pathways display different temporal response characteristics, with the impulse response function for the S-ON pathway being 30-70ms faster than those for the S-OFF pathway (Shinomori & Werner, 2008).

The ganglion cells corresponding to S-OFF signals have been difficult to locate and previous studies have estimated their number to be significantly lower than S-ON ganglion cells (Lee, 1996). At present the S-OFF pathway has not been fully characterised, however if the density of S-OFF ganglion cells is indeed lower than that of the S-ON ganglion cells, then this would contribute to asymmetries in responsiveness for the two channels (Vassilev et al, 2000, Dacey et al, 2014).

The fact that the thresholds for yellow and blue stimuli obtained in this chapter were based on the responses of two separate pathways with known functional differences provides a likely candidate to explain the observed results. The aforementioned differences in L and M contribution to the different pathways could have resulted in the background adaptation field producing a greater degree of inhibition for the S-OFF pathway, thereby increasing yellow detection thresholds.

Another possibility is that in conditions where yellow / blue detection would result from scattered light from a small, foveal light source falling over the S cone containing retina, the level of stimulation produced would have been less for the S-OFF stimuli due to the smaller receptive fields of the midget bipolar cells. Increasing the size of the luminance pedestal targets, allowing for greater spatial summation of the colour signals, produced more symmetrical detection thresholds as illustrated in Figures 3-8, 3-9 and 3-10.

The dynamic random luminance noise masking (employed by the CAD test in this case) is more effective at isolating the use of colour signals and in stimulating S-cones because it employs larger stimuli than the four-alternative, forced-choice luminance pedestal procedure. Figures 3-3 and 3-4 illustrate that thresholds obtained were consistently lower for the CAD test for the yellow and blue directions. Between various test procedures, a lower threshold for the same subject for an equivalent stimulus on a one of the tests would indicate that it is the most sensory-determinate and hence more accurately defines performance for the chosen stimulus (Blackwell, 1952).

The changes in chromatic sensitivities measured over the visual field, as well as the variation in threshold detection of stimuli defined by both colour and luminance contrast investigated in this chapter have implications for tasks involving the use of coloured targets. The efficiency of colour signals will vary with the size and chromaticity of the coloured objects and the luminance contrast and eccentricity at which stimuli are presented. The ability to quickly locate relevant targets based on their saliency will be further examined in the next chapter.

4 COLOUR VISION IN AIR TRAFFIC CONTROL

4.1 CLASS 3 EUROPEAN MEDICAL REQUIREMENTS FOR AIR TRAFFIC CONTROL

Air traffic control (ATC) is an occupation that requires performance of many tasks that are safety-critical and the consequences of error can have extensive repercussions. Air traffic control officers (ATCOs) are required to correctly identify the colours of aviation lights, and effectively make use of display screen equipment that allows for the management of air traffic. Accordingly, ATCO applicants must obtain the European Class 3 Air Traffic Controller medical certificate, which requires normal trichromatic colour vision. The criteria for obtaining this is set at no errors on the first 15 plates of the Ishihara test (38 plates edition) (European Class 3 Medical Certification of Air Traffic Controllers UK CAA Guidance v1.1, 2009), with secondary testing specified as diagnosis by the Nagel anomaloscope or equivalent. Although normal trichromatic colour vision is requested, neither of the two proposed tests is capable of assessing YB colour vision.

Based on these regulations it is likely that there will be some mild deuteranomalous trichromats already working as ATCOs. From the data in 2.4.3 there will be some deutans that are able to pass the first 15 plates of the Ishihara test without error, and there will be normal subjects that fail this criterion. In order to ensure that 100% of colour normals pass the pass criteria would have to be set at 4 errors or less, however at this limit 10% of deutans and 1% of protans would also pass (Rodriguez-Carmona et al, 2012).

This evidence therefore suggests that using current Class 3 assessment guidelines some subjects with mild deutan deficiency pass and become ATCOs. The absence of any evidence for poor practice in the ATC environment that can be linked directly to colour vision deficiencies suggests that it might be possible for some mild colour deficient subjects to carry out ATCO work as effectively as normal trichromats.

The UK Civil Aviation Authority (CAA) now uses the CAD test as a secondary test for those applicants that fail the Ishihara (the pass criteria for which is 0 errors). This means that the EASA class 3 certification requirements can be implemented accurately and that no subjects with congenital colour deficiency (however mild) can pass. The problem cannot be considered solved since given the historical evidence one is justified to question EASA's current requirements for normal trichromatic colour vision.

4.1.1 Air traffic control display screens and visual requirements

The immediate airport environment is controlled by visual observation from the airport control tower, including movement of aircraft and vehicles operating on taxiways and runways and aircraft in the air near the airport (within a range of 9 to 18 km). Surveillance displays are also available to ATCOs for airborne traffic approaching and departing. These displays include a map of the area, the position of various aircraft, and data tags that include aircraft identification, speed, altitude, and other relevant information. En-route ATCOs work in separate facilities and provide information services to aircraft in flight between airports. Each centre is responsible for many thousands of square kilometres of airspace, known as a Flight Information Region, and for the airports within that airspace.

En-route air traffic control facilities do not require a direct view of the airport or surrounding airspace, and so ambient lighting conditions can be controlled. The control tower, however, presents a more varied environment: changing ambient light levels and very rarely the possibility of direct sunlight falling on the displays means constant and unpredictable variation in the effectiveness of coloured stimuli, as well as overall effective contrast of screen objects (Cardosi & Hannon, 1999). The main task of ATCOs remains the provision of accurate information for the en-route environment. This study therefore focuses on colour vision requirements that relate directly to effective performance on visual displays.

Originally the primary colour-related task of controllers involved the identification of coloured text on flight progress strips, and the recognition of aircraft and their direction of flight at night from control towers based on perception of red, white and green navigation lights. These first techniques of colour coding involved mainly non-redundant cues (Mertens 1990). The use of colour has increased greatly in the ATC environment and has become a vital aid in the acquisition of information. This can be attributed to the development of visual displays, the diversity of applications and flexibility in software. As new technologies and automation tools have been added to existing displays which allow users to customise their own colour schemes, there have been many recommendations to the use of colour for ATC (Cardosi & Hannon 1999; FAA report HF-STD-001, 2003; FAA report HF-STD-002, 2007, CAA report CAP 670, 2014). ATCOs have to process a large amount of information and it is clear that colour may be useful, and in many cases necessary, to help organise information and to reduce the amount of physical and cognitive clutter on the displays.

For the coding of visual information in display screen applications, colour is arguable the most effective attribute in facilitating improved performance: it can be used to shorten the time needed to locate objects, especially when other objects or distractors are displayed simultaneously (Carter 1982), and accumulated visual studies have shown that colour is superior to achromatic visual attributes in many tasks such as searching for targets and organising complex visual scenes (Christ 1975). A fundamental mechanism underlying the superiority of colour in object location is that the human visual system processes colour and achromatic information separately via different anatomic pathways (Kaiser & Boynton 1996). Only at the higher levels of brain information processing are signals about colour and forms integrated. Therefore, while achromatic visual cues (such as luminance, shape, and text) are used to convey detailed information, colour can be used as a distinctive dimension to organize achromatic information.

During consultation with the CAA it became clear that different UK air traffic control centres use different display screen equipment, ambient lighting is not standardised and ATCOs have the option

to change the colour palette within the air traffic control software. Therefore a full task analysis of all the potential combinations of screens, possible colours of screen objects and lighting conditions that may be present in ATC centres would not be possible. As ATCOs can change the luminance, contrast and chromaticity of the items on the display, and the volume of air traffic being monitored varies between locations, there is no set information on an 'average' ATC display.

It would therefore be useful to produce a set of guidelines on the use of colour in ATC that are based on parameter combinations that yield best visual performance. By determining the most difficult tasks that require the use of colour, and by assessing the performance of colour deficient subjects and normal trichromats on these tasks, it is possible to identify whether there is an overlap in performance between the two groups. By relating the subject's remaining chromatic sensitivity to performance, it is possible to determine statistically the lower limits of chromatic sensitivity that yield visual performance equivalent to what one can achieve in normal trichromatic vision. Air traffic control screens employing the current technologies and practices were demonstrated for this project at the National Air Traffic Services (NATS) en-route air traffic control centre at Swanwick, UK. Aircraft are tracked as 'data blocks': clusters of small text containing descriptive information of a flight (as per Figure 4 -1). Data blocks have a colour associated with them based on whether they are owned or not, and whether there are any warnings associated with that aircraft.

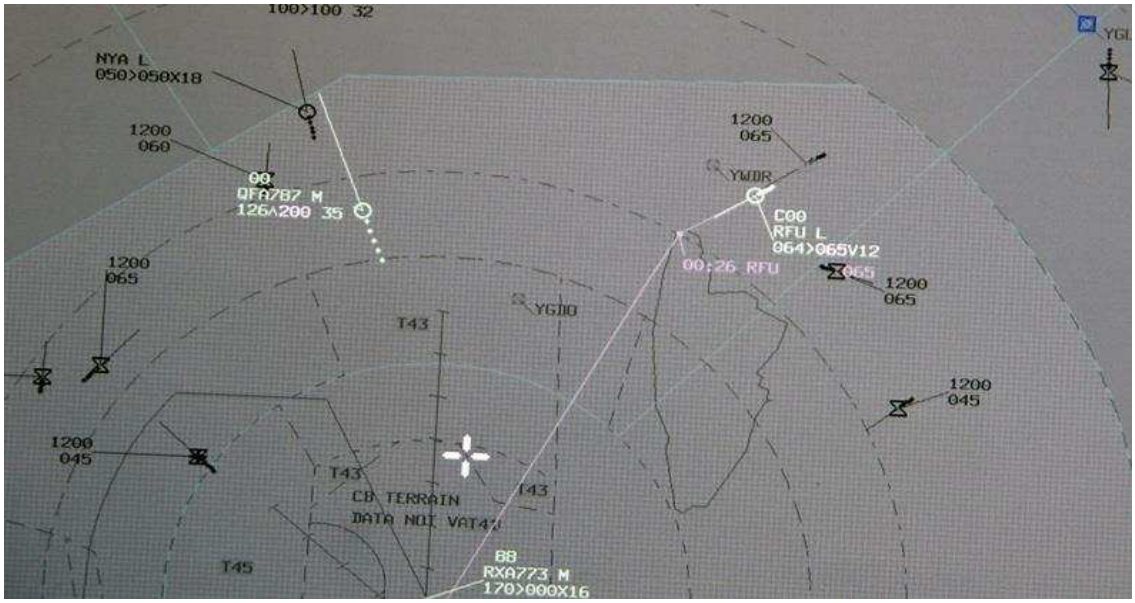


Figure 4 -1: Example of colour coded data blocks used in air traffic control, in this case from the EUROCAT air traffic control system used in the UK and many other countries (from airserviceaustralia.com, accessed 13/11/2014).

The colour-related task presented by ATC is effectively one of visual search and decision making; targets of interest presented on a display must be located amongst multiple distractors. Based on the fact that any colours could potentially be selected to convey warnings related to a particular flight, the most critical condition in terms of colour deficient use would be when two or more target chromaticities fall along the colour confusion lines of subjects with deutan or protan deficiency.

The effect of colour deficiency in visual search for redundantly coloured targets has been investigated in earlier studies (Cole & Macdonald, 1988; Cole et al, 1994; O'Brien et al, 2002). It was concluded that the conspicuity of coloured targets for colour deficient subjects is reduced and overall search times are longer than for normal subjects. This work was carried out without paying specific interest to the advantages of colour in relation to the specific demands of the ATC task; furthermore the relative chromatic sensitivities of the colour deficient subjects involved were not considered beyond determining which were dichromats and which were anomalous trichromats.

4.2 OVERVIEW OF VISUAL SEARCH

Complex scenes contain more visual information than can be processed in parallel; attentional mechanisms provide a 'bottleneck' that allows for the selection of a limited number of stimuli for

more detailed processing. Visual search is the process by which attention is deployed at relevant points in the visual field (Wolfe & Horowitz, 2004).

Although attention can be deployed in the absence of eye movements, the high spatial and temporal resolution offered by the fovea, compared with the relatively reduced performance in the periphery, often necessitates eye movement to bring objects of interest into foveal viewing. It is also possible that stimuli of significant magnitude can be attended to without eye movements; however this still requires the deployment of attention.

Colour has been well established as an object feature that can pre-attentively guide visual search, if adequately salient, and this is dependent on the strength of the chromatic signal and the heterogeneity of the coloured object with its surround (Nagy & Sanchez, 1990; Bauer et al, 1996; Wolf& Horowitz, 2004). Similarly the motion, size, and orientation of objects are features that are well established as being able to guide attentional deployment, amongst many possible candidates (a more extensive list can be found in Appendix C).

Where a stimulus is inconspicuous enough to require multiple eye movements over the scene, the search is often termed serial, and in this condition search times increase in proportion with the number of distracters. Parallel search generally refers to the ability to quickly locate a target in a scene irrespective of the number of distractors. These two descriptions infer different neural mechanisms for processing of stimuli, however in practice it is problematic to say with confidence whether the results of a visual search test fall into either the 'serial' or 'parallel' category as there is no clear indication where the separation occurs. While there is evidence for the two neural mechanisms existing, the deployment of either is hard to infer purely from search times for a given stimulus (Egeth & Dagenbach, 1991; Wolfe, 1998).

Psychophysical measurements of visual search generally involve measuring the time taken to locate, or determine the absence of, a target stimulus amongst distractors, thereby testing the visual

system's capacity for detection under specified conditions. Searching for a target that is distinguishable from distractors on the basis of one or more basic features is generally referred to as feature search, while searches for targets that are identifiable based on combination of two or more features, however share at least one of these features with the distractors, is referred to as conjunction search (Carrasco et al, 2006).

In most natural scenes, some objects or regions will be more salient than their surroundings by differing significantly in one or more features. When viewing such a scene without any specific task objectives, there is a greater chance of these more salient stimuli being attended to (Triesman & Gelade, 1980). Various theories have been put forward regarding the mechanisms by which certain objects in the visual field are attended to over others. One of the most influential of these was the Feature Integration Theory (FIT): a two stage model in which an initial, preattentive stage in which a limited set of basic features are processed in parallel, followed by a conscious stage in which objects are selected in a serial manner by the deployment of attention (Treisman & Gelade, 1980).

In the initial stage, basic stimulus features are processed separately and in parallel across the entire visual scene in a preattentive manner, producing 'saliency maps' which are a spatial representation of the various stimulus weights for each feature across the visual field. When attention is focussed on a given object, segregated feature information is then combined to form the perception of that object; in this case attention is referred to as being the 'glue' that binds these features (Treisman & Gelade, 1980).

This model is supported with data for various conditions involving the detection of single features (colour, shape etc), however there are instances where this original framework of visual search is not supported. As aforementioned, search times rarely fit into two separable groups as would be expected for the two stage model. Most notably, conjunction searches – where a target is detected by two or more features that separate it from the surrounding objects – can produce search times that are independent of set size and hence are being mediated by the first, preattentive stage where

processing of features was thought to be segregated (Treisman & Sato, 1990). It is unlikely that mechanisms exist that would produce feature maps for all of these different features, at any retinotopic size and resolution (Nakayama & Joseph, 1998).The converse can also apply, where some features that can be detected preattentitively but do not appear to be able to guide the deployment of attention (Wolfe & Horrowitz, 2004).The original model of FIT has since been modified to reflect these findings, proposing a mechanism of feature inhibition in which conjunctions of stimuli can suppress the detection of distractors, thereby allowing these targets to 'pop out' compared with the rest of the scene (Treisman & Sato, 1990).

A later model of visual search, termed ‘guided search’, follows on from FIT and retains the two-stage model of processing. Guided search proposes that in the preattentive stage only a limited amount of information about object features can be captured, and these features are capable of subsequently used to guide the deployment of attention (Wolfe et al, 1989).

First stage input produces feature maps that are presumed to exist for a limited set of features; there may be multiple maps for features within the same category (e.g. multiple separate maps for colours). These maps form the basis for ‘bottom up’ activation – where the deployment of attention is guided by spatial differences in the intensities of the features sampled. In this model the preattentive sampling of stimuli is not the only component for guidance. The conscious task objectives of the subject are also capable of guiding the deployment of attention. It is possible that a task will require the search for a particular feature that is not more salient than others in the scene, for example a search for a red amongst many other colours of equal intensity. Under these conditions bottom-up guidance would not be enough to produce an efficient search, where experience would indicate that if no other reds are present the search would be relatively quick. For the red stimulus to be located top-down input is used in combination with the preattentive processes to prefer areas of the scene that may contain the required stimulus (Wolfe, 1994).The sum of the bottom-up and top-down activations are used to produce an overall ‘activation map’

which contains various peaks at areas where the strength of input is the highest. This map is used to guide the deployment of attention (Wolfe, 2007).

4.3 THE CRATO TEST

In order to examine the advantages the use of colour brings to ATC display work it is desirable to measure visual search times in a series of tasks that simulate the key uses of colour information on real life displays. As per 4.1.1, the user has the ability to change the colours of objects on an ATC display, and coloured objects are always accompanied by a luminance contrast relative to the background; the user is required to attend to certain coloured data blocks with multiple possible distractors.

The Colour Requirements for Air Traffic Operators (CRATO) test was designed to measure visual search times for stimuli of equivalent size to the data blocks on an ATC display, over an equivalent area and at specified luminance contrast that are typical of display usage. The test runs on a Windows computer (Dell Precision T5600) and employs a fully calibrated 30" NEC MultiSync PA301W monitor (NEC, Tokyo, Japan) display similar to those used in ATC applications, which was calibrated using the same procedures as for the CAD test. The luminance and chromaticity of the display were calibrated using the LUMCAL program (City Occupational Ltd), a Gamma Scientific telespectralradiometer (Model 1980B) and a LMT photometer (L1003, LMT) as per section 3.2, regularly throughout testing. The design of the tests and the calibration techniques were done by Prof. John Barbur and the programming work was carried out by Mr Alister Harlow (City Occupational Ltd).

In experiments 4.1 and 4.2, the subject was required to locate a Landolt C amongst 40 distractors. The Landolt C is a standard optotype of specified geometry that is used frequently in optometric measurements; the width of the annulus and the gap size are the same and equal to 1/5 of the outer diameter (Danilova & Bondarko, 2007). Distractors were either Landolt Cs or complete rings of equal

size, depending on the experiment. During each presentation, the orientation of the gap in the Landolt C target was selected randomly to correspond to one of four diagonal directions.

As mentioned in 4.2, where a target differs from the distractors on the basis of one feature, and is adequately salient, then increasing the number of distractors should have little to no effect on search times. This number of distractors was selected in order to ensure a serial search - where chromatic discrimination was not sufficient to allow for an efficient search – and therefore would result in substantially higher response times than where a target could be efficiently located. This allows for segregation of the performance of observers based on their visual search times; too few distractors would compress this variation. The number chosen was also a compromise between the size of stimuli used and the size of the display. In relation to ATC, the number of data blocks that an ATCO would have to attend to varies over time and at different ATC locations; fewer than 40 distractors would represent an equally (or less) challenging task, conversely use of colour coding should allow for an efficient search independent of set size even if more distractors were present.

The subject is instructed to locate the target based on the criteria given in each experiment, and make an initial button press that halts the search timer. The subject's next task is to report the orientation of the gap in the Landolt C in order to check for a correct response. This approach removes the need to select one of four response buttons to indicate the detection of the target, a task that may lengthen the visual search time. The initial button press also causes all stimuli to be removed from the screen, thereby ensuring that the search time recorded relates to the time taken to locate the target. Responses were made using a Microsoft USB keypad which was adapted specifically for the task.

Stimuli were presented over a square field of 20° of visual angle. The background field was set at a luminance of 32 cd/m^2 and had a chromaticity of x = 0.305, y = 0.323 in CIE 1931 colour space; coloured stimuli in all experiments were defined as chromatic displacements away from this background chromaticity in any specific colour direction.

In order to provide a measure of chromatic sensitivity for comparison with visual search performance, all subjects carried out the CAD test, with the parameters and conditions described in Section 2.2. The saturations of the colours used in the CRATO test were expressed in terms of CAD units. This facilitates straightforward comparison between the performance resulting from a given saturation of a coloured target in visual search, and a subject's chromatic discrimination thresholds for that colour.

Stimulus size is an important parameter in visual search and the task of locating a stimulus becomes more difficult with decreasing stimulus size. In our experiments we have employed stimuli that are just above the smallest size limits considered useful on visual displays. The size of each stimulus on the display (either target or distractor) was selected randomly in each presentation in the range 25' to 30' of arc. During each experiment, search times were obtained for targets of positive and negative luminance contrast with respect to the background field; distractors also varied in luminance contrast on each presentation within the same specified values.

The typical visual acuity under normal lighting levels is taken to be around 1' of arc, which corresponds to ~ 5' per letter size in Snellen acuity tasks. Display designers recommend at least 2 to three times this acuity limit (Smith, 1979). The range of stimulus sizes employed in our study (i.e., 25'-30') is therefore well resolved when viewed at the fovea. Visual acuity of ATCOs is presumed to be 6/9 or better as per CAA guidelines. The choice of target size in our studies ensures that although the task remains challenging, no operator will have difficulty in resolving the gap size when the Landolt ring is viewed foveally.

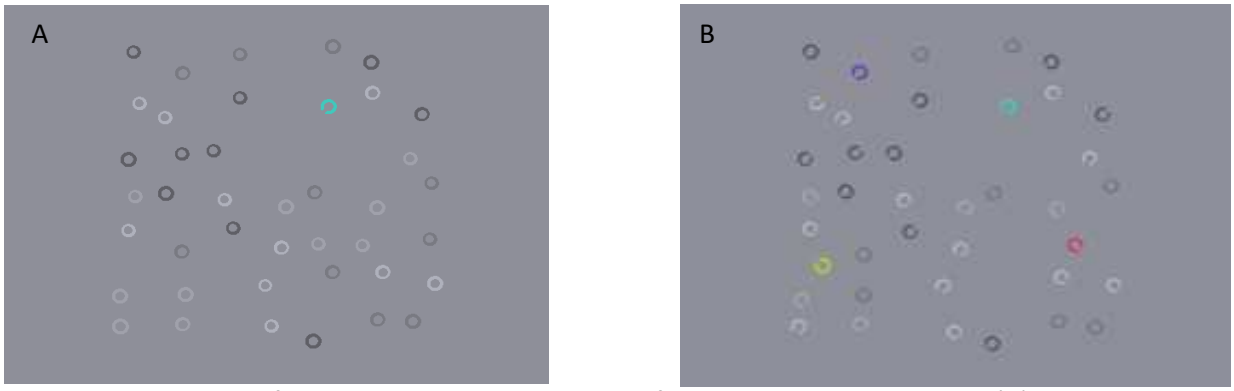


Figure 4-2: Examples of the two CRATO test conditions for experiments 4.1 and 4.2. (A) Shows the condition in which the target is differently coloured than the distractors and has a spatial cue. (B) Shows the condition in which all stimuli are spatially identical and multiple distractors are coloured. The subject is instructed to report the orientation of the gap for the specified colour of the Landolt ring selected for that experiment.

Prior to each presentation, a central fixation is displayed for 900 milliseconds. For each combination of colour, saturation and luminance contrast, the mean visual search time was computed as the mean of 90 measurements. If a subject failed to detect the target within 12 seconds from the start of a presentation (and hence failed to respond), that presentation was terminated and recorded as a failed search; in some conditions the target did not have a redundant cue (Fig. 4-8) and therefore if the chromatic saturation was below the subject's detection threshold, the visual search would not be possible. Errors due to incorrect button presses or search time-outs were not included when calculating the mean search time, however to ensure that a subject could not simply respond in any direction as quickly as possible, the percentage of correct responses was recorded.

Three experimental conditions were employed to determine the use of colour in visual search for normal trichromats and subjects with congenital colour deficiency. A fourth experiment investigated differences in performance for normal trichromats based on the colour of a target.

4.4 EXPERIMENT 4.1

4.4.1 Introduction

This first experiment was designed to determine the improvement in performance that results from adding colour to a target defined by luminance contrast. This allows for measurement of the ability of observers to make use of 'pop-out', in which colours allow for rapid separation of target objects

from distractors. In each presentation the target was a Landolt C and the 40 distractors were complete rings, therefore a successful visual search was possible even in the absence of colour information.

Colour can increase the conspicuity of targets that have a relatively low luminance contrast, and on display screens there will be situational variation in the luminance contrasts of relevant objects (Barbur & Forsyth, 1988). In general, the luminance contrasts employed to define targets on visual displays in ATC applications are high and as a result the addition of colour information does not cause a large change in the effective contrast of the target. In view of these observations, targets and distractors were presented at ±60% and ±30% luminance contrast with respect to the uniform background. Preliminary measurements for achromatic targets carried out as a function of luminance contrast have been carried out to establish reference levels of search performance and are summarized in Appendix D.

4.4.2 Methods

Colours were expressed as a displacement away from the background chromaticity in the following directions: 337° (red), 157° (green), 62° (yellow) and 242° (blue) in CIE 1931 chromaticity space. As per Section 3.2.1, these colour directions selected fall largely along the colour confusion lines for congenital colour deficiency and must therefore represent the most challenging conditions. Yellow and blue targets were employed in order to establish the usefulness of YB colour differences in relation to RG differences. It was also of interest to establish whether colour deficient subjects can achieve normal performance for targets that do not involve RG colour differences.

The target and distractors can differ in either colour, the presence or absence of the gap, or both. According to the visual search literature, the latter task is usually described as conjunction search. Therefore subjects initially performed a search for an achromatic target amongst achromatic distractors, in order to give a baseline measurement against which the improvement in performance due to the addition of colour could be extracted. Visual search times were then measured for a

single coloured Landolt C that were either red, green yellow or blue. Trials for different colours were not interleaved. Following achromatic measurements, subjects then carried out trials for yellow and blue, before moving on to red and green. This may have allowed for some effect of learning in terms of the operation of the test; breaks were given between trials in order to avoid fatigue.

Data were obtained for chromatic saturations at intervals from 2 up to 28 CAD units for red and green targets and from 2 to 12 CAD units for yellow and blue targets. This range of saturations reflects the maximum possible displacements in the chosen colour directions for the display and background chromaticity. Three normal trichromats were tested, as well as two protan subjects (one mildly-affected and one severely-affected) and two deutan subjects (one mildly-affected and one severely-affected).The mild protan subject (DC) had a CAD RG threshold of 6.8 SNU and a YB threshold of 0.75; the severe protan (JY) subject had a CAD RG threshold of 21.5 and a YB threshold of 0.63. The mild deutan (JL) had a CAD RG threshold of 3.38 SNU and a YB threshold of 0.78; the severe deutan (LS) had a CAD RG threshold of 19.5 SNU and a YB threshold of 1.16. All subjects failed the CAA criteria for entry based on their colour vision test results.

The presence of a redundant spatial cue means that even when the colour strength of the target is below a subject's threshold, the task is still possible to carry out. The percentage of correct responses was recorded to ensure that the observers were capable of carrying out the test.

4.4.3 Results for Experiment 4.1

4.4.3.1 Visual search for yellow and blue targets

Visual search times of a normal trichromat for yellow and blue Landolt C stimuli are shown in Figure 4-3; results for the 3 other normal trichromats can be found in Appendix E.

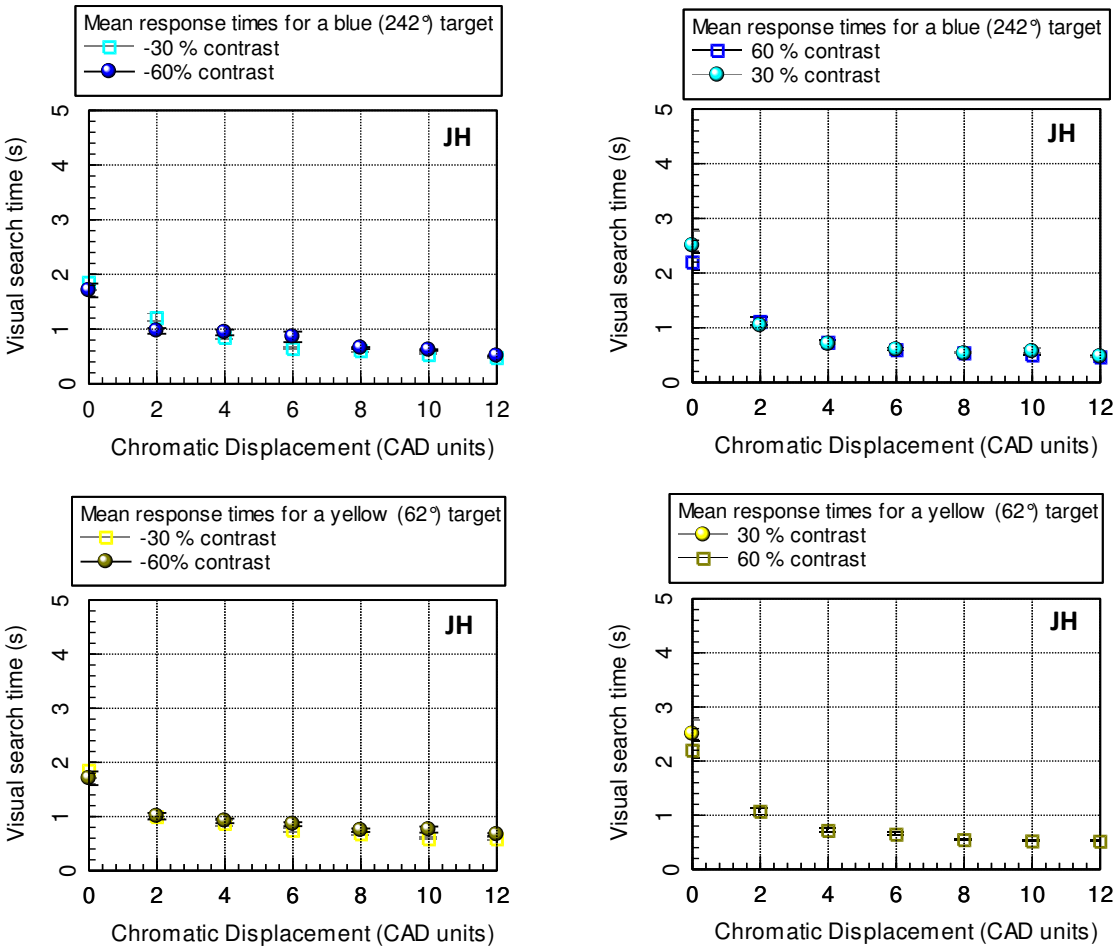


Figure 4-3: Visual search response times of normal trichromat JH for blue and yellow targets amongst 40 achromatic distractors. The target had an additional spatial cue; achromatic response times to the same target are shown at a chromatic displacement of 0. Data points represent the mean response times of 90 presentations, with error bars representing standard error.

The results in Figure 4-3 show that the addition of a blue or yellow colour signal to the Landolt C target improved search times compared with the achromatic search at 0 CAD units. There was gradual improvement with increasing target saturation; however after a saturation of 4 CAD units this effect was minimal. The polarity of luminance contrast for coloured targets did not appear to affect search times for any subjects; ANOVAs were carried out for each colour direction, and revealed no significant difference between results for any of the luminance contrasts employed (full results can be found in appendix G). For blue targets, the average percentage of correct responses was 97.4% (ranging between 92.2% and 100% for each combination of saturation and luminance contrast). For yellow targets the average percentage correct was 96.6%, ranging between 94.4% and 98.8%. There was no effect of saturation or luminance contrast on the percentage of correct

responses for either colour direction (tables containing the percentage of correct responses for each subject and condition in this experiment can be found in Appendix G).

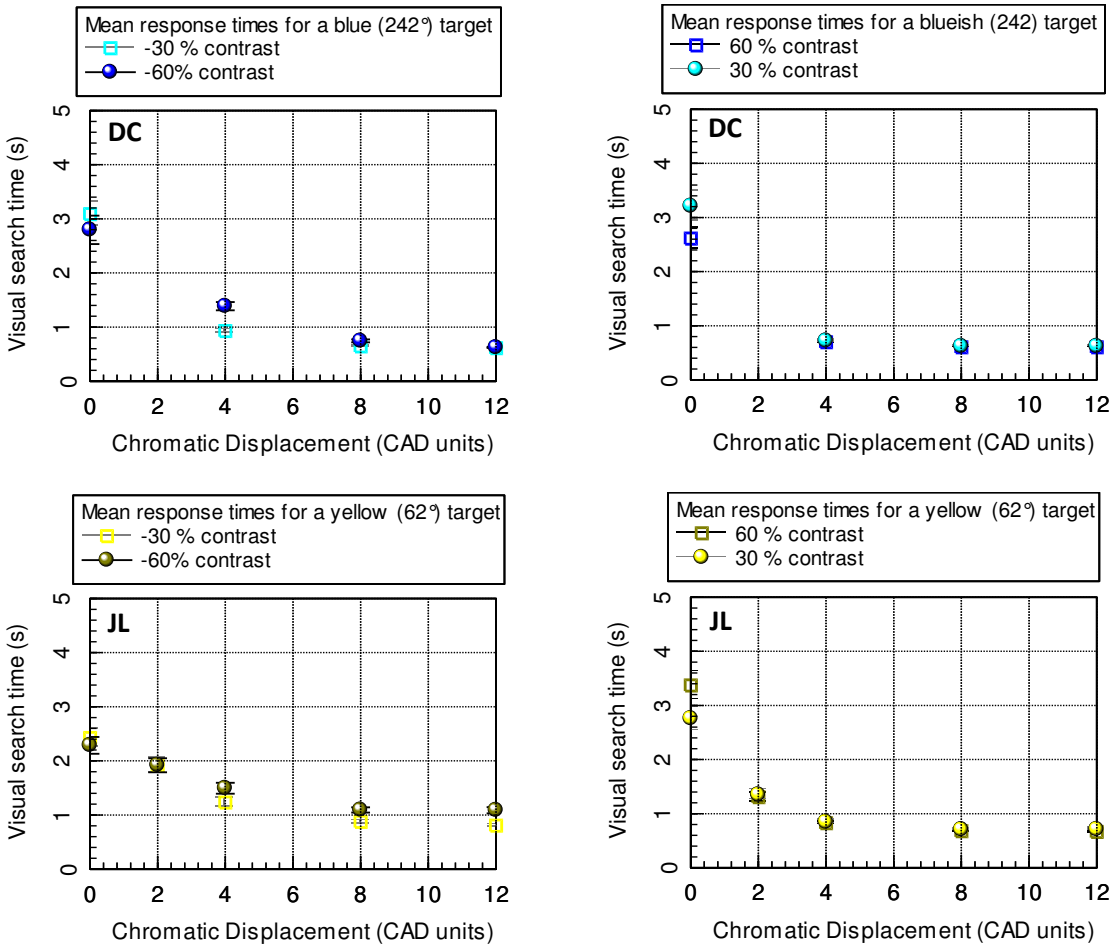


Figure 4-4: Example visual search response times for colour deficient observers for yellow and blue targets: (A) shows search times of deutan subject JL for blue and (B) shows search times of protan subject DC for yellow. The target had an additional spatial cue; achromatic response times to the same target are shown at a chromatic displacement of 0. Data points represent the mean response times of 90 presentations. Error bars show standard error. Response times for all colour deficient observers for yellow and blue were within error of the normal trichromats tested (Appendix E).

Figure 4-4 shows the responses to yellow and blue targets for a protan and deutan subject. Results for other colour deficient subjects for these conditions are found in Appendix F. As with normal trichromats, yellow and blue causes an increase in conspicuity of the Landolt C target that becomes more pronounced with increasing saturation. There is only a slight improvement above 4 CAD units, with search times generally under 1 second at the maximum saturation of 12 CAD units. Colour deficient subjects also carried out the task with accuracy equivalent to normal trichromats. This was

expected as the additional spatial cue ensures that the task can be completed without the need for colour perception; in subsequent tests involving red and green targets this level of accuracy was maintained.

As stated in 4.4.2, all colour deficient subjects in this experiment had yellow/blue CAD thresholds within the normal range, and so normal performance on the visual search task was expected. Figure 4-5 shows a comparison between one particular condition (a yellow target at -60% luminance contrast), illustrating that protan and deutan search times are within error of those of normal subjects for this task.

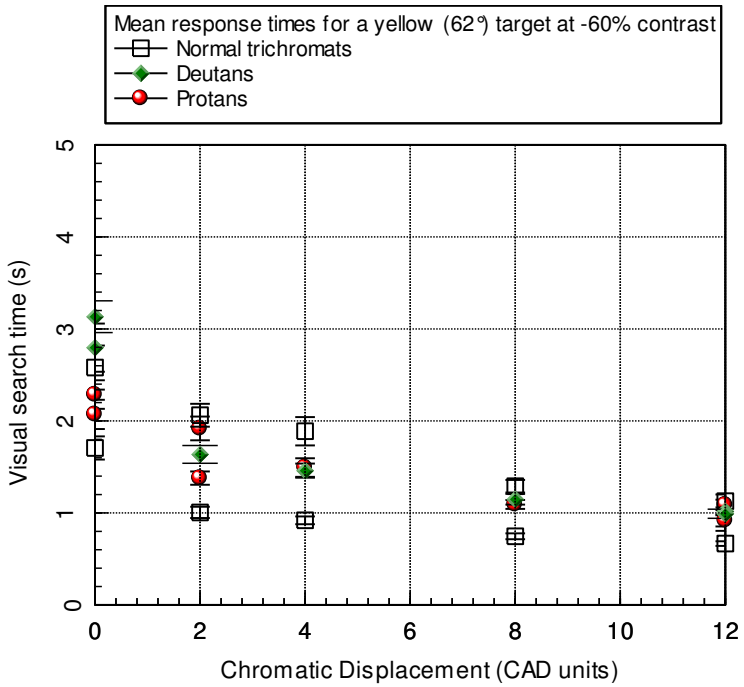


Figure 4-5: Visual search response times for a yellow target amongst 40 achromatic distractors, at -60% luminance contrast: data for 2 normal trichromats, 2 deutans and 2 protans. Error bars show standard error. Response times of colour deficient observers are within error of those of normal trichromats.

4.4.3.2 Visual search for red and green targets for normal trichromats

Visual search times of a normal trichromat for red and green Landolt C stimuli are shown in Fig. 4-6; results for the 3 other normal trichromats can be found in Appendix E.

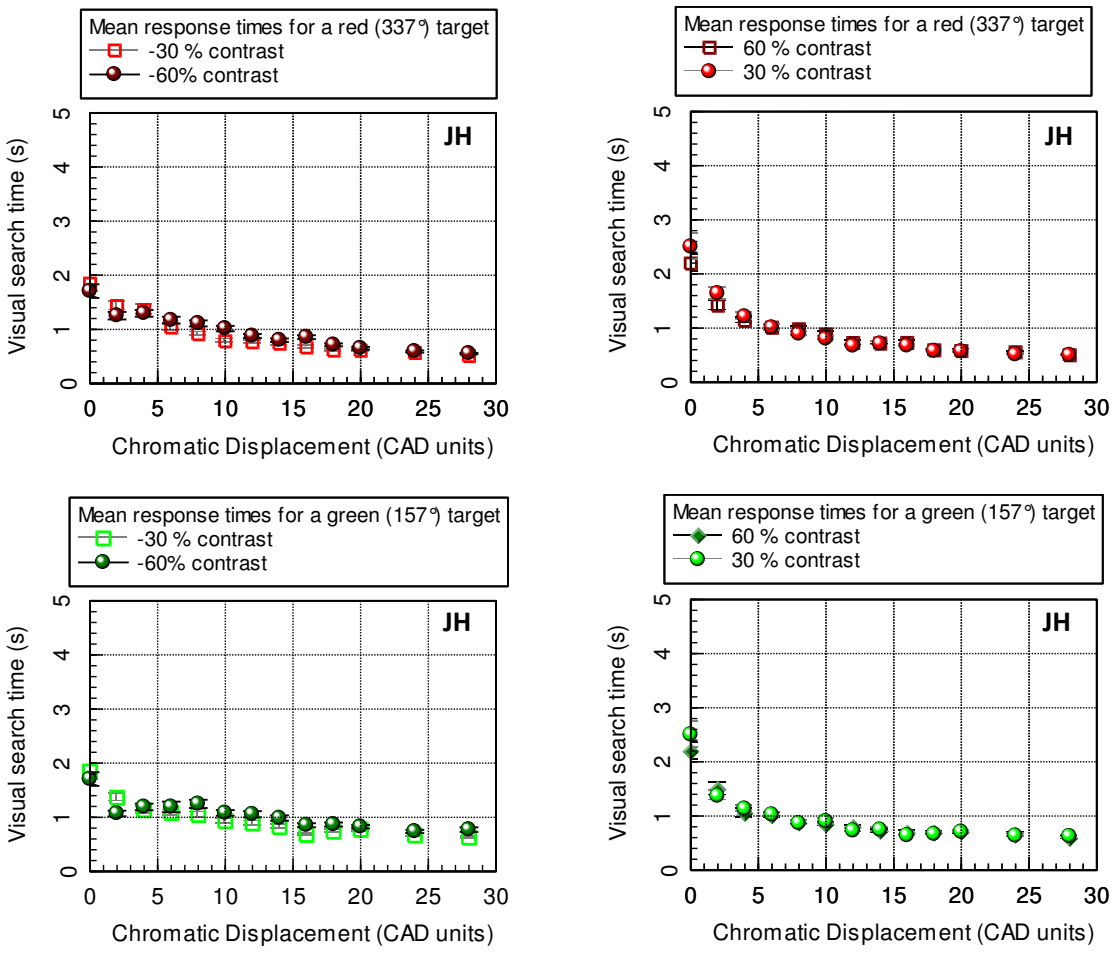


Figure 4-6: Visual search response times of normal trichromat JH for red and green targets amongst 40 achromatic distractors. The target had an additional spatial cue; achromatic response times to the same target are shown at a chromatic displacement of 0. Data points represent the mean response times of 90 presentations. Error bars show standard error.

The addition of red or green to the Landolt C target improved search times with increasing saturation as illustrated in Figure 4-6. For red targets, the average percentage of correct responses was 98% (ranging between 93.3% and 100% for each combination of saturation and luminance contrast). For green targets the average percentage correct was 97.3%, ranging between 91.1% and 100%. There was no effect of saturation or luminance contrast on the percentage of correct

responses for either colour direction; this was to be expected as the presence of a spatial cue that differentiates the target from the background allows all subjects with normal visual acuity to identify the target correctly. One-way ANOVAs were carried out for each colour direction, and revealed no significant difference between results for any of the luminance contrasts employed (full results can be found in appendix G). As with yellow and blue colour directions; search times reached a speed of less than 1 second at the higher saturations. However, comparing the search times in Fig 4-3 and 4-6, yellow and blue colours appear to illicit faster responses at equivalent saturations. This is examined further in Section 4.7.

4.4.3.3 Protan performance: red targets with positive luminance contrasts

The performance of protan observers for red targets with a positive contrast in experiment 4.1 is shown in Figure 4-7. The same targets presented with negative luminance contrasts offered reduced improvement in performance compared with positive contrasts for colour deficient observers. Graphs for targets of negative luminance contrast can be found in appendix F.

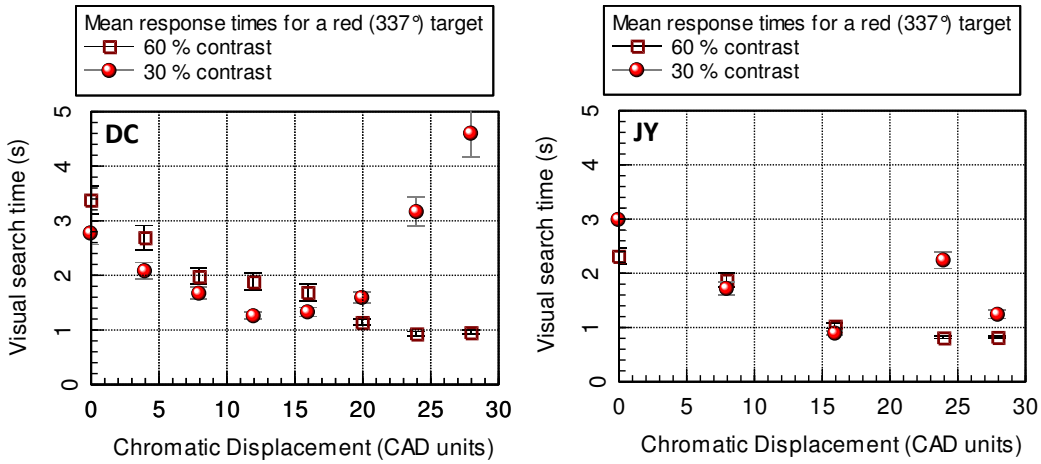


Figure 4-7: Visual search response times for protan observers for a red target with a +30% and +60% luminance contrasts compared with the background field, amongst 40 achromatic distractors. Subject DC was a mild protan with a CAD threshold of 6.8 and subject JY was a severe protan with a threshold of 21.5. Error bars show standard error.

Visual search times of these protanomalous subjects for red appear to be influenced by the luminance contrast of the target. With a 60% luminance contrast relative to the background, search

times improved steadily for both the mild (DC) and the severe (JY) subject however performance was significantly worse than that of normal trichromats in both cases. At 30 % luminance contrast there is an initial improvement at a similar rate, however this appears to be counteracted at higher saturations and in the case of subject DC there is a U-shaped distribution with search times becoming significantly worse than achromatic search times. This can only be explained as a reduction in effective luminance contrast when compared with the achromatic target. For subject JY there is a noticeable increase in search times at 24 CAD units however with some improvement by 28 CAD units. Such findings are likely to reflect the complex interaction between subject's level of deficiency and the combination of residual colour and luminance contrast signals in the target. These potential explanations are discussed further in Section 4.8.

4.4.3.4 Deutan performance: red targets with positive luminance contrasts

The performance of deutan observers for red targets with a positive contrast in experiment 4.1 is shown in Figure 4-8. The same targets presented with negative luminance contrasts offered reduced improvement in performance compared with positive contrasts for colour deficient observers. Graphs for targets of negative luminance contrast can be found in Appendix F.

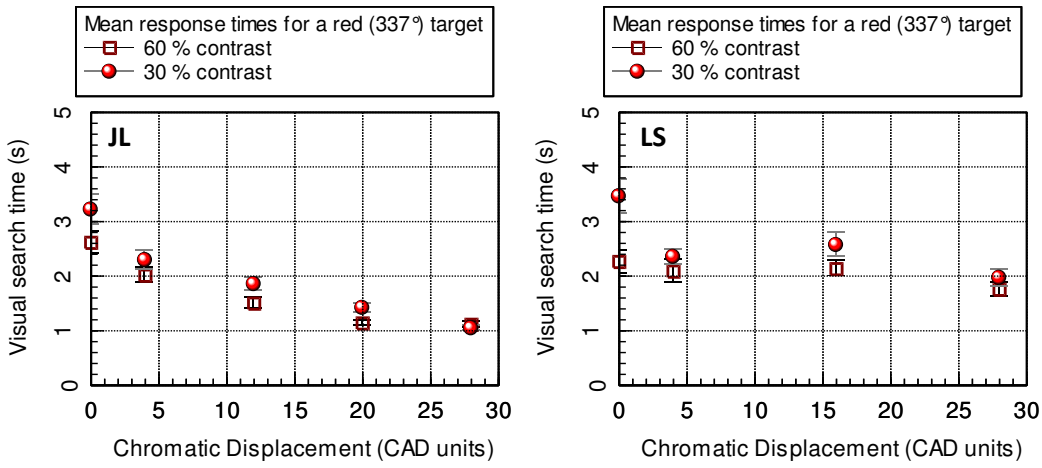


Figure 4-8: Visual search response times for deutan observers for a red target with a +30% and +60% luminance contrasts compared with the background field, amongst 40 achromatic distractors. Subject JL was a mild deutan with a threshold of 3.38 and subject LS was a severe deutan with a threshold of 19.5. Error bars show standard error.

Deutan subjects show some improvement in search times as a function of increasing target saturation. This is more pronounced for the mildly affected subject (JL), whereas for the more severe subject (LS) this improvement is less obvious, with only a slight reduction in search times at the maximum saturation employed. Targets of 60% luminance contrast were more easily detected than those at 30% contrast apart from JL at 28 CAD units, indicating an interaction between colour and luminance in determining search times.

4.4.3.5 Protan performance: green targets with positive luminance contrasts

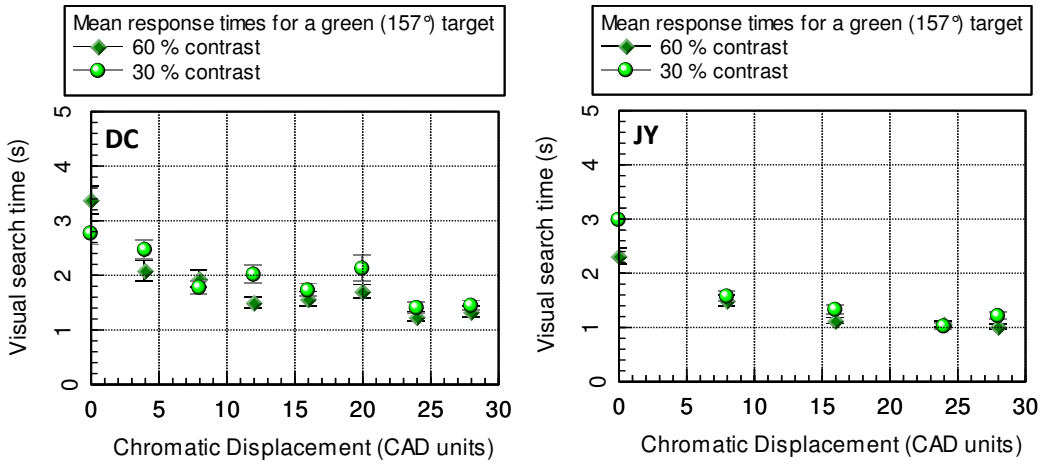


Figure 4-9: Visual search response times for protan observers for a green target with a +30% and +60% luminance contrasts compared with the background field, amongst 40 achromatic distractors. Subject DC was a mild protan with a threshold of 6.8 and subject JY was a severe protan with a threshold of 21.5. Error bars show standard error.

For a green target, both protan subjects showed an improvement in search times as a function of increasing saturation. Protan subjects do not appear to show any adverse effect at higher saturations. The results observed with a red target were likely due to the decrease in effective luminance contrast of the target, resulting from the lack of sensitivity at the long-wavelength end of the visual spectrum. Deutan observers, however, do not experience the same reduction in stimulus luminance for green targets that protans do for reds due to the overlapping wavelength sensitivities from other classes of photoreceptors.

4.4.3.6 Deutan performance: green targets with positive luminance contrasts

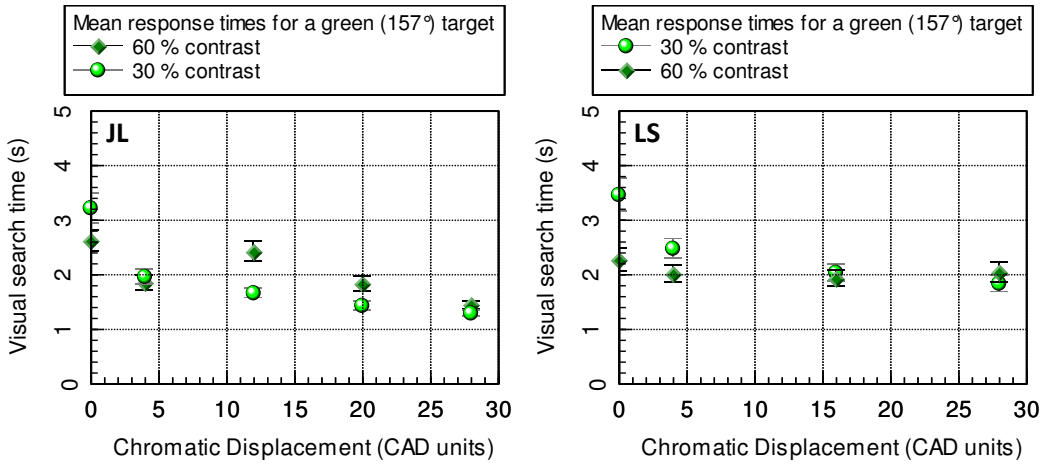


Figure 4-10: Visual search response times for deutan observers for a green target with a +30% and +60% luminance contrasts measured with respect to the background field, amongst 40 achromatic distractors. Subject JL was a mild deutan with a threshold of 3.38 and subject LS was a severe deutan with a threshold of 19.5. Error bars show standard error.

For a green target, the mild deutan JL showed reduced search times with increasing saturation in a similar manner to those observed for a red target. The severe subject LS showed little improvement however.

Performance for colour deficient observers was noticeably different from that of normal trichromats for red and green, but not unexpectedly, they performed as well as normal trichromats for yellow and blue colours. In several cases colour deficient subjects could reach normal search times, however required much higher colour signal strength in order to do so.

These measurements indicate that visual search times can be improved in colour deficient subjects by adding a RG colour signal to an achromatic target. It is important to identify whether based on this, any colour deficient subjects can carry out visual search within the normal range for reasonably saturated targets under conditions more similar to those found on ATC displays. While the spatial cue used in this experiment made it possible to carry out the test even in the absence of colour and allowed for the effect of colour on improving search times to be established, it is also useful to examine how effective RG colour signals are in visual search in the absence of other cues. This was examined in experiment 4.2.

4.5 EXPERIMENT 4.2

4.5.1 Introduction

The second experiment was designed to investigate the ability of colour deficient subjects to perform visual search tasks where colour is the only identifying feature for the target. Data blocks contain different information, however this information must be read in a serial manner in order to determine which are the relevant or 'attended' and which are not. There will therefore often be no guiding spatial cue that delineates target data blocks from others on the display, and so in order to achieve a relatively efficient search, ATCOs must be able to locate a target based on its colour signal only. In addition, multiple colours can be present on ATC displays, and therefore an ATCO is required to identify relevant data blocks based on their colour in the presence of other, potentially confusable colours.

4.5.2 Methods

In experiment 4.2, visual search performance was measured when all items on the screen (targets and distractors) were Landolt Cs, and therefore targets could only be separated from distractors if the subject had adequate chromatic sensitivity to do so. In each presentation, there were four coloured stimuli present: 337° (red), 157° (green), 62° (yellow) and 242° (blue). One was selected as being the target, and the rest were distractors; subjects were instructed as to which would be the target colour before each run of the experiment. The subject's visual search performance was therefore measured in the presence of other coloured targets which the subject had to judge as different to the target colour. Compared with the results from the first experiment, preliminary results for normal trichromats (Appendix E) indicated that there was no significant difference in performance when there was no spatial cue; little improvement on search times was shown above saturations of 12 CAD units. Based on this, visual search times were obtained for normal and colour deficient subjects in the absence of a spatial cue, for the red (337°) and green (157°) colour directions at a saturation of 12 CAD units. Furthermore, normal subjects carried out repeat

measurements over a range of saturations (3, 6 and 12 SNU); this normal range of performance was related to colour deficient observers' responses.

A subset of normal trichromats and colour deficient subjects carried out the same procedure for yellow (62°) and blue (242°) targets, in order to examine whether the lack of a spatial cue had any effect on search times in these directions.

Luminance contrasts of targets and distractors were set at ±45%; this was a refinement from experiment 4.1 to allow for more straightforward comparison between positive and negative contrasts, to illustrate any significant disadvantage to colour deficient observers in either condition. As the aim was to determine if colour deficient subjects were capable of performing the search task within the range of visual search time and levels of accuracy as normal trichromats, greater emphasis was placed on testing subjects with minimal deutan deficiencies (i.e. those that may have been capable of passing the previous colour vision test procedure used by the CAA).

4.5.3 Results for Experiment 4.2

4.5.3.1 Normal and colour deficient performance for red and green targets in the absence of an identifying spatial cue

Visual search times were obtained for normal and colour deficient subjects in the absence of a spatial cue, for the red and green colour directions at a saturation of 12 CAD units. Performance was measured in terms of visual search time and the percentage of correct responses, compared with subjects' CAD thresholds.

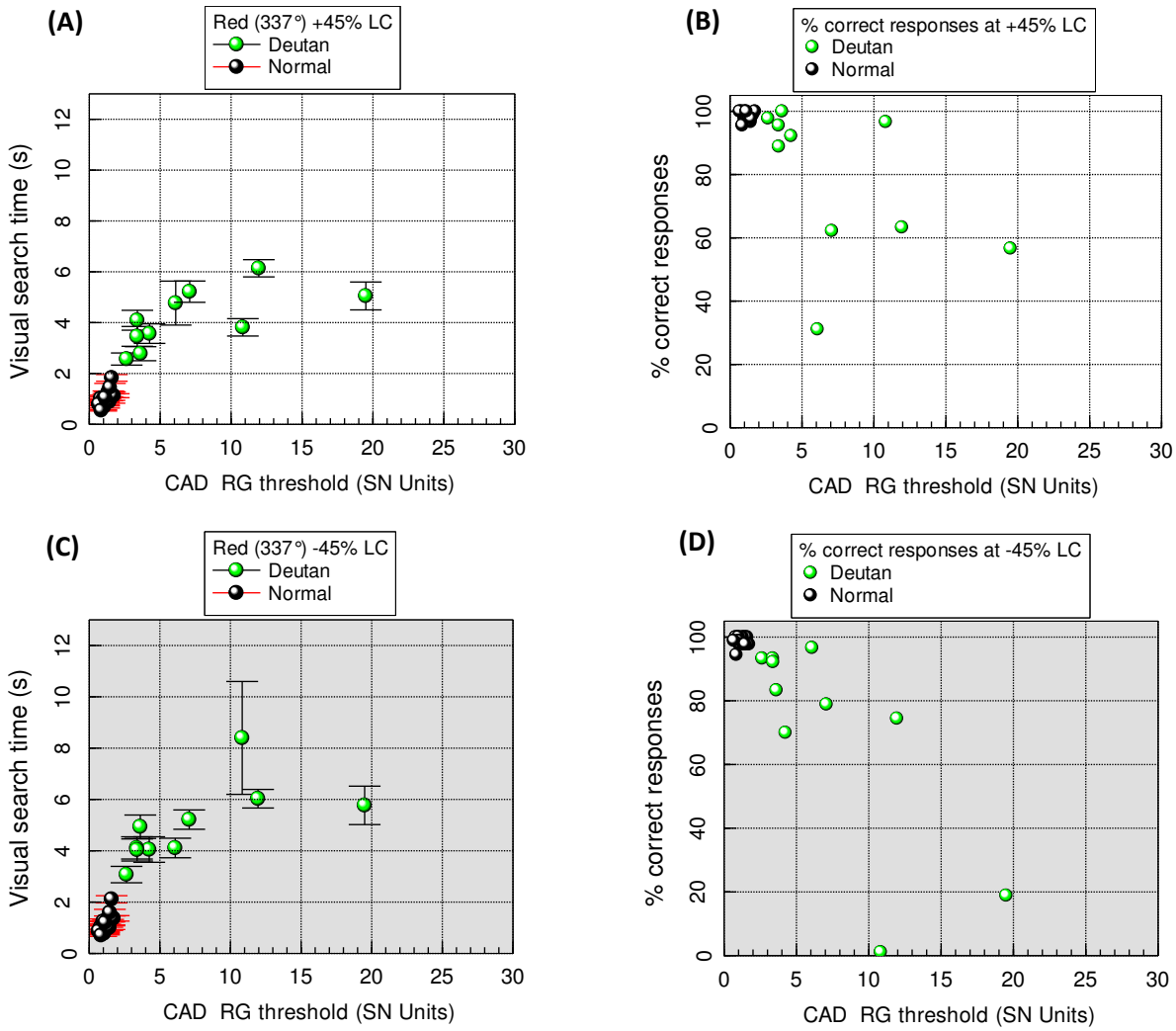


Figure 4-11: Mean visual search times and percentage of correct responses for normal and colour deficient subjects for a red target (A and B) with a +45% luminance contrast and (C and D) with a -45% luminance contrast, at a saturation of 12 CAD units, amongst 37 achromatic and 3 differently coloured targets with no defining spatial attribute for target identification. Data is shown for 15 normal trichromats and 10 deutans. Error bars show standard error.

Figure 4-11 shows the performance of 10 deutan subjects and 15 normal trichromats for a red target at +45% and -45% luminance contrast. Several minimally affected deutan subjects were tested, however for either condition, deutan subjects could not produce visual search times within error of the normal range. It was possible for some deutans to respond with normal levels of accuracy however. Paired t-tests showed no significant difference between positive and negative contrasts for visual search time ($p = 0.67$), however there was a significant difference for the percentage of correct responses ($p < 0.01$). The results suggest that some deutan subjects are able to carry out the task of locating the coloured target with the same precision as normal trichromats under certain

conditions, but the visual times are longer than those measured in normal trichromats. There is obvious variation in the percentage of correct responses as a function of CAD threshold; one subject was unable to correctly identify nearly all targets whereas a subject with a higher CAD RG threshold was able to correctly identify a higher proportion. Nevertheless there was a significant correlation between the two (Spearman's rho gave a significant correlation, $p < 0.05$ (two tailed)). Furthermore there was a significant correlation between CAD threshold and search time (Spearman's rho gave a significant correlation, $p < 0.01$ (two tailed), for search times for both positive and negative luminance contrasts).

Although detection of the target is somewhat dependent on chromatic sensitivity, there are a range of other factors that affect visual search (as mentioned in section 4.2 and appendix 6.3) which may explain these results. The search time for the deutan subject (CAD threshold 10.83) who achieved a very low percentage of correct responses is based on that small sample of responses, hence the corresponding large error bars for search time. It is also not possible to entirely control for the attention or motivation of the subject and this must also be taken in to account.

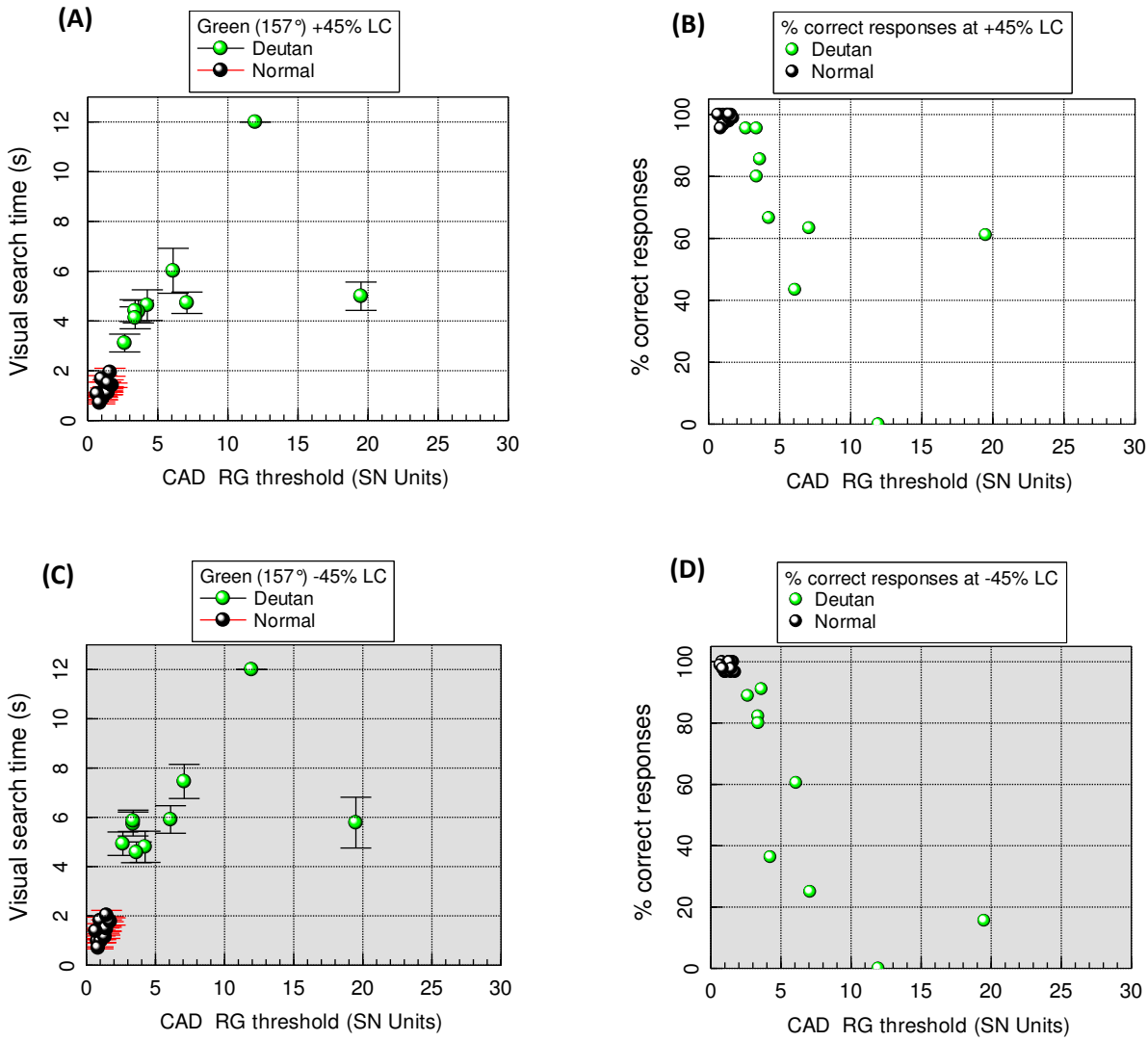


Figure 4-12: Mean visual search times and percentage of correct responses for normal and colour deficient subjects for a green target (A and B) with a +45% luminance contrast and (C and D) with a -45% luminance contrast, at a saturation of 12 CAD units, amongst 37 achromatic and 3 differently coloured targets with no defining spatial attribute for target identification. Data is shown for 15 normal trichromats and 10 deutans. Error bars show standard error.

Figure 4-12 shows the performance of 10 deutan subjects and 15 normal trichromats for a green target at +45% and -45% luminance contrast. For +45%, deutan subjects could not produce visual search times within error of the normal range however, as with the red target, it was possible for some deutans to respond with normal levels of accuracy. This was not the case in the -45% luminance contrast condition; there was a clearer separation in visual search times between normal and deutan subjects, and no deutans achieved the same accuracy of responses as the normal group. Paired t-tests showed no significant difference between positive and negative contrasts for visual search time ($p = 0.58$), however there was a significant difference for the percentage of correct

responses ($p < 0.01$). As in the results of experiment 4.1, the use of colour in visual search, for colour deficient subjects, appears to be affected by the polarity of luminance contrast of the target.

As with search for red targets, there were significant correlations between CAD threshold and percentage correct, and CAD threshold and search time (Spearman's rho gave significant correlations, $p < 0.01$ (two tailed) in both cases) for search times for both positive and negative luminance contrasts).

The luminous efficacy function for colour deficient subjects is different to the typical normal trichromat and this affects directly the luminance contrast of a coloured target. It remains to be established the extent to which changes in effective luminance contrast for coloured target in RG colour deficient account for the measured difference in performance with increasing chromatic saturation.

Deutans showed similar results for both red and green targets. The chromatic discrimination ellipse for colour deficient observers, as per results from the CAD test plotted in CIE 1931 colour space, is roughly equivalent in the red and green directions with respect to background chromaticity (Barbur & Rodriguez-Carmona, 2012). Therefore approximately equivalent saliency of the red and green targets in this experiment, which were selected to be at the centre of the protan/deutan axes, would be expected.

The response times of normal trichromats were measured for the same condition, but over a range of saturations (3, 6 and 12 SNU). A number of deutan subjects with varying RG colour thresholds were examined using a single coloured target with a saturation of 12 CAD units. In order to test whether for certain colours the subject's reduced chromatic sensitivity is the major factor that causes decreased visual search times, the colour signal strength was expressed as a fraction of the subject's red-green detection threshold (i.e., target colour signal strength / subject's RG threshold, both in CAD units), thereby 'normalizing' the effective chromatic signal strength for deutans and

normal trichromats. Normalized deutan responses (see Figures 4-13 and 4-14) are shown together with the range of responses measured in normal trichromats.

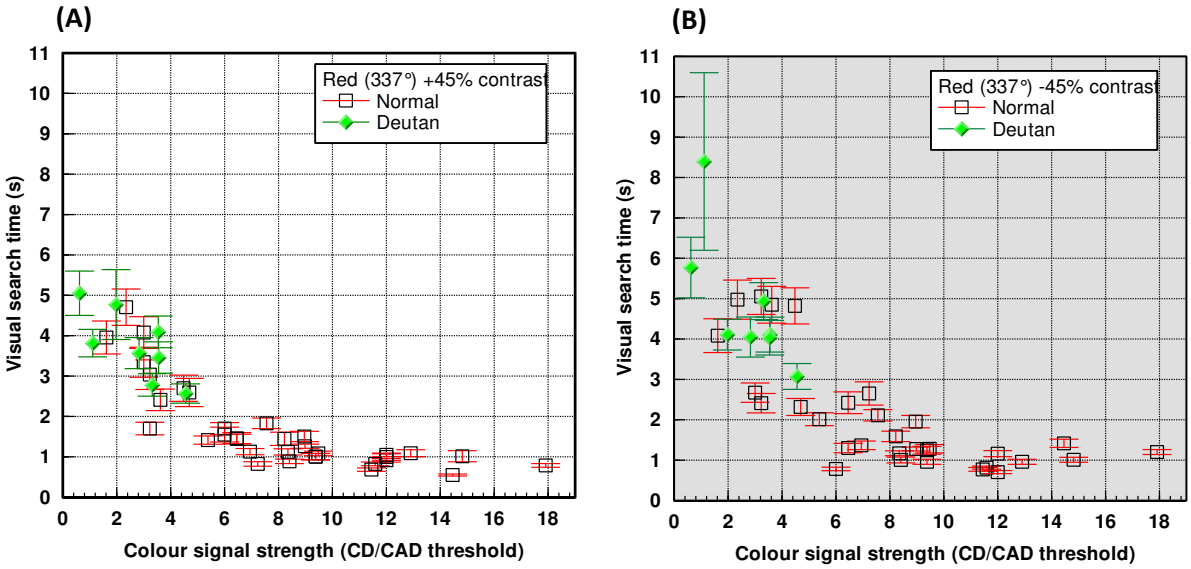


Figure 4-13: Visual search times for a red target in experiment 4.2 at (A) +45% luminance contrast and (B)-45 % luminance contrast. Search times are shown for 8 deutans and 11 normal trichromats. The effective colour signal strength is calculated by dividing the target saturation by a subject's CAD RG threshold. Error bars show standard error.

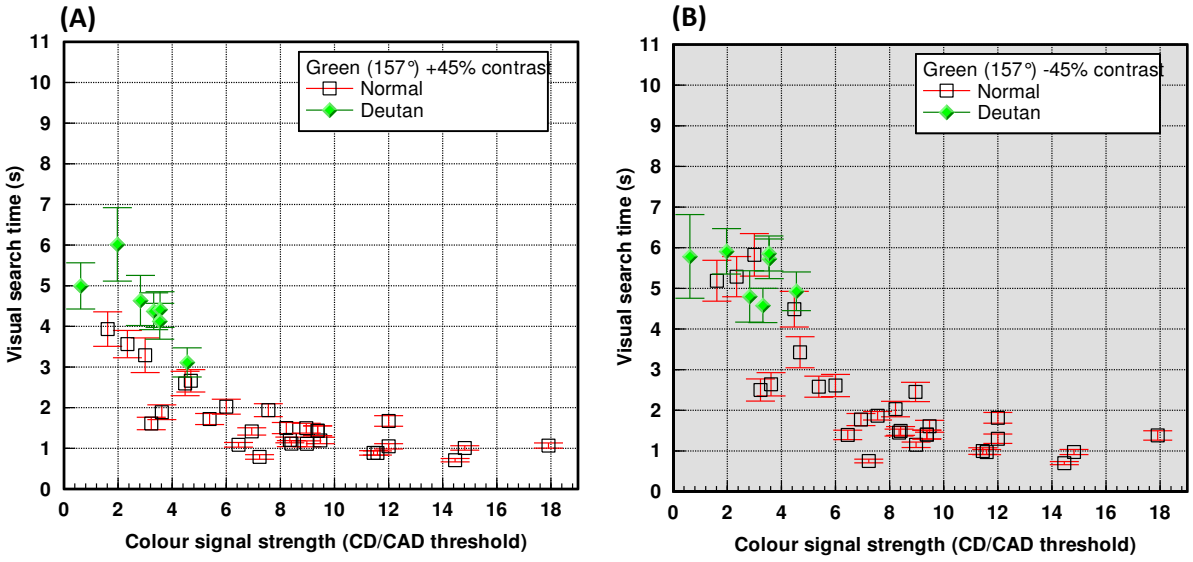


Figure 4-14: Visual search times for a green target in experiment 4.2 at (A) +45% luminance contrast and (B)-45 % luminance contrast. Search times are shown for 7 deutans and 11 normal trichromats. The effective colour signal strength is calculated by dividing the target saturation by a subject's CAD RG threshold. Error bars show standard error.

As per Figures 4-13 and 4-14, when the saturation of the target is expressed in the subject's own red-green detection threshold, deutan responses fall within the range of normal responses. The

results show that for target luminance contrasts within the ±45% range, with large chromatic saturations, deutan-like subjects can perform as well as normal trichromats for lower saturations. When the strength of the colour signal is expressed in the subject's specific red-green threshold unit, normal and colour deficient subjects respond similarly at equivalent saturations.

4.5.3.2 Normal and colour deficient performance for yellow and blue targets in the absence of an identifying spatial cue

Visual search times were obtained for 15 normal trichromat subjects and 13 congenital colour deficient subjects (7 deuteranomalous trichromats and 1 deuteranope; 4 protanomalous trichromats and 1 protanope) in the absence of a spatial cue, for the yellow and blue colour directions at a saturation of 12 CAD units, at either +45% or -45% luminance contrast relative to the background. Performance was measured in terms of visual search time and the percentage of correct responses, compared with subjects' CAD RG thresholds, as per Figures 4-15 and 4-16.

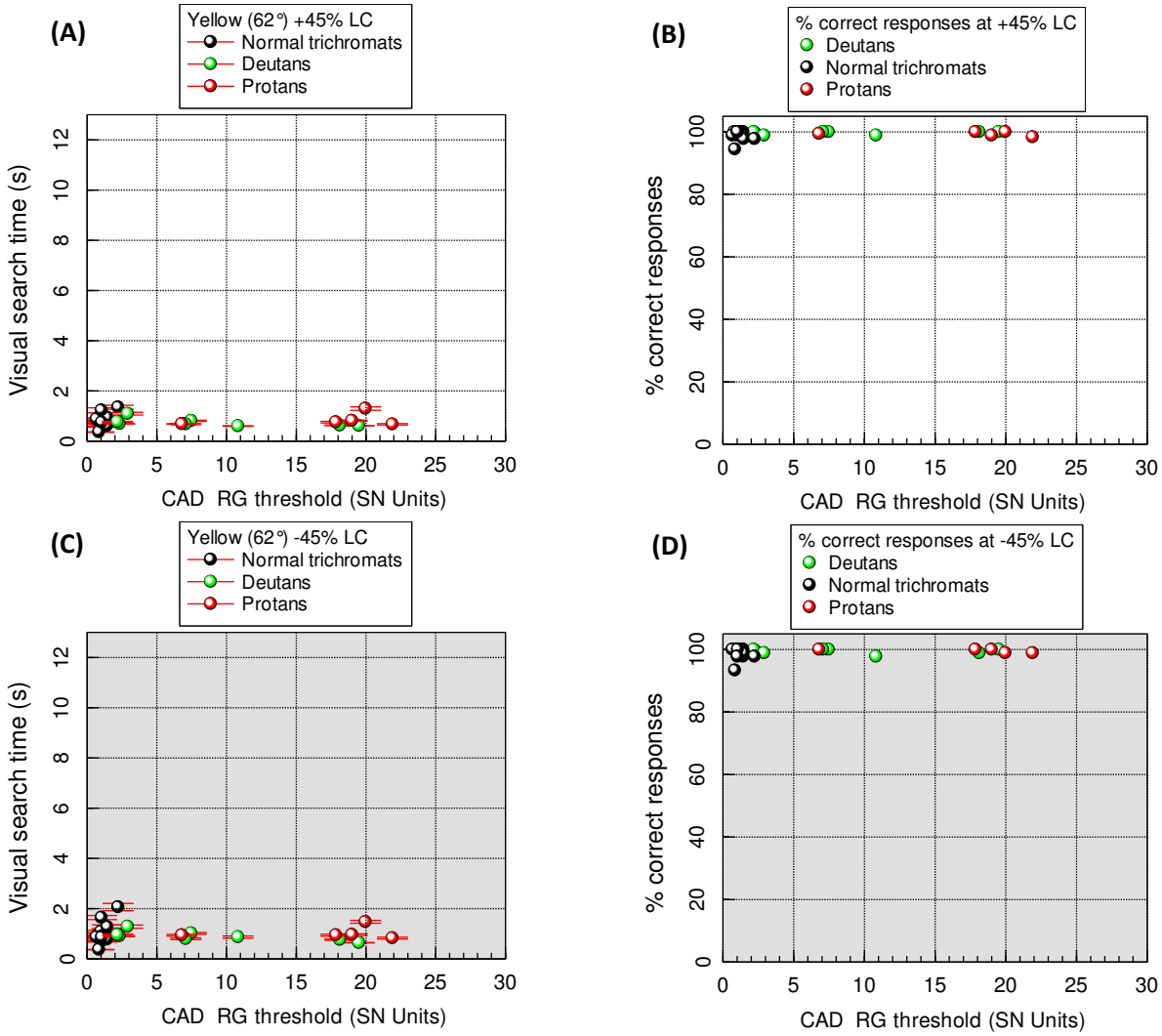


Figure 4-15: Mean visual search times and percentage of correct responses for normal and colour deficient subjects for a yellow target (A and B) with a +45% luminance contrast and (C and D) with a -45% luminance contrast, at a saturation of 12 CAD units, amongst 37 achromatic and 3 differently coloured targets with no defining spatial attribute for target identification. Data is shown for 10 normal trichromats, 8 deutans and 5 protans. Error bars show standard error.

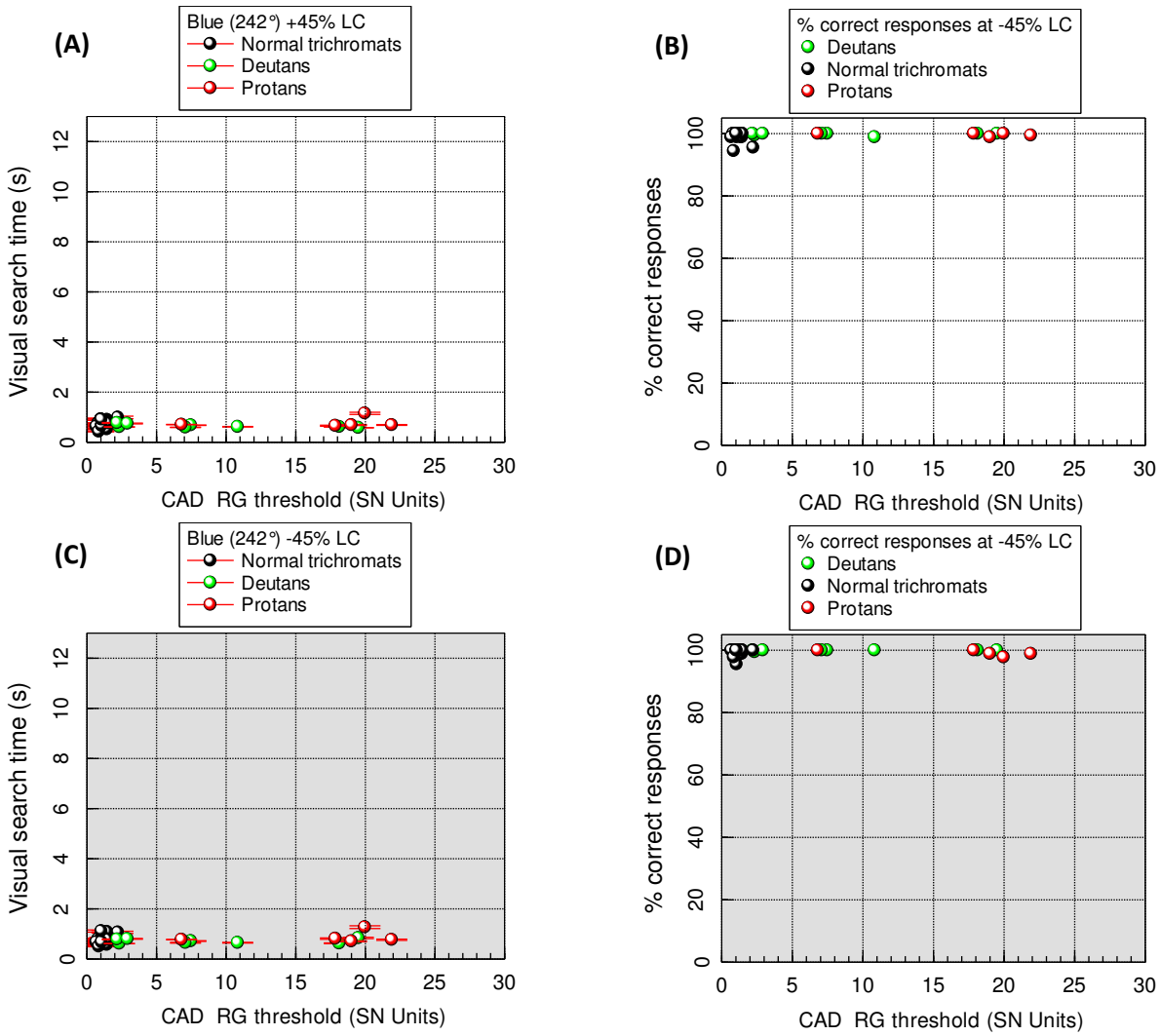


Figure 4-16: Mean visual search times and percentage of correct responses for normal and colour deficient subjects for a blue target (A and B) with a +45% luminance contrast and (C and D) with a -45% luminance contrast, at a saturation of 12 CAD units, amongst 37 achromatic and 3 differently coloured targets with no defining spatial attribute for target identification. Data is shown for 10 normal trichromats, 8 deutans and 5 protans. Error bars show standard error.

For either the yellow or blue coloured target, with either a positive or negative luminance contrast, there was no effect of colour deficiency on visual search time or response accuracy. While not every subject obtained 100% correct responses, this is likely due to errors in operating the keypad, or other lapses in attention, rather than an inability to perceive the colour of the target. There was no significant difference between the search times of the normal and colour deficient populations, and no significant difference between the positive and negative search times for either colour ($p > 0.05$ in each case). Dichromats tested achieved search times and levels of accuracy within the normal range for both colour directions, highlighting that, as with the results for yellow and blue in experiment

4.1, colour deficient subjects are capable of carrying out visual search tasks for these colours effectively. The lack of a spatial cue for target identification did not have any effect of impairing performance in subjects with colour deficiency.

4.6 EXPERIMENT 4.3

4.6.1 Introduction

In the third experiment, stimulus conditions were kept identical to those in experiment 4.2, however the colour directions employed were changed in order to test visual performance for a range of target chromaticities that elicit both RG and YB colour differences with respect to the achromatic background.

Based on results from experiments 4.1 and 4.2, it became clear that colour deficient performance was, in terms of visual search time and accuracy of response, equivalent to those of the normal trichromats tested for targets defined by a cardinal yellow or blue. Furthermore, the results of experiment 4.2 indicated that even the most mildly-affected colour deficient subjects could not perform within the normal range for targets defined only by RG colour signals. These observations suggest that the performance of colour deficient observers may well improve as the selected chromaticities generate both RG and YB colour signals.

4.6.2 Methods

Experiment 4.3 was designed to test this hypothesis and hence to establish whether colour deficient subjects may be able to carry out visual search tasks as effectively as normal trichromats for colour directions combining RG and YB signals. For convenience, four colour directions were selected away from the deutan and protan colour confusion bands as shown in Figure 4-17. Colours were selected as 22°, 109°, 198° and 293° in CIE 1931 colour space; these do not constitute an equal mixture, and still lie closer to the RG confusion axes than the YB confusion axes.

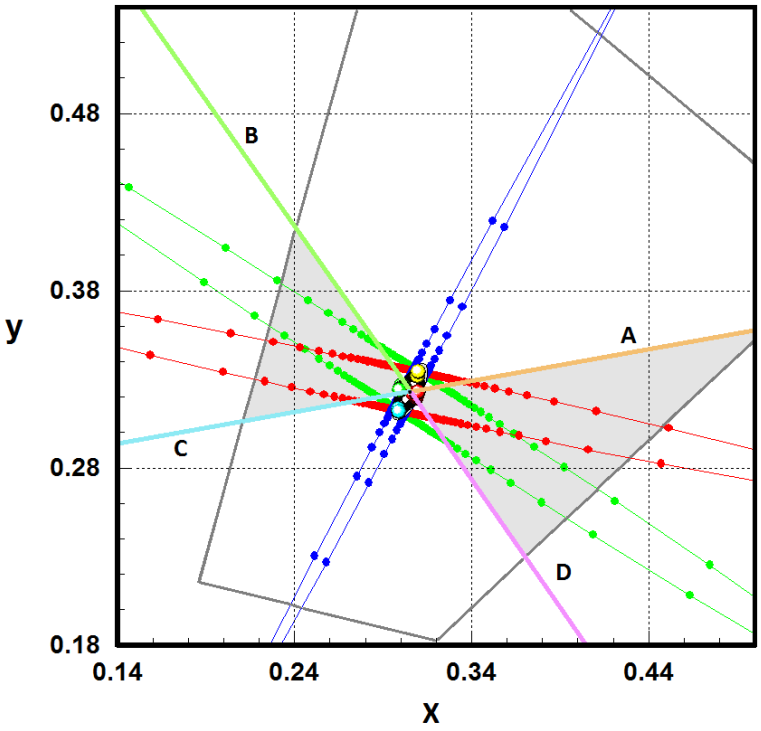


Figure 4-17:Colour directions (lines A (22°), B (109°), C (198°) and D (293°) plotted in CIE 1931 colour space. The central point indicates the background chromaticity. Protan, deutan and tritan confusion axes are indicated by the regions within the corresponding dotted lines; the phosphor limits of the monitor are indicated by the area encompassed by the grey line. Within the phosphor limits of the monitor, the grey shaded regions indicate those colour directions that produce lower YB signals than those selected.

Based on the results from experiment 4.2, those congenital colour deficient subjects that are able to perform within the normal range for all four colours, for both negative and positive luminance contrast, would be expected to perform at least as well for all other chromaticities that generate even greater YB colour differences.

4.6.3 Results for Experiment 4.3

Visual search times were measured in 31 normal trichromats and 39 congenital colour deficient subjects (21 deuteranomalous trichromats and 4 deuteranopes; 10 protanomalous trichromats and 4 protanopes) in the absence of a spatial cue, for the four colour directions that generate some YB colour difference signals. As with experiment 4.2, coloured stimuli were presented at a saturation of 12 CAD units and either +45% or -45% luminance contrast relative to the background. Performance was measured in terms of visual search time and the percentage of correct responses, compared

initially with subjects' CAD RG thresholds, as per Figures 4-19 - 4-22, and then with subjects' CAD thresholds for the specific target colour direction as per Figures 4-23 - 4-26.

4.6.3.1 Comparison of normal trichromat and colour deficient performance

The distribution of normal visual search times is shown in Figure 4-18 for each of the four colours tested, at positive and negative luminance contrasts. Descriptive values for these data set are shown in Tables 4-1 and 4-2. Outliers were determined as any value above Q3 + (1.5 x IQR), where Q3 is the 75th percentile and IQR is 75th – 25thpercentile for the data set (Upton & Cook, 1996).

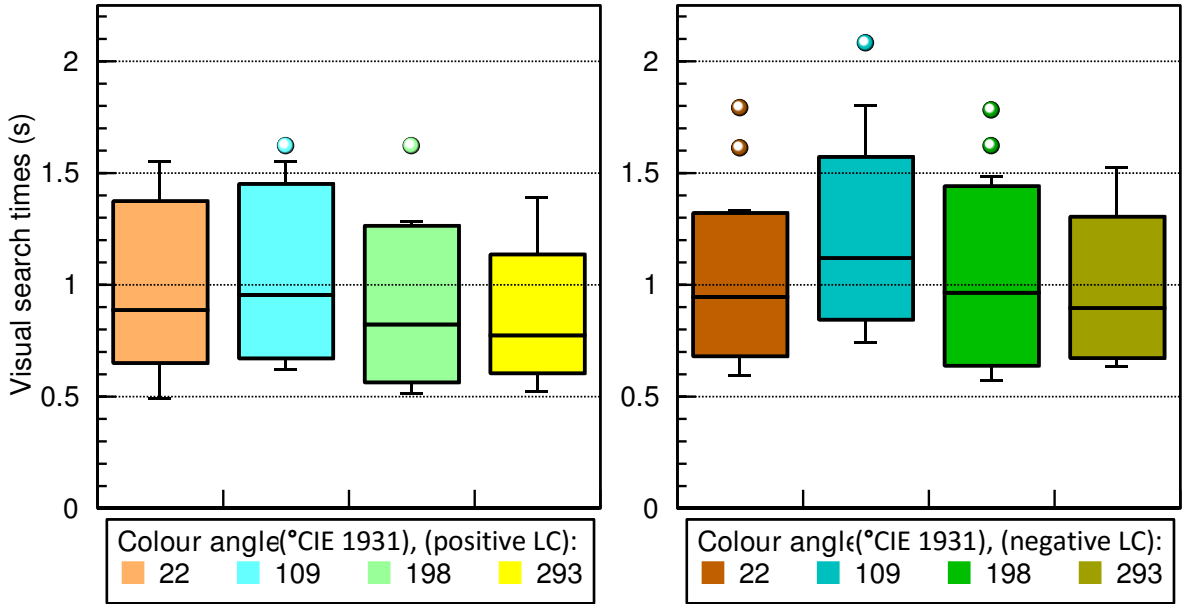


Figure 4-18: Box plots showing the normal range of performance for the four colour directions, at ±45% luminance contrast, with outliers highlighted.

The ranges and mean values for positive luminance contrasts were lower than those for negative contrasts in each direction. Paired t-tests between positive and negative contrasts of the same colours revealed significant differences in visual search times ($p < 0.01$), with targets at positive luminance contrast being located more rapidly. Bonferroni corrections (Armstrong, 2014) were applied ($p = 0.5/21 = 0.0024$), and with the alpha adjusted significant differences still applied between positive and negative contrasts of the pairs of colours ($p < 0.01$).

	22°	109°	198°	293°
Mean (seconds)	0.96	1.01	0.86	0.83
Std. deviation	0.27	0.26	0.25	0.20
Upper limit (seconds)	1.62	1.55	1.29	1.40

Table 4-1: Statistical data for the visual search times of normal trichromats in experiment 4.3, where colours were presented with a +45% luminance contrast. The upper limit represents the highest search time within the normal range, excluding outliers.

	22°	109°	198°	293°
Mean (seconds)	1.01	1.18	0.99	0.95
Std. deviation	0.26	0.32	0.29	0.23
Upper limit (seconds)	1.56	2.02	1.52	1.56

Table 4-2: Statistical data for the visual search times of normal trichromats in experiment 4.3, where colours were presented with a -45% luminance contrast. The upper limit represents the highest search time within the normal range, excluding outliers.

Colour deficient performance is compared with that of normal trichromats in Figures 4-19 – 4-21, showing the visual search times and percentage of correct responses, as functions of their CAD RG detection thresholds.

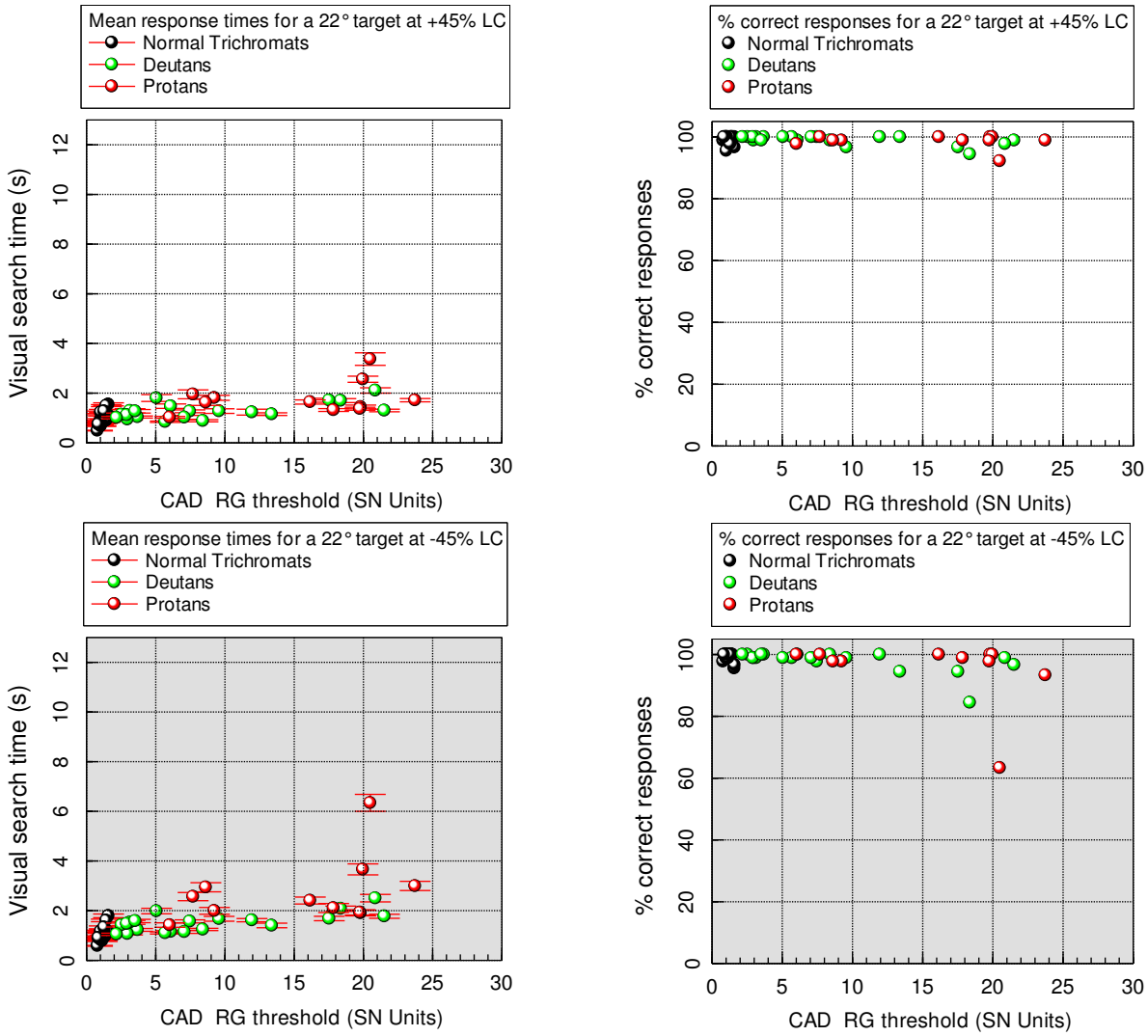


Figure 4-19: Mean visual search times and percentage of correct responses for normal and colour deficient subjects for a target with a colour direction 22° with respect to background chromaticity, *with (A and B) a +45% luminance contrast and (C and D) a -45% luminance contrast, at a saturation of 12 CAD units, amongst 37 achromatic and 3 differently coloured targets with no defining spatial attribute for target identification. Data are shown for 31 normal trichromats, 25 deutans and 14 protans. Error bars show standard error.*

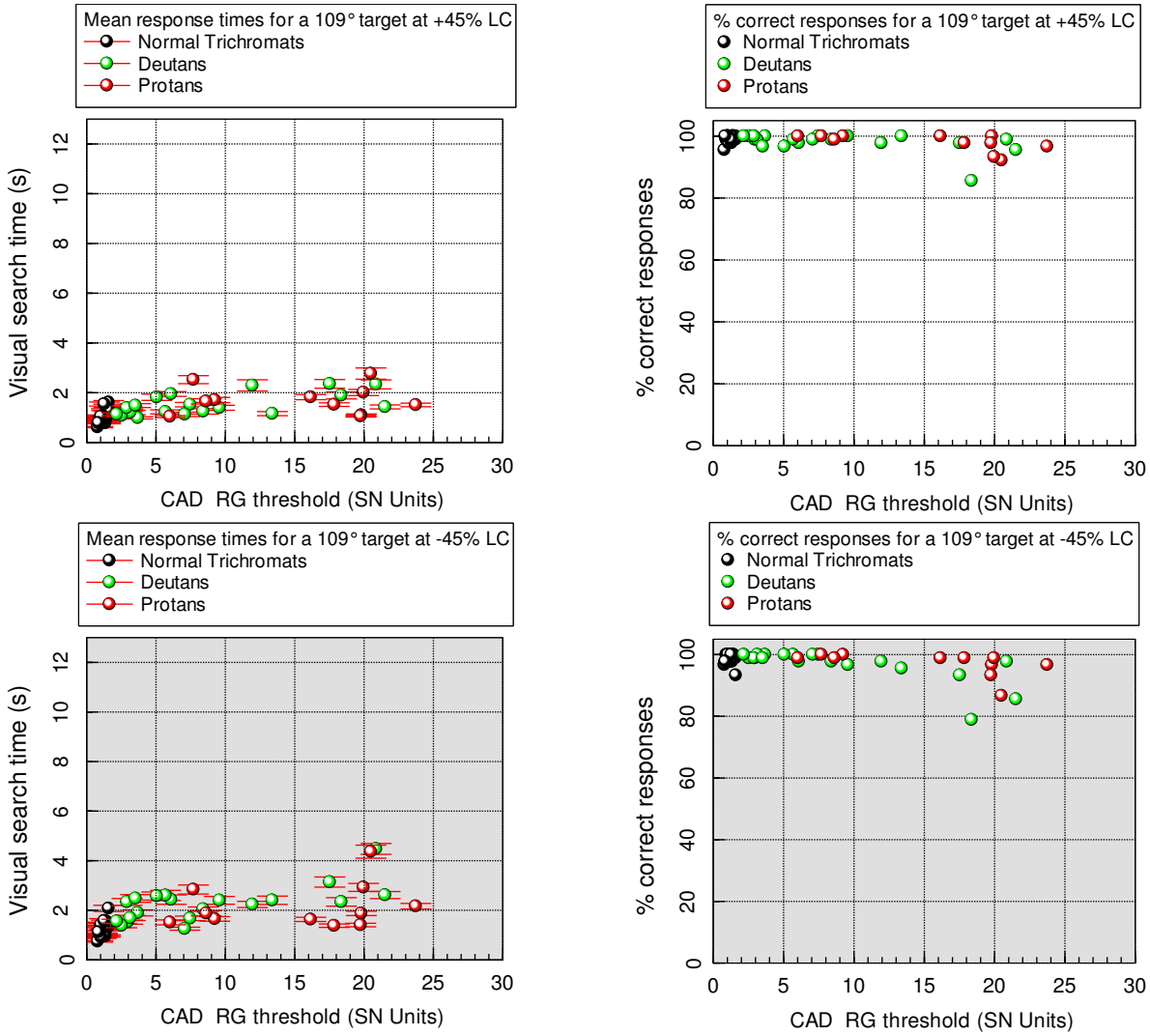


Figure 4-20: Mean visual search times and percentage of correct responses for normal and colour deficient subjects for a target with a colour direction 109° with respect to background chromaticity, *with (A and B) a +45% luminance contrast and (C and D) a -45% luminance contrast, at a saturation of 12 CAD units, amongst 37 achromatic and 3 differently coloured targets with no defining spatial attribute for target identification. Data is shown for 31 normal trichromats, 25 deutans and 14 protans. Error bars show standard error.*

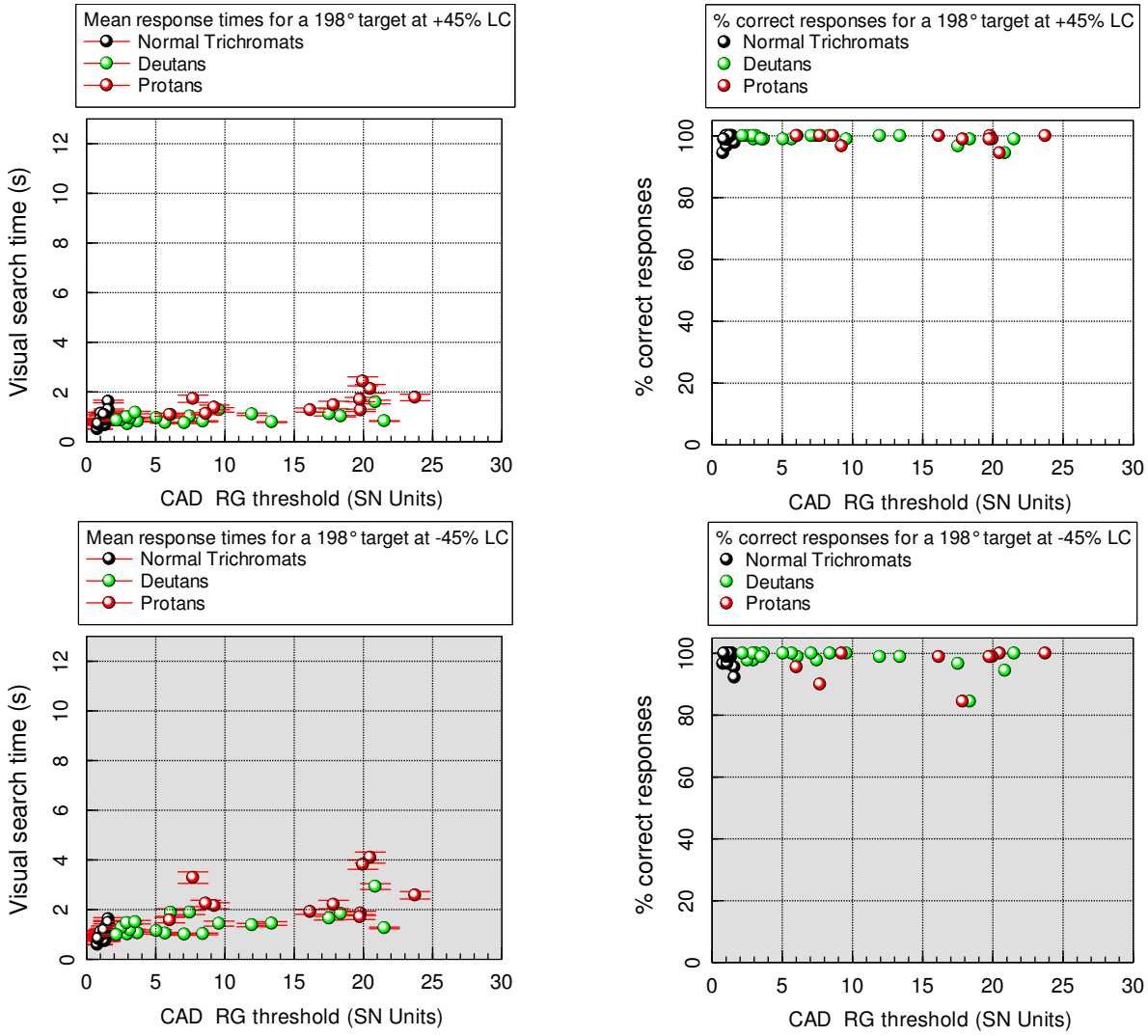


Figure 4-21: Mean visual search times and percentage of correct responses for normal and colour deficient subjects for a target with a colour direction 198° with respect to background chromaticity, *with (A and B) a +45% luminance contrast and (C and D) a -45% luminance contrast, at a saturation of 12 CAD units, amongst 37 achromatic and 3 differently coloured targets with no defining spatial attribute for target identification. Data is shown for 31 normal trichromats, 25 deutans and 14 protans. Error bars show standard error.*

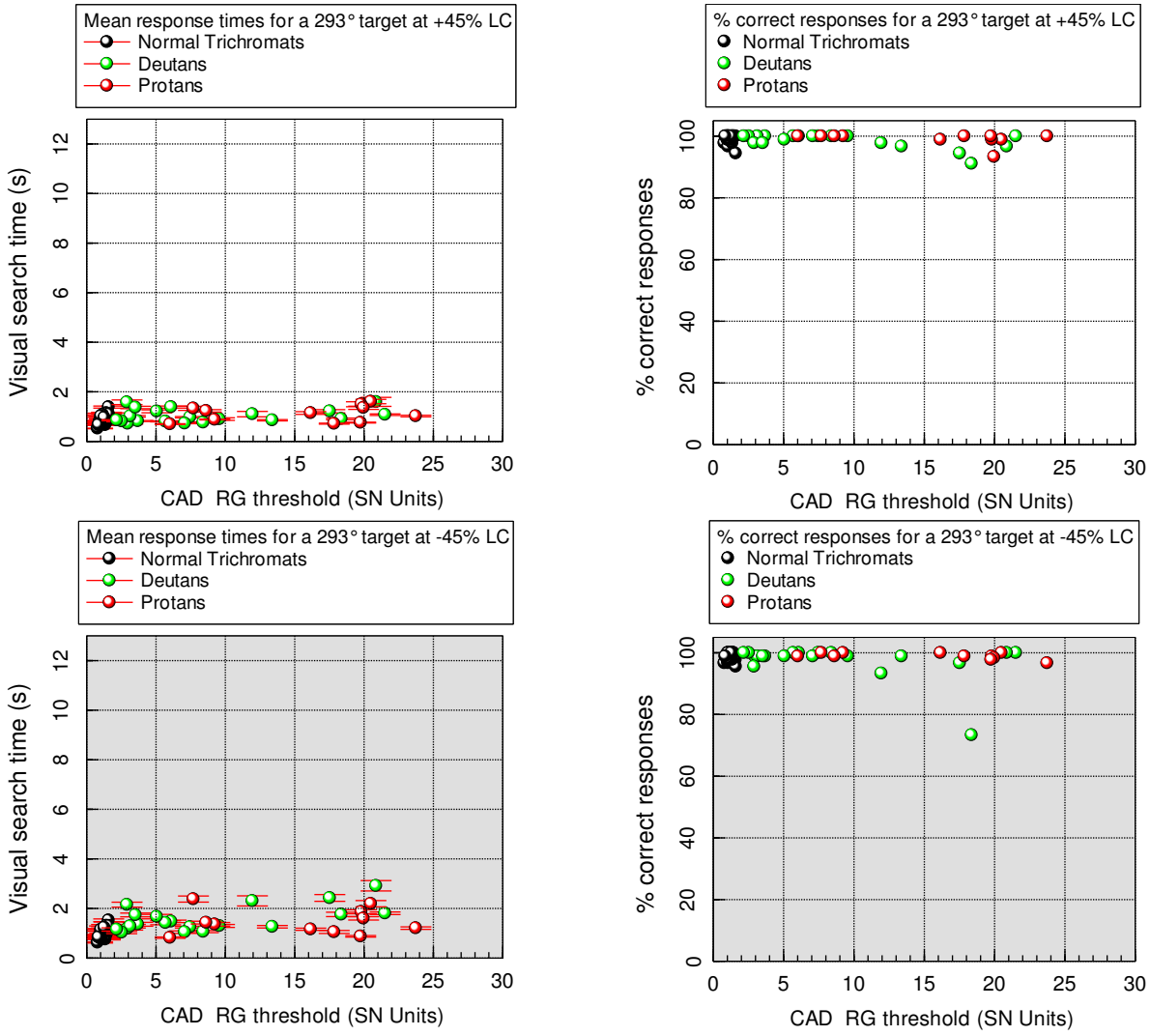


Figure 4-22: Mean visual search times and percentage of correct responses for normal and colour deficient subjects for a target with a colour direction 293° with respect to background chromaticity, *with (A and B) a +45% luminance contrast and (C and D) a -45% luminance contrast, at a saturation of 12 CAD units, amongst 37 achromatic and 3 differently coloured targets with no defining spatial attribute for target identification. Data is shown for 31 normal trichromats, 25 deutans and 14 protans. Error bars show standard error.*

Considering the normal range of visual search times in Figure 4-18 and Tables 4-1 and 4-2, it is clear that visual search times for colour deficient observers for all four colour directions tested (Figures 4-19 to 4-22) show that colour deficient subjects cannot be separated from normal trichromats on the basis of their loss of RG sensitivity, for any of these four colour directions and with either a positive or negative luminance contrast. Similarly, the majority of colour deficient observers (with the exception of those with greatest loss of RG colour vision) could respond with normal levels of accuracy. It should also be noted that some protan subjects, who would have traditionally been

excluded from air traffic control work, perform within the normal range for these conditions. While colour deficient observers performing outside the normal range generally have more severe reduction of RG sensitivity, it was still possible for those with the most severe deficiencies to obtain 100% response accuracy. As with normal trichromats, deutans and protans showed a significant difference in visual search times for colours presented at positive and negative luminance contrasts ($p < 0.01$) with targets at positive luminance contrast being located more rapidly.

Although these colour directions were selected to avoid having to rely entirely on RG colour signals to carry out the task, it is important to establish that the choice of colours that combine RG and YB colour signals does not impair the performance that can be achieved with pure RG colour signals in normal trichromats.

Visual search times for normal subjects for the cardinal red and green colours, in the centre of the colour confusion zones, from experiment 4.2 were compared with the four colour directions investigated in this experiment. Results of t-tests (two tailed, assuming unequal variance) between the red and green colour directions at ±45% LC and each of the four colour directions at the same LC are shown in Table 4-3.

Cardinal colour direction / LC combination	**P value for difference in performance versus 22°**	**P value for difference in performance versus 109°**	**P value for difference in performance versus 198°**	**P value for difference in performance versus 293°**
Red (337°), +45% LC	0.491	0.816	0.120	0.119
Red (337°), -45% LC	0.327	0.811	0.135	0.085
Green (157°), +45% LC	0.028*	0.068	0.003*	0.880
Green (157°), -45% LC	0.016*	0.121	0.003*	0.002*

Table 4-3: P-values returned from t-tests between the visual search times of normal trichromats for the cardinal red and green colour directions in experiment 4.2 and the four colour directions in

*experiment 4.3, at the same luminance contrasts. In the majority of cases there was no significant difference; where a significant difference was found, the results are denoted with *.*

Normal trichromats did not perform worse for these colours than for either red or green cardinal colour directions tested in Experiment 4.2. Where there was a significant difference between the response times of the cardinal colour directions and those of experiment 4.3, the difference was due to faster responses for the latter. The addition of an S cone signal to the target therefore would appear to, in some cases, lead to an improvement in performance for normal trichromats; this is explored further in Section 4.7.

4.6.3.2 Performance as a function of effective detection threshold for the target colour

Colour deficient observers with higher RG thresholds could perform better in some cases than those with lower RG thresholds (figures 4-19 – 4-22). Between individuals with similar CAD RG thresholds, a subject could fall within the normal range of responses or outside of it.

While all of the factors governing individual variations in visual search performance have not been determined (Wolfe, 1994), it seems unlikely that the colour deficient population would differ from the normal trichromat population in any aspects other than colour perception and differences in the effective luminance contrast of targets. While the age of a subject could have been a factor affecting visual search performance, there was no significant effect of age of subject shown in this data set, for any combination of colour or luminance contrast (see Appendix H).

When visual search times were compared to a subject's RG detection threshold, there was no obvious effect, with severely deficient subjects being able to perform within the normal range of search time and accuracy for all combinations of colour direction and luminance contrast. However, colour directions in this experiment were chosen to ensure the presence of both YB and RG colour difference signals.

Comparison of visual search times with subjects' CAD data showed some correlation with both RG thresholds and YB thresholds (tables of the correlation coefficients for this can be found in Appendix

I). In order to further account for the variation shown in graphs 4-19 to 4-22, the subjects' detection thresholds were calculated for the specific colour directions of each of the targets. Visual search times are plotted against these detection thresholds in Figures 4-23 to 4-26.

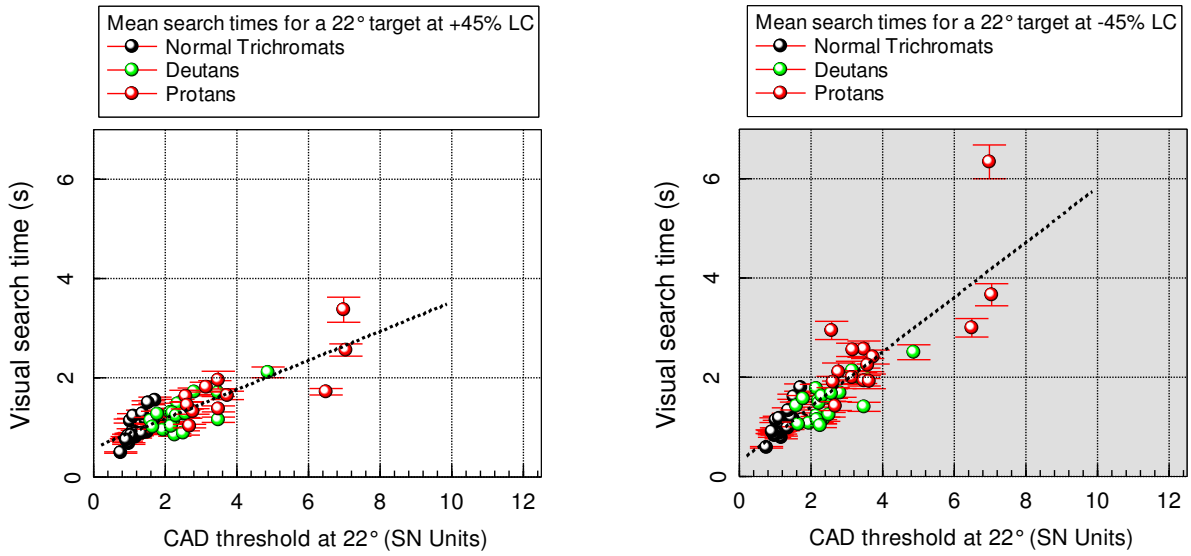


Figure 4-23: Mean visual search times for normal and colour deficient subjects for a target with a colour direction 22° from background chromaticity, with ±45% luminance contrast, as a function of subjects' CAD thresholds for that colour direction. Data are shown for 31 normal trichromats, 25 deutans and 14 protans. Data are fitted by linear functions for +45% luminance contrast (y = 0.284x + 0.607, R^2 = 0.69) and for -45% luminance contrast (y = 0.549x + 0.314, R^2 = 0.76). Error bars show standard error.

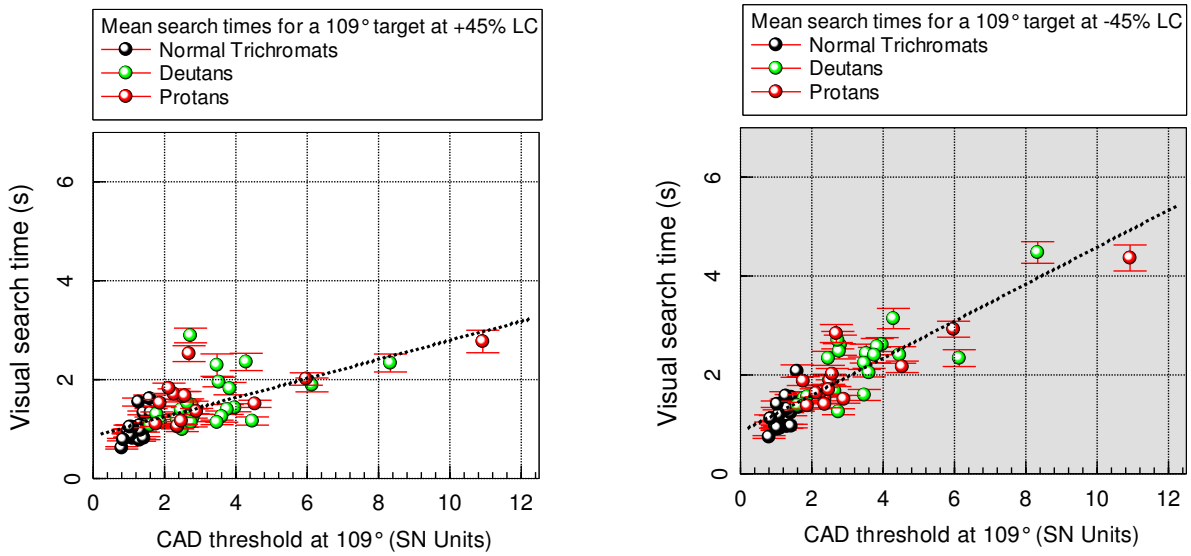


Figure 4-24: Mean visual search times for normal and colour deficient subjects for a target with a colour direction 109° from background chromaticity, with ±45% luminance contrast, as a function of subjects' CAD thresholds for that colour direction. Data is shown for 31 normal trichromats, 25 deutans and 14 protans. Data is fitted by linear functions for +45% luminance contrast (y = 0.204x + 0.836, R^2 = 0. 52) and for -45% luminance contrast (y = 0.378x + 0.820, R^2 = 0. 79). Error bars show standard error.

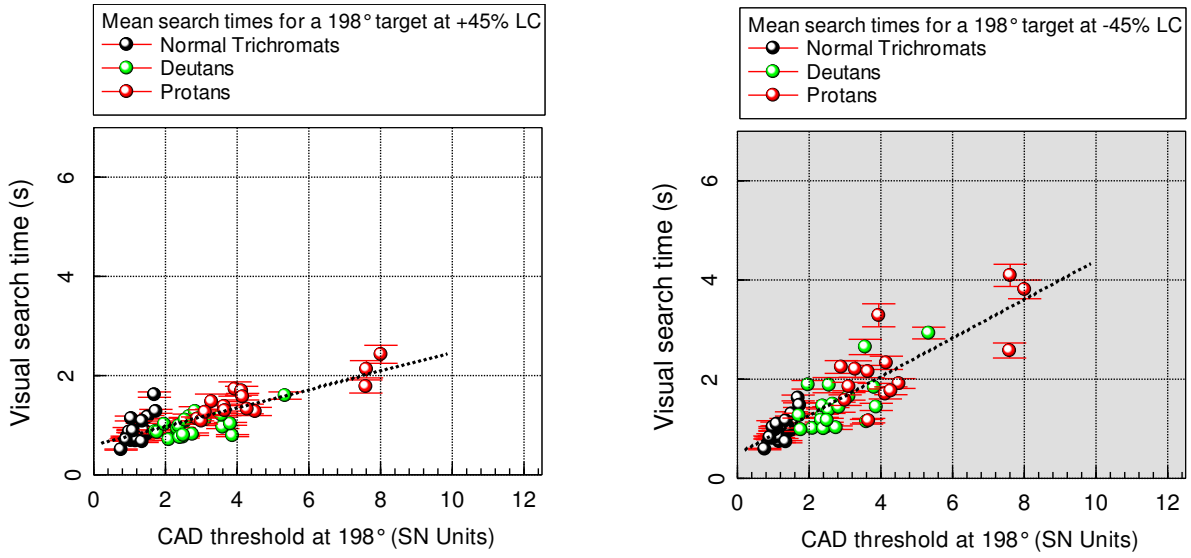


Figure 4-25: Mean visual search times for normal and colour deficient subjects for a target with a colour direction 198° from background chromaticity, with ±45% luminance contrast, as a function of subjects' CAD thresholds for that colour direction. Data is shown for 31 normal trichromats, 25 deutans and 14 protans. Data is fitted by linear functions for +45% luminance contrast (y = 0.186x + 0.589, R^2 = 0. 65) and for -45% luminance contrast (y = 0.377x + 0.517, R^2 = 0. 70). Error bars show standard error.

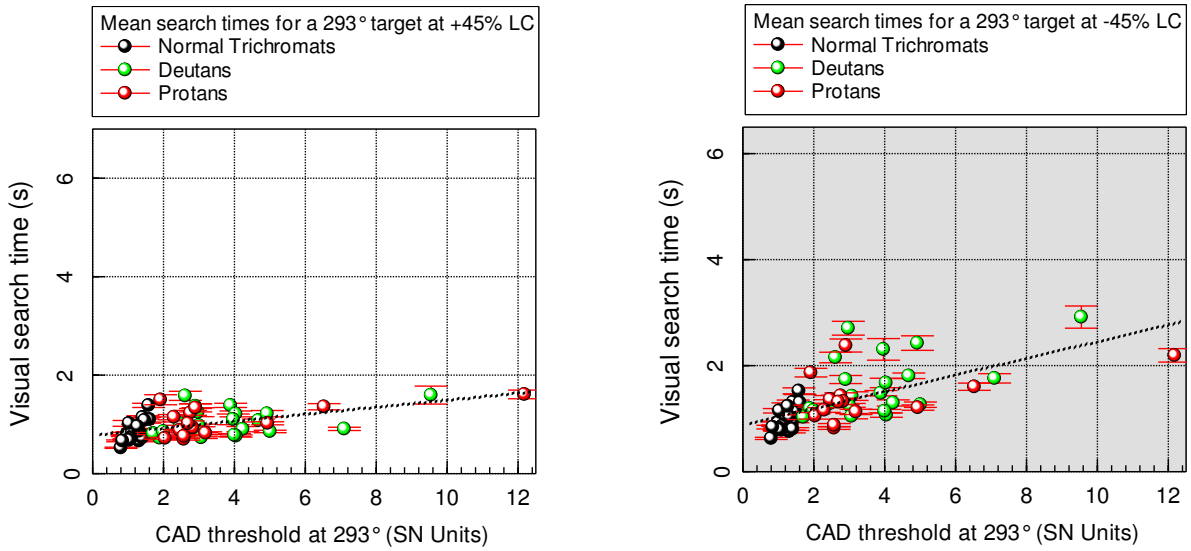


Figure 4-26: Mean visual search times for normal and colour deficient subjects for a target with a colour direction 293° from background chromaticity, with ±45% luminance contrast, as a function of subjects' CAD thresholds for that colour direction. Data is shown for 31 normal trichromats, 25 deutans and 14 protans. Data is fitted by linear functions for +45% luminance contrast (y = 0.072x + 0.762, R^2 = 0. 32) and for -45% luminance contrast (y = 0.169x + 0.828, R^2 = 0. 48). Error bars show standard error.

While congenital colour deficient observers are not necessarily disadvantaged compared with normal trichromats, performance for the selected colour directions appears to be dependent on a

subject's YB and RG chromatic discrimination. Correlation coefficients for the visual search times of subjects as a function of their detection threshold for each of the colours, at positive and negative luminance contrasts, are shown in Table 4 -2.

Colour direction and luminance contrast	R^2 value for VS times versus CAD threshold for that colour direction
22°, +45% LC	0.69
22°, -45% LC	**0.76**
109°, +45% LC	0.52
109°, -45% LC	**0.79**
198°, +45% LC	0.65
198°, -45% LC	**0.70**
293°, +45% LC	0.32
293°, -45% LC	**0.48**

Table 4-4: R^2 values for the linear models fitted to the plots of VS times versus CAD thresholds for each colour at positive and negative luminance contrasts.

Overall, data is better explained when visual search times for a coloured target are expressed in terms of a subject's detection threshold for that colour (as opposed to either red-green or yellow-blue chromatic sensitivity alone). Therefore a RG colour deficient subject that also has reduced YB sensitivity would be more likely to perform outside of the normal range. As shown in Figures 4-19 to 4-22 for targets that contain a suprathreshold YB signal, combined with a RG component, the ability of subjects to correctly identify targets is not affected by colour deficiency in most cases. It should be noted, however, that there are a few data points that represent the higher thresholds in this sample and these have a high impact on the trends mentioned. Without these the trends still describe the data differently than when plotted as a function of RG sensitivity alone, however this highlights the fact that various factors other than pure chromatic sensitivity govern visual search in this experiment.

Additionally, R^2 values indicate that the variability in visual search times is better explained by a subject's CAD detection threshold for a colour when the colour is presented at a negative luminance contrast. There appears to be less correlation with detection thresholds and search times for colour direction 293° than for other colour directions. As per the normal ranges of performance shown in Figure 4-18, this is does not translate to a significant difference in performance.

4.7 EXPERIMENT 4.4

4.7.1 Introduction

Results for normal trichromats in Experiment 4.1 showed a clear effect of yellow and blue targets being more easily detected than red and green targets at equivalent saturations, indicating that the colour of a target in visual search can affect how quickly it is detected. One possibility that could account for this is that there are significant differences in the sensitivities of the colour opponent mechanisms over the visual field of 20° employed in the CRATO test.

4.7.2 Methods

In order to measure chromatic discrimination thresholds across the near peripheral retina, the luminance pedestal procedure described in Section 3.2.1 was modified. A four alternative, forced choice staircase procedure was used to measure colour detection thresholds at 1, 2, 4, 6, 8 and 10 degrees eccentricity from central fixation. The display consisted of a dark background (10 cd/m^2) and four disc-shaped luminance pedestals of 16 cd/m^2 and chromaticity of x= 0.305, y= 0.323 (CIE 1931), each subtending 25' of visual angle and presented in a square formation with pedestals equally spaced from the central fixation point. This provided targets of equal size and luminance contrast to those used in experiment 4.1. Thresholds were obtained under these conditions for the same colour directions used in experiment 4.1 for 3 normal trichromats.

4.7.3 Results for Experiment 4.4

Normal trichromats in experiment 4.1 showed a clear effect of yellow and blue targets being more easily detected than red and green targets at equivalent saturations. The effect was consistent for all luminance contrast levels; comparisons of search times for these stimuli are shown in Figures 4-27 and 4-28 for stimuli at 60% luminance contrast (the same effect was seen at other luminance contrasts also). At each level of saturation, the visual search times for yellow and blue are significantly lower than those for either red or green (paired t-tests, $p > 0.001$). One possibility that could account for this result is that there are significant differences in the sensitivities of the colour opponent mechanisms over the area of the retina corresponding to the visual field of ±10° employed in the CRATO test. Chromatic detection thresholds were measured for the same four colour directions using stimuli of equivalent size and luminance contrast to those in the CRATO test, at eccentricities up to 10°.

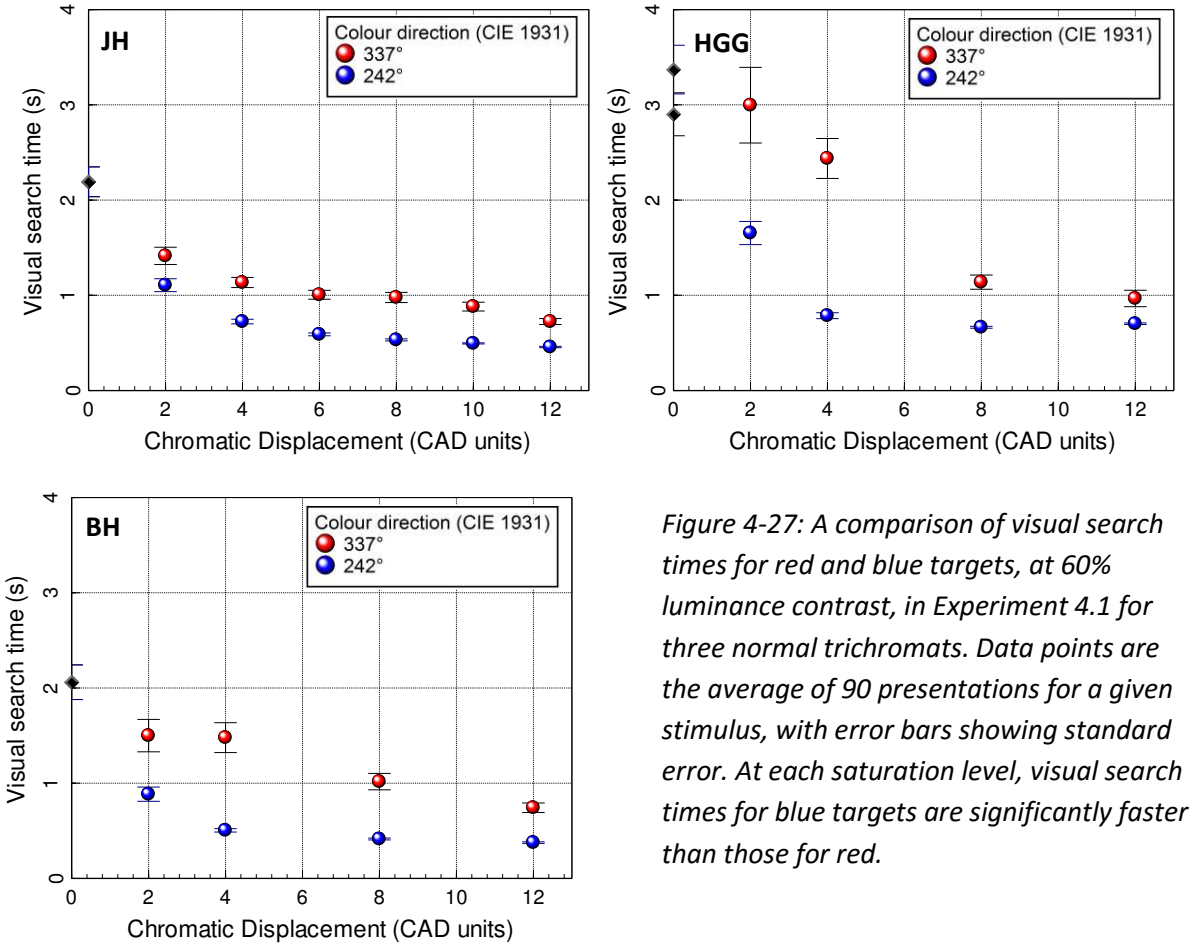


Figure 4-27: A comparison of visual search times for red and blue targets, at 60% luminance contrast, in Experiment 4.1 for three normal trichromats. Data points are the average of 90 presentations for a given stimulus, with error bars showing standard error. At each saturation level, visual search times for blue targets are significantly faster than those for red.

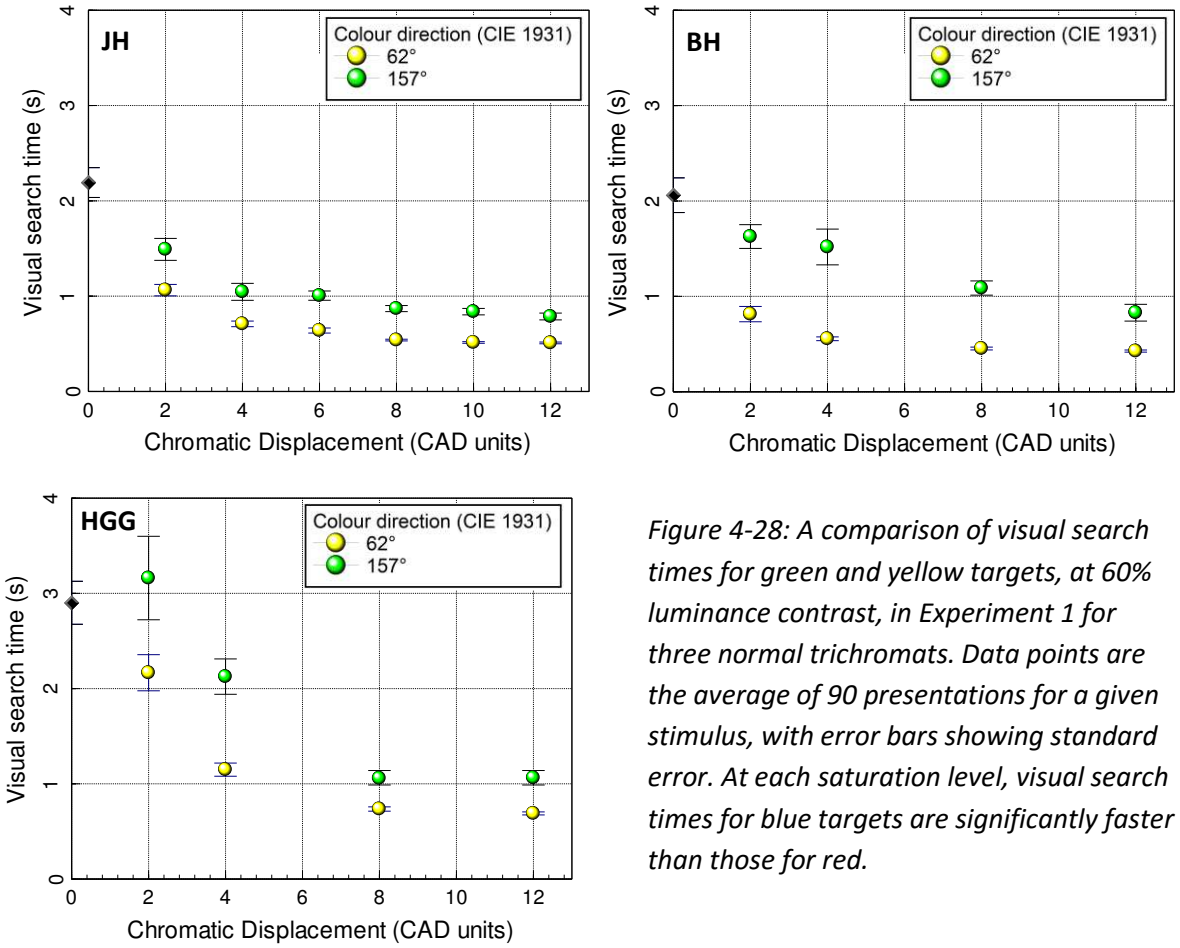


Figure 4-28: A comparison of visual search times for green and yellow targets, at 60% luminance contrast, in Experiment 1 for three normal trichromats. Data points are the average of 90 presentations for a given stimulus, with error bars showing standard error. At each saturation level, visual search times for blue targets are significantly faster than those for red.

Visual search times over a given area will differ between colours that an observer is differently sensitive to, as seen with congenital colour deficient performance measured in experiment 4.1. The difference in visual search performance between RG and YB for saturations at equivalent saturations could be due to variations in the sensitivities of L, M and S cone mechanisms over the visual angle of which targets are presented. Chromatic detection thresholds were measured via the luminance pedestal technique at eccentricities up to ±10, for red, green, yellow and blue targets of equivalent size and luminance contrasts to those used in experiment 4.1 and 4.2.

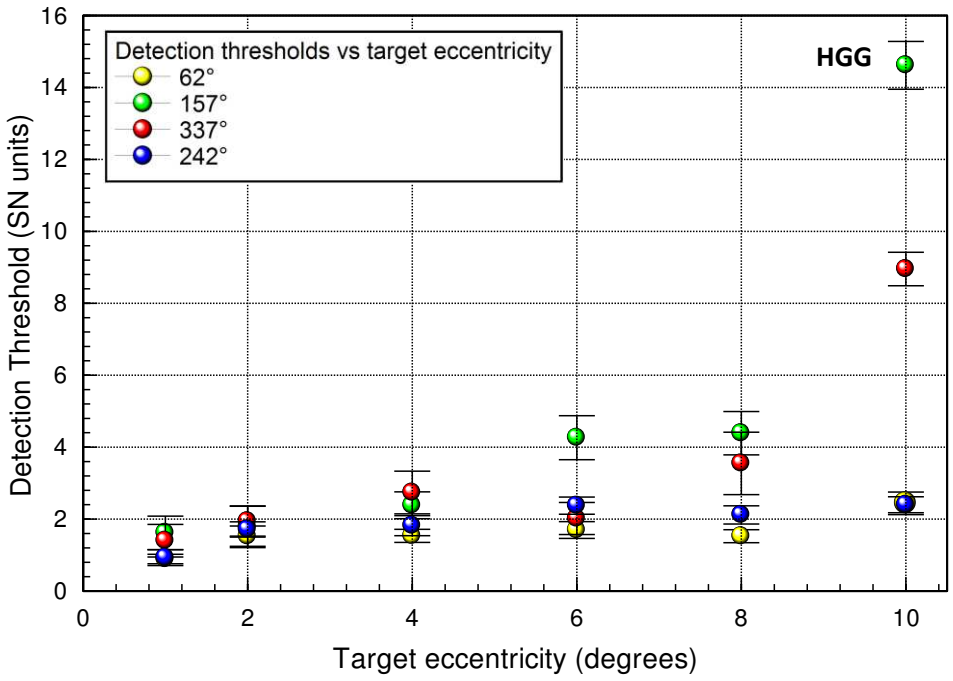


Figure 4-29: Chromatic detection thresholds for red, green, yellow and blue luminance pedestals subtending 25' at 60% luminance contrast, as a function of eccentricity for normal trichromat HGG. Yellow-blue thresholds remain relatively constant where red-green thresholds increase significantly by 10 degrees. Error bars show standard error.

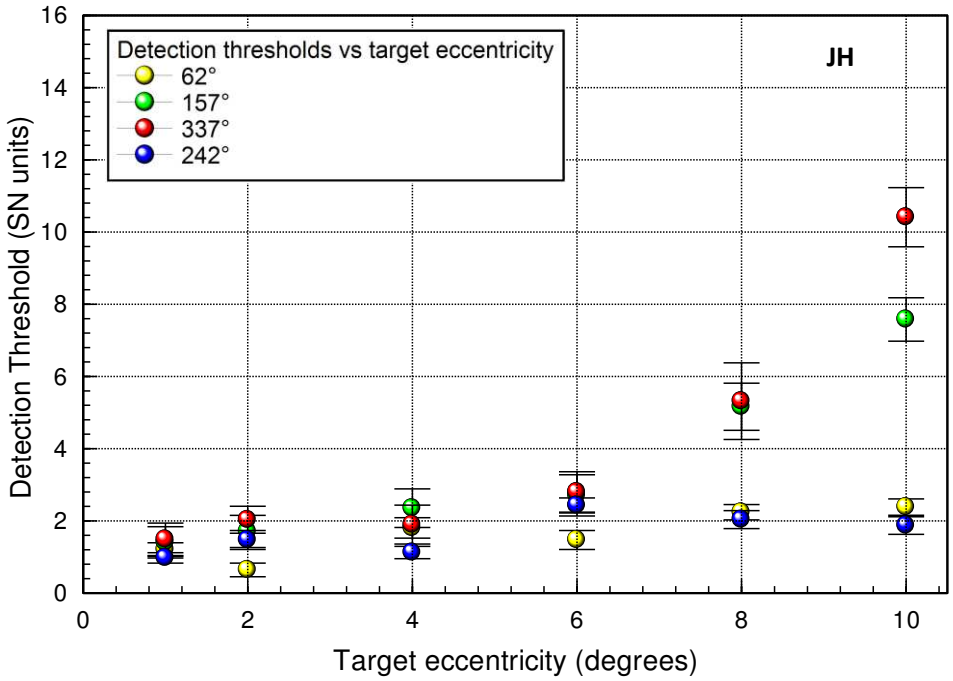


Figure 4-30: Chromatic detection thresholds for red, green, yellow and blue luminance pedestals subtending 25' at 60% luminance contrast, as a function of eccentricity for normal trichromat JH. Yellow-blue thresholds remain relatively constant where red-green thresholds increase significantly by 10 degrees. Error bars show standard error.

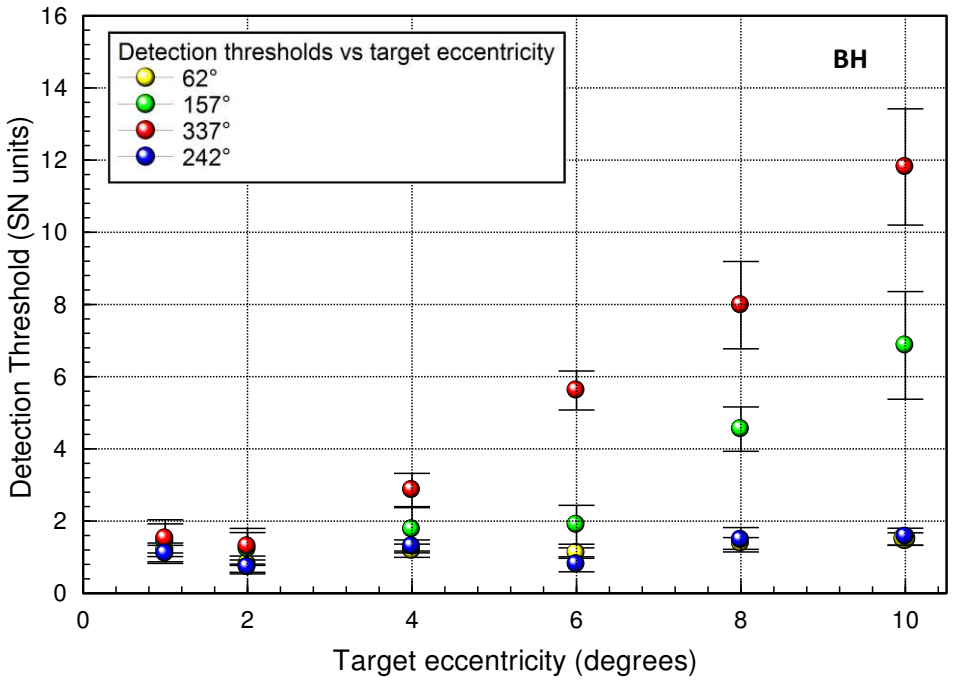


Figure 4-31: Chromatic detection thresholds for red, green, yellow and blue luminance pedestals subtending 25' at 60% luminance contrast, as a function of eccentricity for normal trichromat BH. Yellow-blue thresholds remain relatively constant where red-green thresholds increase significantly by 10 degrees. Error bars show standard error.

As per Figures 4-29, 4-30 and 4-31 yellow and blue detection thresholds remained relatively constant between 1° and 10° eccentricity from fixation, whereas red and green detection thresholds increased over that range, with clear separation after 6°.

These results indicate that if a target is presented in the central ~6° from fixation then a subject will have approximately equal levels of chromatic discrimination for that target, and hence there should be no noticeable difference in saliency between colours in that region. However, a red or green target presented in the ~6 °to 10° degree region of the field would be harder to detect. As targets are randomly presented at eccentricities up to 10° in the CRATO test, then this may account for the difference in performance for these colours.

As seen in the normalised thresholds in Figures 4-15 and 4-16, a subject's level of chromatic discrimination accounts for the performance difference between deutans and normal trichromats. It follows that for the more eccentric red and green targets, as illustrated here, a normal trichromat

could have a detection threshold many times that for central targets, the response time would be expected to be slower even at 12 times the normal threshold.

It is important to note that the stimuli used in the luminance pedestal test were complete circles rather than Landolt C's used in the CRATO test. Therefore in direct comparison, the luminance pedestal stimuli should be slightly easier to detect due to increased spatial summation, as per Section 3.2.6. The reduced detection capability for red and green at higher eccentricities in the luminance pedestal test could therefore be even more pronounced for stimuli in the CRATO test.

4.8 CONCLUSIONS

Colour signals affect significantly visual search times, causing pop-up and resulting in increased efficiency when compared to what can be achieved with an achromatic target, even when colour provides only a secondary cue. In addition, the use of colour also allows for segmentation of objects into meaningful groups. In ATC this is an essential feature of the displays used, allowing ATCOs to respond rapidly to objects of interest and separate them from other information on the screen.

As stated in 4.1, due to the colour vision testing protocol that was used in the past for applicant selection, some minimally deuteranomalous trichromats have passed as normal and became ATCOs. The lack of any reported accidents in air traffic control that relate directly to colour vision deficiency indicates that those with minimal deutan deficiency are capable of performing the role effectively.

In these experiments, colour deficient subjects were first tested under the most demanding stimulus conditions, using target chromaticities that generate mostly RG colour signals and are therefore not seen by RG dichromats. Under these conditions, it became clear that even the most mildly affected colour deficient subjects were not able to perform as normal trichromats, when target saturations were set at 12 CAD units (significantly above their detection threshold). When the effective saturation of the target is considered – i.e. how saturated a target would be based on the subjects' RG thresholds – it was shown that colour deficient subjects are capable of performance equivalent

to that of normal trichromats searching for a less saturated target. As additional findings show, the use of suprathreshold colours with target chromaticities that generate both RG and YB colour differences yield good performance in subjects with mild RG colour deficiency, similar to that which normal trichromats can achieve.

While the CAD test could be employed to filter out practically all applicants with colour deficiency, it is of great interest to establish whether normal colour vision is an essential requirement in ATC work.

In order to provide some insight into the use of colour to enhance performance in visual search tasks similar to those encountered in air traffic control work, the first experiment compared the performance of normal trichromats with mild and severe deutans and protans.The results show clear differences in the response times of colour deficient subjects to red and green targets when compared to normal trichromats, particularly for coloured targets with negative luminance contrast with respect to the uniform background. Normal subjects showed little improvement in search times above some 12 CAD units for red and green coloured targets. In some cases colour deficient subjects could achieve search times similar to those of normal trichromats; however they required significantly higher colour saturations in order to do so.

When colours were added to a target defined by negative luminance contrast, colour deficient subjects showed much reduced improvement in visual search times. These findings could relate to a number of factors. It is known that the background luminance level affects threshold discrimination of coloured stimuli; a greater L and M cone excitation is required to produce detection at lower background luminances, and that the thresholds decrease linearly with increasing luminance (Jennings & Barbur, 2010). This observation is consistent with lower detection thresholds for negative luminance contrast targets observed in these experiments; although the surrounding background has a higher light level, detection thresholds could still be higher due to the luminance

level of the target, when compared with the higher luminance contrast targets where colour discrimination is improved.

Additionally there appear to be differences between the responses of deutan and protan subjects under certain conditions that relate to the luminance contrast of the target. Visual search in protan observers can improve with increasing saturation for red targets when the luminance contrast is high (Figure 4-7). This is not however the case for lower, positive luminance contrasts, and beyond a certain level of chromatic saturation, search times begin to worsen. This may well reflect changes in the effective luminance contrast of the target which only remains constant for a normal trichromat. The fact that this effect caused search times to become longer than those for an achromatic target for subject DC indicates that it cannot be explained in terms of loss of sensitivity to the colour signal generated by the target. As per Section 1.2.4 protan subjects can see red objects as being darker due to a reduction in sensitivity to the long wavelength region of the visible spectrum. As the targets are produced on the display by a combination of red, green and blue sub-pixels, in order to increase the saturation of the target in the red direction there must be a reduction in the relative proportion of green. For protan subjects it follows that this would cause an overall reduction in the luminance signal of that target. A possible explanation would be that for the 30% luminance contrast target, this reduction may cause the effective target luminance for a protan to become close to that of the background field, thereby cancelling the increase in salience provided by the colour signal. When the target contrast is significantly higher, the reduction in luminance contrast caused by increase chromatic saturation may be as significant. More subjects need to be examined to investigate and to model these preliminary observations.

The most difficult condition in ATC for a colour deficient observer would be where a target is displayed in the presence of other, potentially confusable colours and there is no obvious spatial cue that allows for rapid target location. Based on the results from experiment 1, it seemed likely that

only the most minimally affected colour deficient subjects could potentially carry out this task within the normal range of search times and accuracy.

A surprising finding in experiment 2 was that although mild colour deficient subjects could generally perform the visual search task at a saturation of 12 CAD units (which was significantly above their detection threshold) with the same accuracy as normal trichromats, no colour deficient subjects could carry out the search task within the normal range of response times for either red or green colour directions. Various models of visual search imply that stimuli that are sufficiently different from the surround are capable of guiding the deployment of attention. As sensitivity to the target colour is reduced in the case of the congenital colour deficient subjects, the overall colour difference between target and distractors is reduced, lowering overall saliency of the target and resulting in less efficient search.

While there is an interaction between luminance and colour contrast, this difference in performance can largely be accounted for on the basis of reduced chromatic sensitivity. By determining the 'effective' colour signal strength of targets, based on the chromatic sensitivity of a given observer, colour deficient performance is within error of that of normal trichromats, as per Figures 4-14 and 4-15.

With the clear differences in performance between normal trichromats and colour deficient observers in visual search time, but not necessarily response accuracy, in some of the experimental conditions in this chapter, the question arises as to how much extra time taken to locate a target stimulus would constitute impairment to ATC operation. For example, if a colour deficient observer only took one second longer than the slowest normal trichromat to locate a target, but could do so consistently, then this might be permissible. However, given ATCO work involves a series of tasks, a one second delay for each would be cumulative, and hence after 10 searches the colour deficient ATCO could be 10 seconds behind a normal trichromat, assuming no breaks. While this study focussed on the most difficult conditions with a view to setting performance equivalent to normal

trichromats as the acceptable limits, it could be that these pass criteria could be modified for occupational acceptance to allow a higher limit.

The results of experiment 4.1 confirmed that colour deficient subjects exhibit normal visual search performance when YB colour signals are added to a target defined by luminance contrast; it therefore follows that for colours directions that produce both RG and YB colour signals, the differences between normal trichomats and colour deficient observers are likely to reduce, and this may lead to comparable performance. Experiment 4.3 tested the potential of employing target chromaticities that yield suprathreshold RG and YB colour difference signals. Results for such target chromaticities (Figures 4-18 to 4-26), showed that colour deficient performance largely overlapped that of the normal trichromats. Those colour deficient subjects that did fall outside of the normal range of visual search time / percentage of correct responses generally had very high RG CAD thresholds, however the level of colour deficiency alone was not enough to explain the variations in performance. Similarly, the majority of colour deficient observers produced small error scores that were similar to those observed in normal trichromats. While those that fell outside the normal range generally had more severe reduction of RG sensitivity, it was still possible for those with the most severe deficiencies to obtain 100% correct responses.

For colours that generate YB and RG colour difference signals (i.e., chromatic displacement directions of 22 and 109, or 198 and 293 degrees), the question arises as to how colour deficient observers are able to carry out the visual search task without confusing these pairs of colours. This observation may be attributed to a number of factors.

For colour deficient observers, there will be a difference in luminance contrast between the targets, whereas for normal trichromats the luminance signal generated will be remain approximately equal when colours change. For a colour deficient subject, with reduced sensitivity to either the L or M component of the target stimulus, the difference of L:M signal between these colours will not cause an equivalent response. For example, a deutan subject will be less sensitive to the increase in M

cone signal for a target of colour direction 109 degrees than they would for the increase in L cone signal for 22 degrees. Hence the calculation (L + M) will differ between the two conditions, leading to a difference in effective luminance contrast between for the two coloured targets. This would also explain why dichromats, with no perception of the red-green component of the targets (or indeed any subject with a CAD RG threshold over 12SNU) were able to tell the difference between targets with equal S cone contrast.

This difference in perception may not only be due to the effective luminance contrasts of the targets and could extend to the perception of the S cone component of the target. In the case of dichromats, the responses will vary from that of normal trichromats: for a deuteranope (S – (L+M)) can be simplified to (S- L), and as there is a different L cone signal between 22 degrees and 109 degrees, and between 198 degrees and 293 degrees, the overall response will vary and could lead to different perceptions of the S cone component. In the case of anomalous trichromats, who have reduced sensitivity to either the L or M cone component, the responses may also not be equivalent.

Correlation coefficients for visual search times compared with detection thresholds for the colour directions of the test targets (Figures 4-23 to 4-26), showed higher overall correlations for targets with a negative luminance contrast than for those with a positive luminance contrast in every case. One explanation could be that, as per the results described in Chapter 3, the yellow blue component is harder to detect at negative luminance contrasts and therefore chromatic sensitivity, as a factor in determining visual search times, will gain more weight. Overall, correlations were somewhat affected by the few subjects with high combined YB and RG thresholds and so this may limit the extent to which these can be relied on as predictors of performance.

Normal performance was not impaired when searching for stimuli defined by both RG and YB colour signals, and in some cases actually improved significantly, compared with targets defined by only RG colour signals. While ATCOs have the ability to define the palette of colours used on their own

display, this result demonstrates that the use of selected chromaticities would still be a viable option for those with normal trichromacy.

In terms of a new approach to ATCO colour vision assessment, it could be possible to use the CRATO test with targets that generate a combined RG and YB signal and see if a subject falls within the normal range of performance, whilst ensuring that screen objects used, following acceptance into the role, are of chromaticities that generate at least as much YB signal. It would be important to ensure that the colours selected are sufficiently different from each other to prevent confusion. However, it could also be possible to use the CAD test cut-offs for red-green and yellow-blue sensitivity that allow for performance within the normal range of visual search times (Tables 4-1 and 4-2). While the latter option provides a high degree of certainty that a subject could perform well, the results from experiment 4.3 show that it is still quite possible for a subject outside of these cut-offs to achieve normal performance.

The factors affecting visual search variation between individuals are not completely understood– currently ATCOs do not receive any testing to specifically assess baseline achromatic visual search performance. The CRATO test has the advantage of including this aspect of performance in addition to the effects of chromatic discrimination and sensitivity.

An observation relating to the performance of normal trichromat observers was that yellow and blue targets are located more quickly than red and green targets at equivalent levels of saturation compared with threshold detection. As colours in the CRATO test are expressed in CAD units (which relate to the mean chromatic displacements needed for threshold detection in foveal viewing in the normal population) centrally located targets of any of the four colours should be equally salient at the same saturation. A likely candidate for this effect is that targets in the CRATO test are displayed over a field extending 20 degrees of visual angle.

When a stimulus is presented in the periphery, the effectiveness of YB colour signals remains high and this leads to improved performance. This effect of stimulus location of visual search, known as the 'eccentricity effect' has been described for target detection (Carrasco et al, 1995). Retinal contribution to the eccentricity effect is generally explained in terms of reduced spatial resolution in the periphery (Carrasco & Friedner, 1997). It has also been argued that attentional bias to central over peripheral stimuli drives at least part of the eccentricity effect, and in addition there may be preferences for direction e.g. right visual field over left (Wolfe & O'Neill, 1998). Less consideration has been given to the effects of eccentricity on the search times for differently coloured stimuli in the absence of additional spatial cues.

The sensitivity of RG chromatic mechanisms drops off more rapidly with eccentricity away from the fovea, more so than YB and achromatic contrast sensitivity, particularly when large stimuli are involved. Various physiological changes underlie this reduction in performance. Populations of L and M opponent ganglion cells decrease while their receptive fields, as well as receptive field centres, increase in size. This is accompanied by a smaller cortical representation for the peripheral retina (Hansen et al, 2009). Outside of the S cone free region of the central fovea, S cone sensitivity decreases more gradually with eccentricity, attributed to a more even distribution of bipolar and ganglion cells (Mullen, 2002).

The resulting psychophysical measurements relating to these factors are illustrated in Figures 4-19, 4-20 and 4-21, in which RG chromatic detection threshold measurements for normal trichromats increase up to 10 degrees eccentricity from fixation, where YB detection remains relatively constant. Reduced sensitivity to red and green targets towards the periphery of the CRATO display would result in an overall reduction in target salience and hence longer visual search times. As per Figures 4-26 and 4-27, the visual search times of normal trichromats were significantly improved for target stimuli containing an S-cone component, over those stimuli defined by a pure L- or M-cone

component. This has further implications for the optimisation of display screens and colour coding for occupational tasks requiring rapid responses.

5 SUMMARY AND CONCLUSIONS

Normal vision and the ability to respond to visual stimuli are key requirements which underpin successful completion of visually demanding tasks in many occupations. The effectiveness of individuals carrying out such roles is dependent on their capacity to make efficient and reliable use of complex visual information. When coloured stimuli are employed in safety or time critical functions within a given role, it is necessary to ensure applicants have sufficient chromatic sensitivity to do so safely.

In order to effectively segregate those applicants that perform within the required range of ability from those that do not, it is important that testing procedures are accurate, reliable, and provide useful diagnoses that relate directly to the requirements of the role in question. However, the identification and interpretation of chromatic stimuli is variable based on the parameters of the stimuli involved, the nature of the environment and the inherent physiology of the observer, and so many traditional tests of colour vision fall short of these criteria.

The studies described in this thesis examine the fundamental causes of variability in visual performance, and outline an approach to the measurement of chromatic sensitivity for occupational environments that relates directly to the difficulty of a given task.

In the second chapter the analysis of the results of various traditional colour vision tests highlights the inherent variability between tests and compares their relative effectiveness. Examination of current practices and outcomes suggests that current methods and procedures for colour vision assessment are not always satisfactory.

The Ishihara test is used to screen applicants for many occupational roles; where misreadings or errors are made it is common practice to use a secondary colour vision test in order to assess the severity of colour deficiency. The Ishihara is a relatively quick and highly sensitive screening test; the sensitivity of the test varies depending on the number of errors that are allowed. Where no errors

on the first 25 plates constitutes a pass, 7.0% of normal subjects fail as per the results (section 2.4.3), however this number has been reported as being higher in other cohorts (Rodriguez-Carmona et al, 2012). Increasing the number of errors allowed to ensure that all normal subjects pass would increase the number of colour deficient that are able to pass. For safety critical roles this would not be advisable, and therefore a secondary test that correctly identifies all normal subjects would be required in order to avoid misclassification.

Traditionally the Nagel anomaloscope is the preferred secondary test and has been viewed as the 'gold standard' in colour vision assessment. While the anomaloscope remains a very effective test for detecting congenital RG deficiency and for distinguishing between deutan and protan observers, the parameters of the yellow match fail to provide accurate assessment of the severity of colour vision loss (Wright, 1956). The relative scarcity of the anomaloscope and the requirement for an expert examiner to obtain reliable results are two additional drawbacks in recommending it for occupational assessment.

Furthermore, performance on the Nagel is based on more than just the spectral responsivity functions of cones: the optical density of photopigment, L:M cone ratio and noise of the L/M channel affect the result. As a result, some normal trichromats can produce matches outside of the normal range, while colour deficient observers who rely on both hybrid M' and L' cones are often classified as normal trichromats (Barbur et al, 2008).

The procedure employed in the past by the UK Fire Service involves initial screening with the Ishihara test and then, in the case of any errors, secondary testing with the Farnsworth D15 and Nagel anomaloscope. Due to the fact that the D15 favours protan subjects, this procedure is only effective in excluding them where the Nagel is available. For deutan subjects, there is high variability in the chromatic detection thresholds of subjects that pass, and therefore this procedure, which was selected to exclude those subjects who might struggle to identify the surface colours of various gas cylinders, is unlikely to be an effective predictor of performance. Colour vision requirements for fire

fighters were based on the colours of gas cylinders that are hazardous at the scene of a fire (Margrain et al, 1996); however, this did not take into account the dramatically reduced visibility that would be caused by smoke, or the change in perception from wearing protective equipment. Good chromatic discrimination therefore may be important if a new standard was to be determined, however the testing procedure used should be more directly relevant to the performance of the role.

Good colour perception for rapid response drivers is based on the ability to correctly identify the colours of traffic lights when driving at high speeds; colour deficient observers have been shown to perform worse at this task than normal trichromats (Verriest et al, 1980). The correct identification of red signal lights for protans has been shown to be worse than those of normal trichromats (Nathan et al, 1964), however conversely the performance of protans versus deutans for a task that simulates use of traffic lights has been reported to be better for roughly equivalent levels of deficiency (Atchison, 2003). Studies thus far have not related the specific chromatic sensitivities of subjects to the detection of traffic lights whilst driving. Furthermore, dichromacy is not a legal barrier to normal driving. Therefore the specific increase in difficulty of recognising coloured signal lights whilst driving at high speeds would need to be quantified, and related to a subject's type and severity of deficiency, in order to determine the importance of colour vision requirements for this role. The UK Police rapid response driver criteria based on 3 or more errors on the City University test is ineffective as this would allow any subjects other than deuteranopes to pass; for any functional purpose involving the use of colour it should be revised.

The Holmes-Wright lanterns are robust and relatively effective, however they are no longer in production and so there is the need to find a suitable replacement. The Marine Coastguard Agency uses the type B lantern to screen for normal trichromacy, however the difficulty involved is such that some normal trichromats also fail the test. When the type A lantern is used as part of the testing protocol, it is possible to use the CAD test as a replacement. HW-type A was used by the CAA before

the introduction of the CAD test. The advantage of this lantern when used with the CAA protocol is that all normal trichromats pass. Subjects with RG thresholds less than 2.35 SNU also pass HW-type A with zero errors. 22% of deutan subjects end up with RG CAD thresholds less than 4 SNU and this matches the percentage of deutans that pass the HW-type A lantern when using the CAA protocol. One is therefore justified to use a RG CAD threshold less than 4 SNU as a pass. This is statistically equivalent to the outcome of the HW-type A lantern using the CAA protocol.

However it is important to consider that for the suprathreshold coloured targets that are typically used in occupational environments, it is very likely that a subject with mild congenital deficiency could perform a suprathreshold, colour-related task within the normal range of time and accuracy.

Traditional colour vision tests are generally quick to administer, but are often not suitable for determining the ability of a subject to carry out a particular occupational task to an acceptable level. A more suitable approach would be a thorough scientific study to determine the specific requirements of a given working environment, and relate the chromatic sensitivity of applicants to performance of the relevant tasks. It should also be considered that colour vision may change over time, either through ageing or the effects of disease or injury, and therefore it would be important to test subjects working in environments where use of colour is safety-critical at regular intervals.

Varying chromatic sensitivities measured over the visual field, as well as the varying performance for the same chromatic signals when these are combined with varying luminance contrast were investigated in the third chapter and have direct implications for tasks involving the use of coloured targets.

Using yellow or blue lights in order to avoid the effects of congenital RG colour deficiency is not a solution to this problem. From the results in section 3.2 it is clear that when yellow and / or blue lights are used in conditions that replicate signal lights (small light sources viewed foveally), a normal subject could be effectively tritanopic and hence unable to make use of the colour.

Further examination of the detection of yellow and blue signal lights revealed an asymmetry in detection thresholds in experiments that isolate the use of colour signals using luminance contrast pedestals. Chromatic detection thresholds for S-OFF signal (yellow) were consistently higher than those for the S-ON signal (blue) over a range of eccentricities. A likely candidate mechanism to account for these differences would simply be the difference in the properties of S-ON and S-OFF pathways, a hypothesis based on physiologically observed differences (Smithson, 2014)

Although the S-OFF pathway has not yet been fully characterised, there are several observations that could underlie differences in threshold detection under certain conditions. The midget bipolar cells of the S-OFF pathway have a small receptive field when compared with the blue-cone bipolar cells of the S-ON pathway. Furthermore the ratio of L- and M-cone input to the two pathways is also thought to differ, the two pathways display different temporal response characteristics and it is estimated that the number of S-OFF ganglion cells is significantly lower than that of S-ON ganglion cells (McLellan & Eskew, 2000; Dacey et al, 2014). It is therefore likely that the asymmetry in threshold detection for the conditions used in experiments 3.3 and 3.4 results from different sensitivities in these two pathways.

An additional finding relating to the psychophysical measurement of colour thresholds was that the detection of yellow and blue targets isolated by high luminance contrasts, such as those employed in luminance pedestal tasks, can be impaired. Comparison of a luminance pedestal procedure with the CAD test revealed that for targets of equivalent size, background adaptation field and luminance, thresholds for the detection of yellow and blue targets were significantly higher for the luminance pedestal technique. Furthermore, such observations confirm findings from many earlier studies which investigated the dependence of colour thresholds on the size, chromaticity, eccentricity and luminance contrast of the stimulus.

The fourth chapter gives an example of a situation where the analysis of the requirements of a visually demanding task involving the use of colour can provide a viable strategy for updating acceptance criteria for the future.

In order to provide some insight into the use of colour in speeding up performance on a visual search task similar to that presented by air traffic control, initial experiments compared the performance of normal trichromats with mild and severe deutans and protans for a visual search task in which targets had a defining spatial cue and were either achromatic or redundantly coloured. Large differences in visual search times for detection of red and green targets were found when colour deficient subjects were compared to normal trichromats. When targets were also defined by a negative luminance contrast, the effect was even more pronounced. Unexpectedly, some colour deficient subjects had greater difficulty in locating more saturated colours for given combinations of luminance and chromatic contrasts.

For a coloured object with a chromaticity that has equal L-, M- and S-cone signal, in order to increase the saturation of a red target this is done by altering the ratio of L to M cone signals. In the case of a protan subject (see section 4.3.1) this will negatively affect the achromatic (L + M) luminance response, and therefore when a target is presented with a positive luminance contrast, an increase in saturation decreases the effective luminance contrast of the target, and this in turn causes an overall reduction in visual search performance. This effect is dependent not only on the type of colour deficiency and the chromaticity and saturation of the target, but also the severity of deficiency and the initial luminance contrast at which the target is presented before the addition of colour. It is therefore important to consider these interactions when presenting colour deficient subjects with coloured stimuli, even when those stimuli are above their detection threshold.

Normal subjects showed little improvement in search times above 12 CAD units for red and green coloured targets. This may therefore represent the useful upper limit recommended for use in display-based applications. When the saturation of red and green targets were set to 12 CAD units,

mild colour deficient subjects could, in some cases, perform the visual search task with the same accuracy as normal trichromats. However, no colour deficient subject could carry out the search task within the normal range of response times. While in some conditions there can be an effect of luminance contrast interacting with chromatic detection for colour deficient observers, this difference in performance versus normal trichromats can largely be attributed to the reduction in chromatic sensitivity. By determining the effective colour signal strength of each subject for a given target, and comparing colour deficient response times to those of normals over a range of chromatic saturation, it was found that colour deficient perform within error of normal trichromats for the same equivalent colour signal strength.

The remaining findings show that in equivalent tasks colour deficient observers perform as well as normal trichromats for colours along the yellow or blue directions. We therefore questioned whether colour directions that produce both RG and YB colour difference signals may yield a level of performance in mild deutan and protan subjects that approaches similar measurements in normal trichromats. Four colour directions that produce both RG and YB colour difference signals were employed and visual search performance measured in 31 normal trichromats, 26 deutans and 14 protans. The results show that for each of the directions selected, both visual search times and the accuracy of colour identification overlapped significantly with normal trichromats for targets of both positive and negative luminance contrast. Selection of appropriate colours for use on ATC displays is not an impossible task since the facility to change the palette of colours that can be used already exists.

A number of observations emerge from this study that may help determine the suitability of applicants for work in ATC applications.

Firstly, it is clear that chromaticities that fall along RG colour confusion directions will yield reduced performance, even in minimally affected colour deficient subjects when large chromatic separations are employed. Increasing the difference in chromatic saturation further to improve performance in

mild colour deficient observers is not a viable option given the phosphor limits of most display screens. However, many colour deficient observers do perform as well as normal trichromats when the latter are presented with a less saturated coloured target. It remains to be decided whether the small increase in visual search time is of functional significance and cannot be accepted within the ATC environment. Furthermore, if it desirable to avoid colour difference with no YB component (i.e., chromatic displacements that correspond to RG colour confusion lines).

It may also be possible to simply use the CRATO test with the parameters similar to those in experiment 4.3 to test whether a subject falls within the normal range of reaction time and accuracy of response. In this case, the properties of the test display, and the chromaticities used, would have to be equivalent to those of the ATC display to ensure the validity of this approach. It is also possible to use the highest CAD thresholds for red-green and yellow-blue sensitivity that still allow for performance equivalent to that of normal trichromats as limits.

Although either of these solutions may be adequate, each yields different advantages and disadvantages. In addition to colour signals, many other factors that vary between individuals, can also affect visual search performance. An exhaustive list of all of these factors has not been established, and therefore by using a visual search task such as the CRATO test, there is an advantage of accounting for variation in visual search performance in addition to the effects of chromatic discrimination and sensitivity. Setting limits based on CAD test performance would allow for confidence that a subject who achieves a pass could perform well and respond well to the stimuli producing combined RG and YB signals, however the results from experiment 4.3 show that it is still quite possible for a subject outside of these cut-offs to achieve normal performance.

If using the CRATO test performance as acceptance criteria, it would be advisable to also carry out the CAD test in order to provide information about the type and severity of deficiency for applicants, and to continue to do this at subsequent medical examinations throughout the career of an air traffic controller, to ensure that their chromatic sensitivity remains satisfactory.

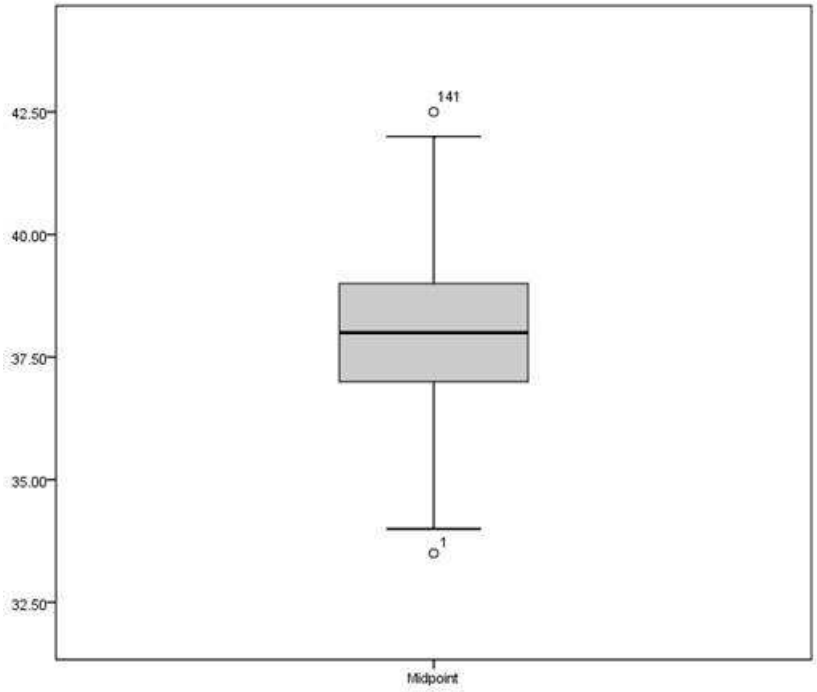
In terms of optimizing visual search performance for normal trichromats when large visual fields are involved, it was observed that yellow and blue targets were located more quickly than red and green targets at equivalent levels of saturation (where saturation is defined in CAD units). As CAD units relate to the mean chromatic displacements needed for threshold detection in foveal viewing in the normal population, centrally located targets of any of the four colours should be equally salient at the same saturation. However the sensitivity of RG chromatic mechanisms decays more rapidly with eccentricity, more so than S cone and achromatic mechanisms. This leads to clear differences in detection thresholds measured up to +/- 10 degrees from central fixation, as per Figures 4-29 to 4-31. Therefore when targets can be located peripherally on a large display screen, it may be more effective to employ yellow or blue colours to allow for rapid location. Alternatively, red and green targets presented at the periphery could be either larger or of higher saturations to compensate for reduced discriminability.

In summary, these findings suggest that it is important to consider the effective luminance contrast of coloured targets in subjects with congenital colour deficiency when assessing the suitability of colour signals for use on visual displays. When colours and contrast levels can be adjusted as required, it may well be possible to create working environments using visual displays in which a certain level of congenital colour deficiency need not be a barrier to acceptance.

6 APPENDICES

6.1 APPENDIX A: DETECTION OF OUTLIERS USING THE MEAN AND INTERQUARTILE RANGE FOR NAGEL MIDPOINTS

The 141 midpoints in this sample reported a median of 38 and an interquartile range of 37 – 39. Extreme values were defined as those observations that fell below Q1 - 1.5(IQR) or above Q3 + 1.5(IQR). In this case this translated to values below 34 and above 42, which resulted in two extreme values as per the figure below.

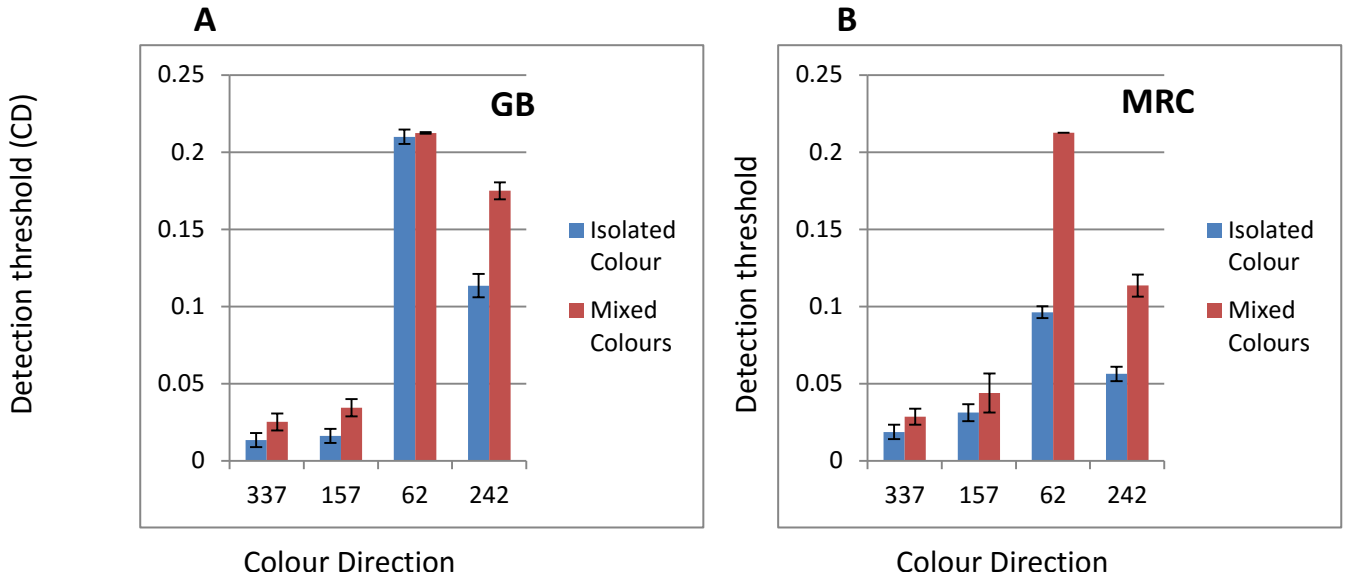


6.2 APPENDIX B: CAD DATA FOR NORMAL TRICHROMAT OBSERVERS USED IN CHAPTER 3

Subject	CAD RG threshold	CAD YB threshold
JH	0.74	0.65
HGG	1.01	1.02
GB	0.93	1.22
EP	1.25	1.05
JB	1.13	1.02

CAD RG and YB thresholds obtained for all normal trichromat observers that participated in the experiments described in chapter 3.

6.3 APPENDIX C: THRESHOLDS FOR INTERLEAVED AND NON-INTERLEAVED COLOURS ON THE LUMINANCE PEDESTAL TEST



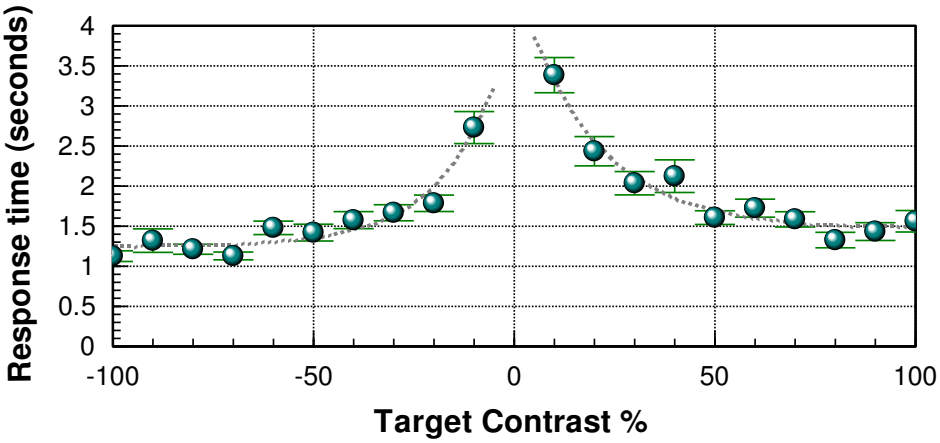
Chromatic detection thresholds (measured as chromatic displacements from background chromaticity (x = 0.305, y = 0.323) in CIE 1931 space), for four colour directions. Results compare the thresholds obtained for non-interleaved colour staircases, where only one colour is available (isolated colour), with interleaved staircases (mixed colours) for two observers. In several cases, there is a significant improvement in performance where only one colour is tested.

6.4 APPENDIX D: OBJECT FEATURES AFFECTING VISUAL ATTENTION

Undoubted attributes	Probable attributes	Possible attributes
Colour	Luminance onset (flicker)	Lighting direction (shading)
Motion	Luminance polarity	Glossiness
Orientation	Vernier offset	Expansion
Size (including object size and spatial frequency)	Stereoscopic depth and tilt	Number
	Pictoral depth cues	Aspect ratio
	Shape	
	Line termination	
	Closure	
	Curvature	
	Topological Status	

Features of objects that are likely to guide the deployment of attention, arranged in categories of probability, adapted from Wolfe & Horowitz, 2004.

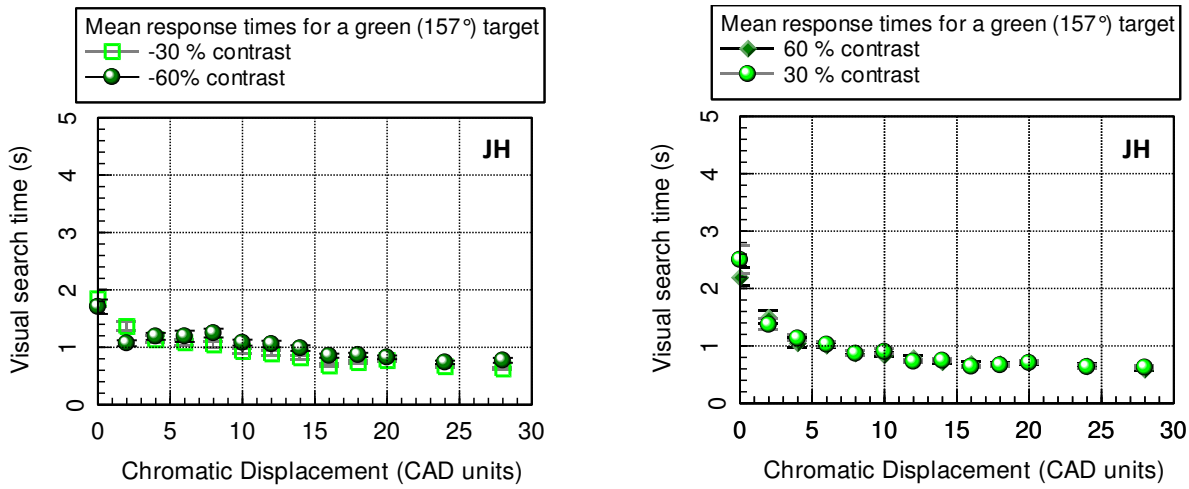
6.4A APPENDIX E: VISUAL SEARCH TIMES AS A FUNCTION OF ACHROMATIC LUMINANCE

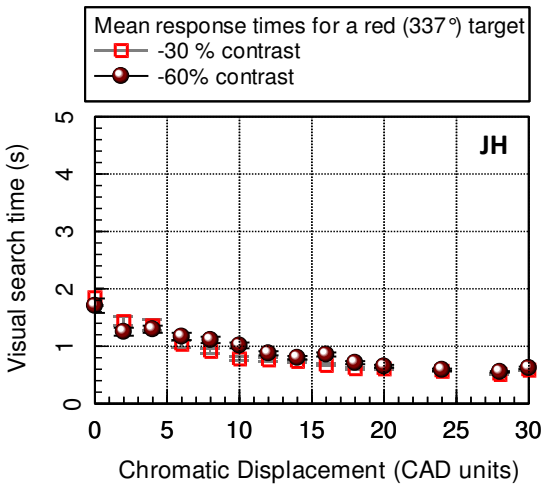


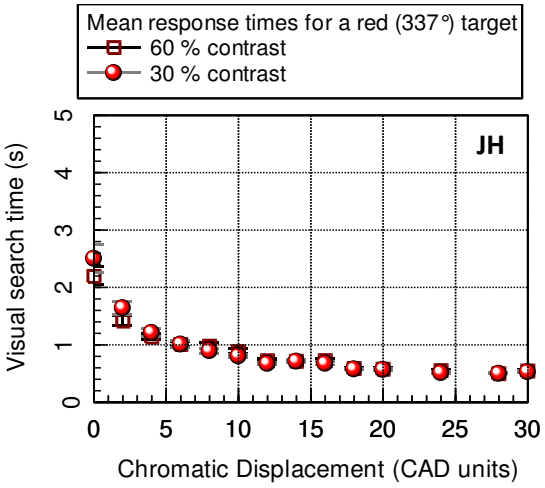
Visual search times as a function of target luminance contrast (versus the background field) for the visual search task described in 4.2.1. As the contrast of the target approaches that of the background, visual search times increase (at 0% contrast the task would be impossible; below 10% contrast, measurements could not be obtained). For either positive or negative luminance contrast, performance is not improved beyond 60%.

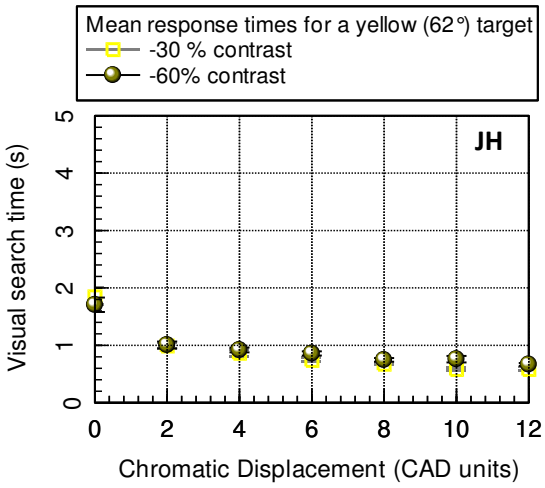
6.5 APPENDIX F: VISUAL SEARCH TIMES FOR NORMAL TRICHROMATS IN EXPERIMENT 4.1

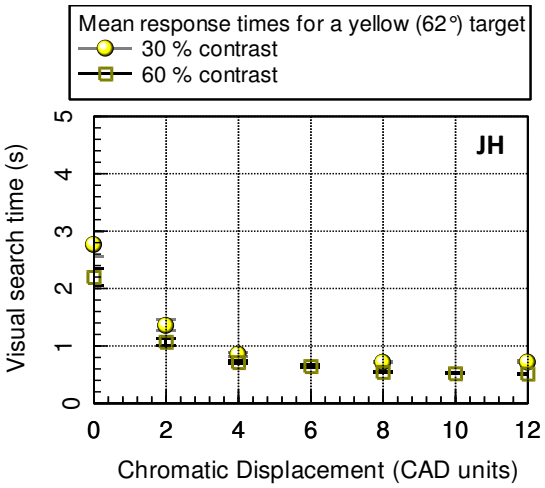
Visual search times, averaged from 90 presentations per combination of saturation and luminance contrast, for subject JH for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

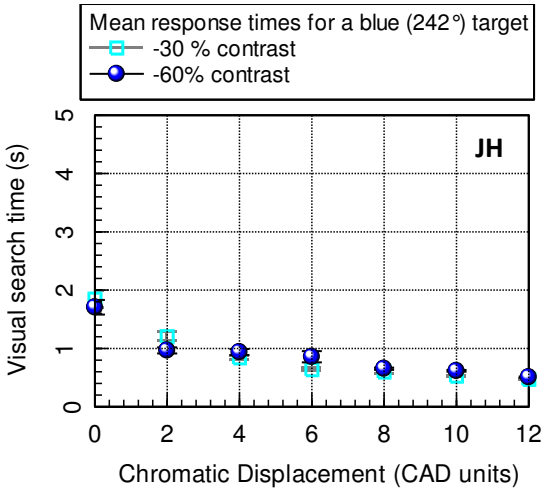


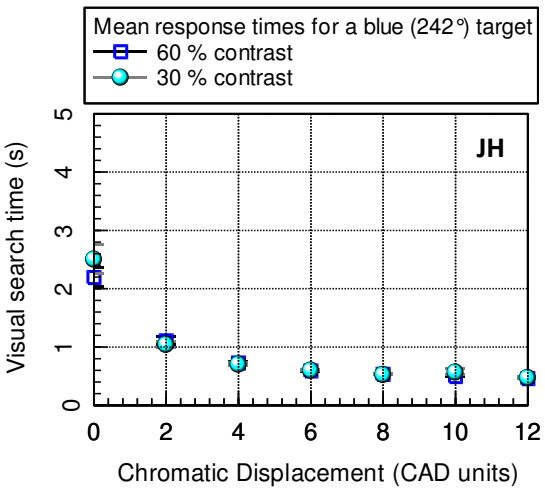

Mean response times for a red (337°) target
-30 % contrast
-60% contrast
JH
Visual search time (s)
Chromatic Displacement (CAD units)


Mean response times for a red (337°) target
60 % contrast
30 % contrast
JH
Visual search time (s)
Chromatic Displacement (CAD units)

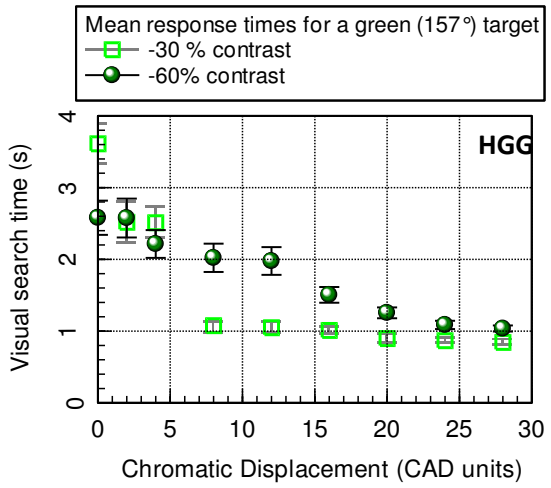

Mean response times for a yellow (62°) target
-30 % contrast
-60% contrast
JH
Visual search time (s)
Chromatic Displacement (CAD units)

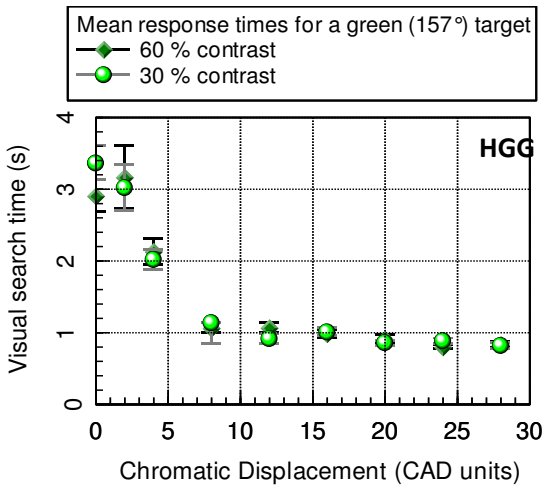

Mean response times for a yellow (62°) target
30 % contrast
60 % contrast
JH
Visual search time (s)
Chromatic Displacement (CAD units)

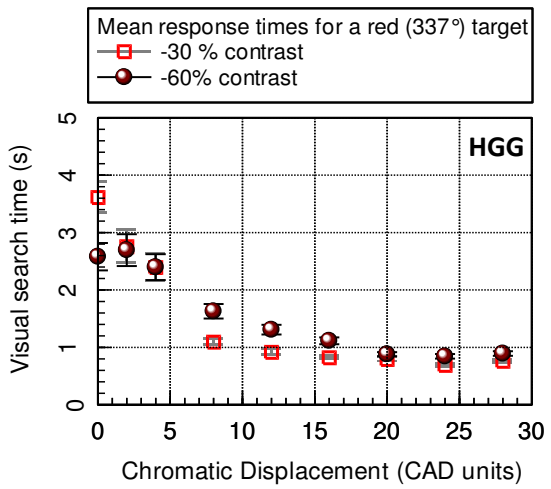

Mean response times for a blue (242°) target
-30 % contrast
-60% contrast
JH
Visual search time (s)
Chromatic Displacement (CAD units)

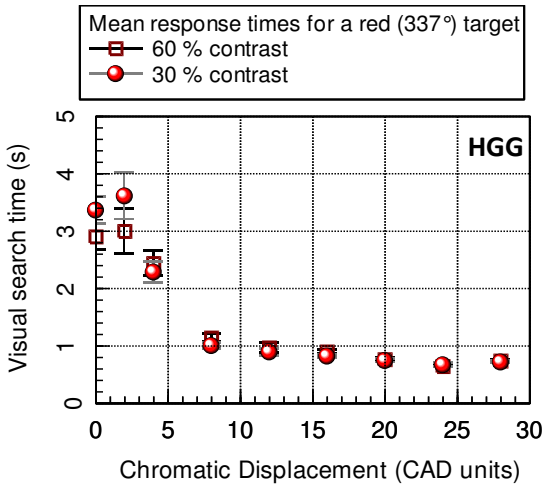

Mean response times for a blue (242°) target
60 % contrast
30 % contrast
JH
Visual search time (s)
Chromatic Displacement (CAD units)

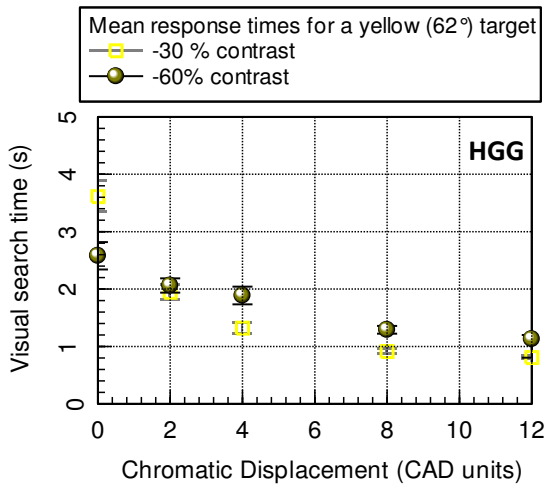
Visual search times, averaged from 90 presentations per combination of saturation and luminance contrast, for subject HGG for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

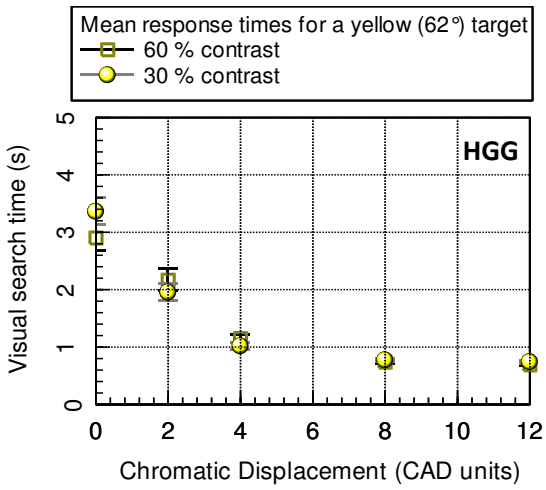


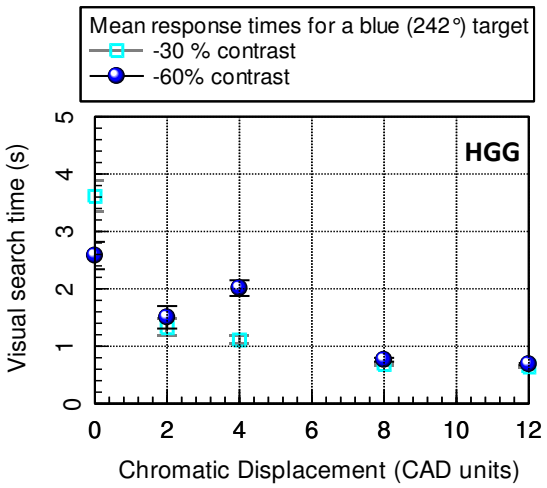


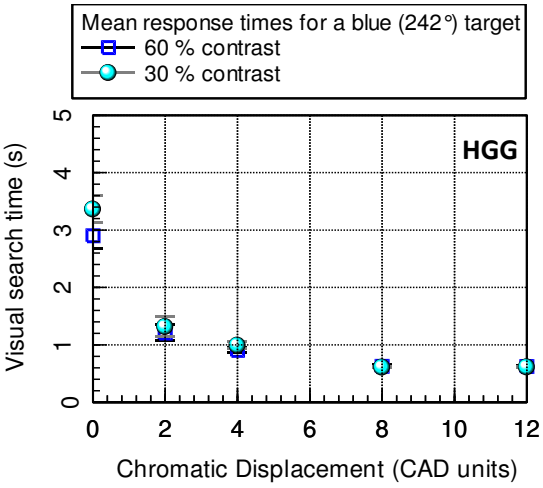




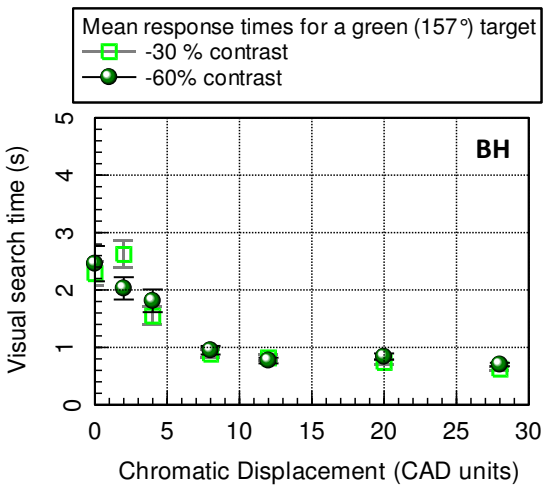


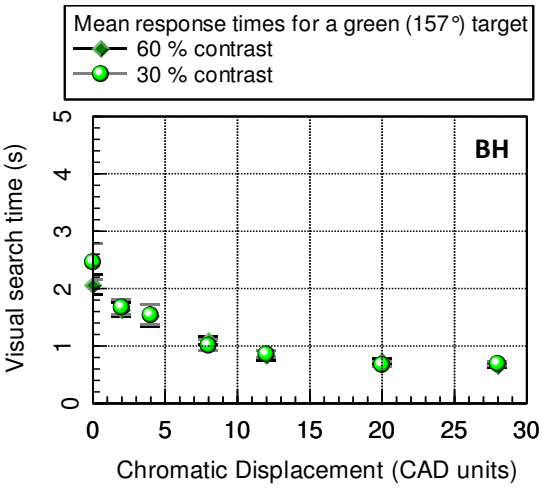


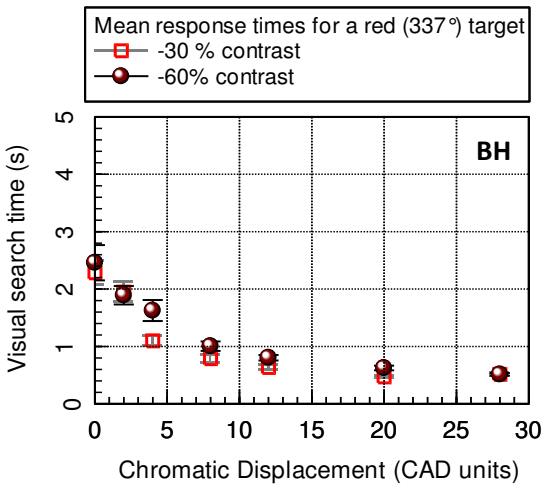


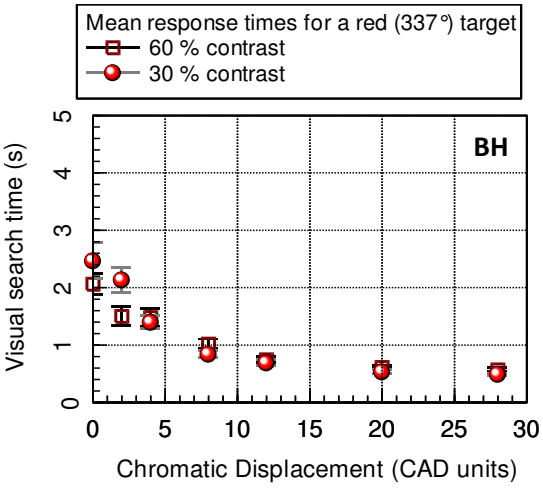


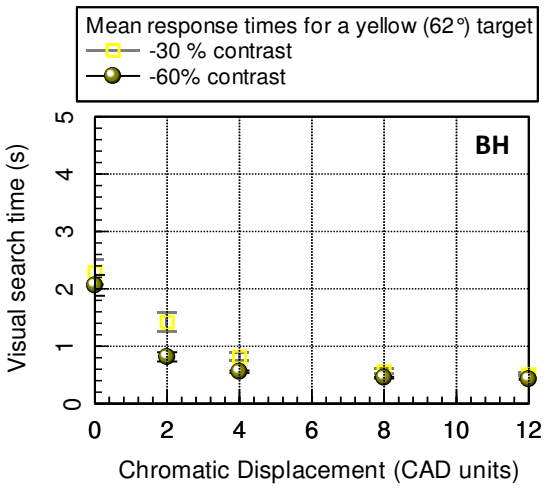
Visual search times, averaged from 90 presentations per combination of saturation and luminance contrast, for subject BH for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

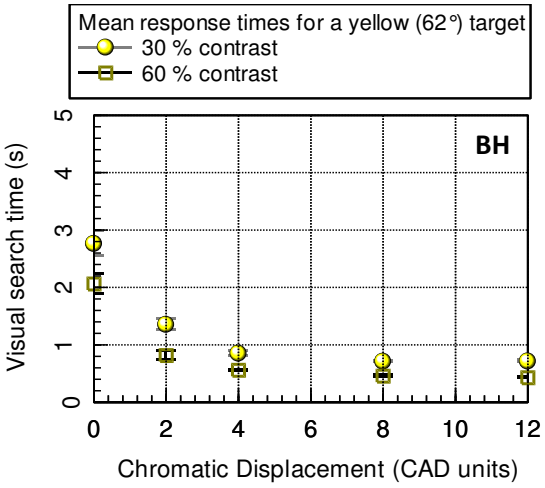


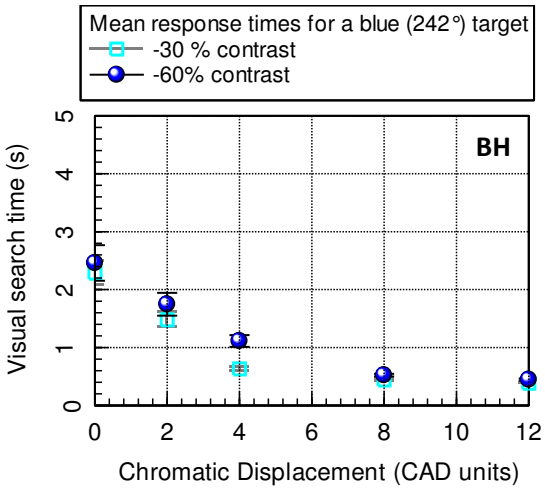


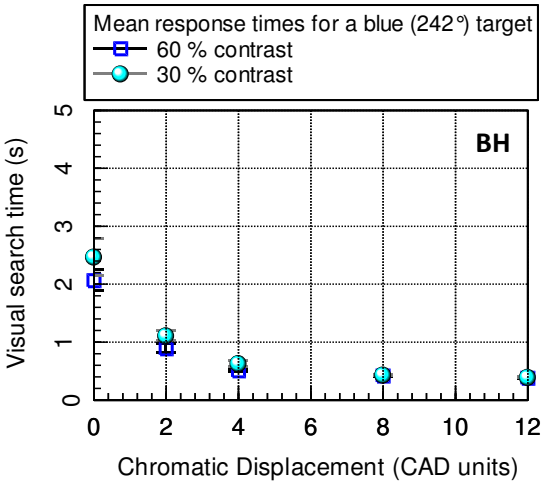





Mean response times for a yellow (62°) target
-30 % contrast
-60% contrast
BH
Visual search time (s)
0
1
2
3
4
5
0
2
4
6
8
10
12
Chromatic Displacement (CAD units)


Mean response times for a yellow (62°) target
30 % contrast
60 % contrast
BH
Visual search time (s)
0
1
2
3
4
5
0
2
4
6
8
10
12
Chromatic Displacement (CAD units)


Mean response times for a blue (242°) target
-30 % contrast
-60% contrast
BH
Visual search time (s)
0
1
2
3
4
5
0
2
4
6
8
10
12
Chromatic Displacement (CAD units)


Mean response times for a blue (242°) target
60 % contrast
30 % contrast
BH
Visual search time (s)
0
1
2
3
4
5
0
2
4
6
8
10
12
Chromatic Displacement (CAD units)

6.6 APPENDIX G: ANOVA RESULTS FOR NORMAL TRICHROMAT (JH) RESULTS BASED ON THE LUMINANCE CONTRAST OF COLOURS IN EXPERIMENT 4.1

ANOVA results for multiple comparisons between the four luminance contrasts are shown for each of the colour directions used in experiment 4.1. Note that the standard error given is the standard error of the mean difference between the comparison groups, rather than the standard error used in calculating the significance of the post-hoc tests, and hence is always the same.

157 degrees (I) Contrast		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
-60.00	-30.00	.09761	.09085	.707	-.1449	.3402
	30.00	.15447	.09085	.336	-.0881	.3970
	60.00	.15217	.09085	.349	-.0904	.3947
-30.00	-60.00	-.09761	.09085	.707	-.3402	.1449
	30.00	.05686	.09085	.923	-.1857	.2994
	60.00	.05456	.09085	.931	-.1880	.2971
30.00	-60.00	-.15447	.09085	.336	-.3970	.0881
	-30.00	-.05686	.09085	.923	-.2994	.1857
	60.00	-.00230	.09085	1.000	-.2449	.2403
60.00	-60.00	-.15217	.09085	.349	-.3947	.0904
	-30.00	-.05456	.09085	.931	-.2971	.1880
	30.00	.00230	.09085	1.000	-.2403	.2449

ANOVA output for 157 degrees visual search times as a factor of luminance contrast. No significant differences were found between groups.

337 degrees (I) Contrast		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
-60.00	-30.00	.07767	.12025	.916	-.2434	.3987
	30.00	.09554	.12025	.857	-.2255	.4166
	60.00	.09172	.12025	.871	-.2293	.4128
-30.00	-60.00	-.07767	.12025	.916	-.3987	.2434
	30.00	.01786	.12025	.999	-.3032	.3389
	60.00	.01404	.12025	.999	-.3070	.3351
30.00	-60.00	-.09554	.12025	.857	-.4166	.2255
	-30.00	-.01786	.12025	.999	-.3389	.3032
	60.00	-.00382	.12025	1.000	-.3249	.3172
60.00	-60.00	-.09172	.12025	.871	-.4128	.2293
	-30.00	-.01404	.12025	.999	-.3351	.3070
	30.00	.00382	.12025	1.000	-.3172	.3249

ANOVA output for 337 degrees visual search times as a factor of luminance contrast. No significant differences were found between groups.

62 degrees (I) Contrast		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
-60.00	-30.00	.08977	.11183	.852	-.2232	.4028
	30.00	.14337	.11183	.584	-.1696	.4564
	60.00	.16383	.11183	.476	-.1492	.4768
-30.00	-60.00	-.08977	.11183	.852	-.4028	.2232
	30.00	.05360	.11183	.963	-.2594	.3666
	60.00	.07406	.11183	.910	-.2389	.3871
30.00	-60.00	-.14337	.11183	.584	-.4564	.1696
	-30.00	-.05360	.11183	.963	-.3666	.2594
	60.00	.02046	.11183	.998	-.2925	.3335
60.00	-60.00	-.16383	.11183	.476	-.4768	.1492
	-30.00	-.07406	.11183	.910	-.3871	.2389
	30.00	-.02046	.11183	.998	-.3335	.2925

ANOVA output for 62 degrees visual search times as a factor of luminance contrast. No significant differences were found between groups.

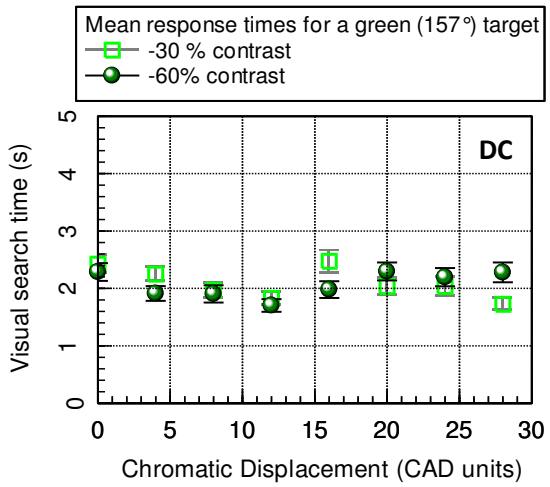
242 degrees (I) Contrast		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
-60.00	-30.00	.04517	.13239	.986	-.3254	.4157
	30.00	.10823	.13239	.845	-.2623	.4788
	60.00	.10609	.13239	.853	-.2645	.4766
-30.00	-60.00	-.04517	.13239	.986	-.4157	.3254
	30.00	.06306	.13239	.963	-.3075	.4336
	60.00	.06092	.13239	.967	-.3096	.4315
30.00	-60.00	-.10823	.13239	.845	-.4788	.2623
	-30.00	-.06306	.13239	.963	-.4336	.3075
	60.00	-.00214	.13239	1.000	-.3727	.3684
60.00	-60.00	-.10609	.13239	.853	-.4766	.2645
	-30.00	-.06092	.13239	.967	-.4315	.3096
	30.00	.00214	.13239	1.000	-.3684	.3727

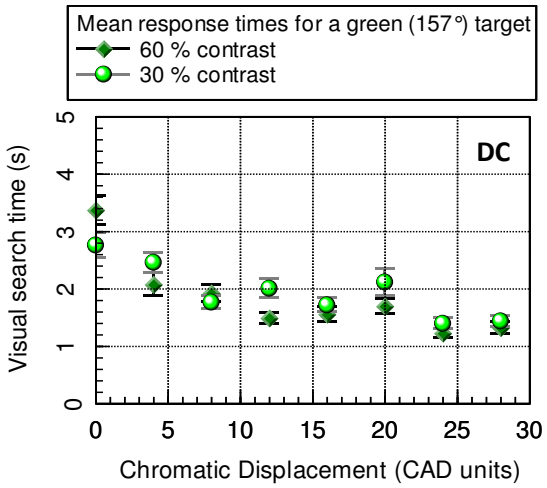
ANOVA output for 242 degrees visual search times as a factor of luminance contrast. No significant differences were found between groups.

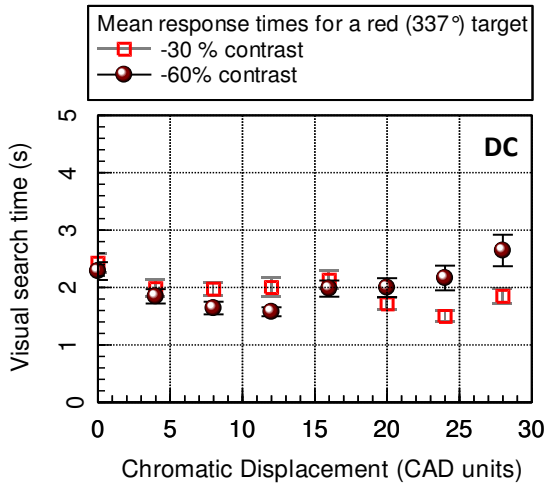
6.7 APPENDIX H: VISUAL SEARCH TIMES FOR COLOUR DEFICIENT OBSERVERS IN EXPERIMENT

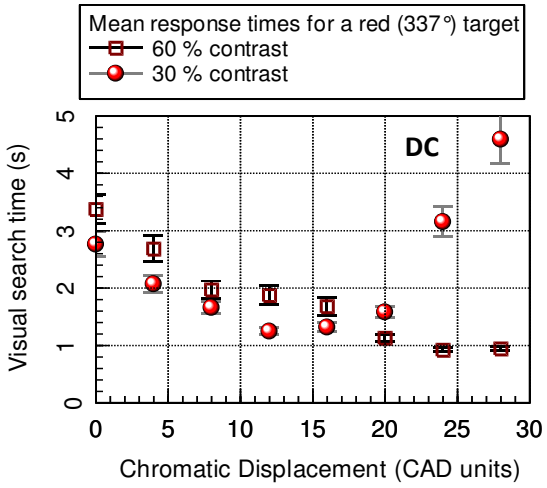
4.1

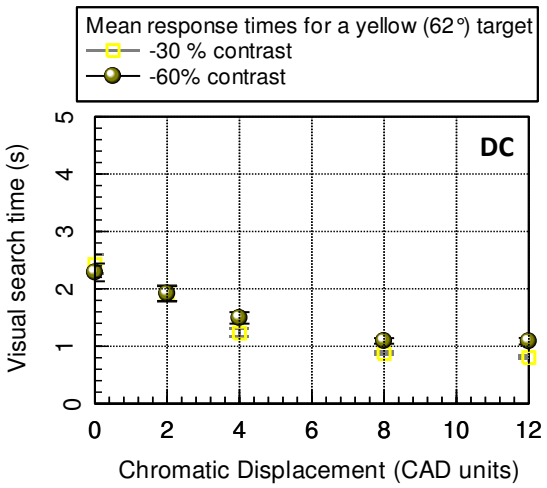
Visual search times, averaged from 90 presentations per combination of saturation and luminance contrast, for subject protan DC for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

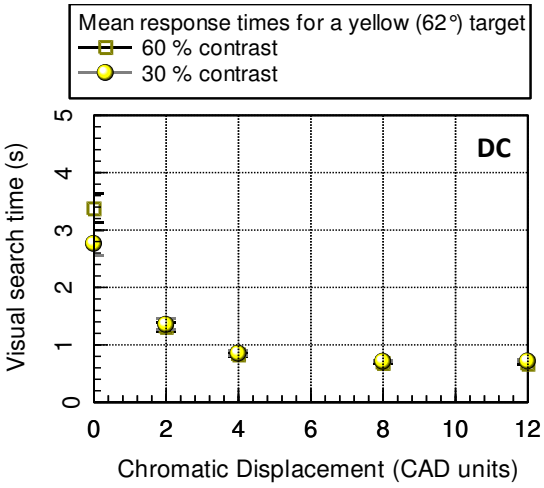


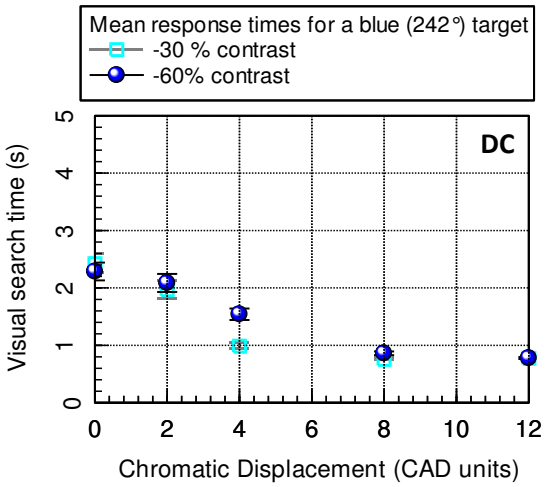


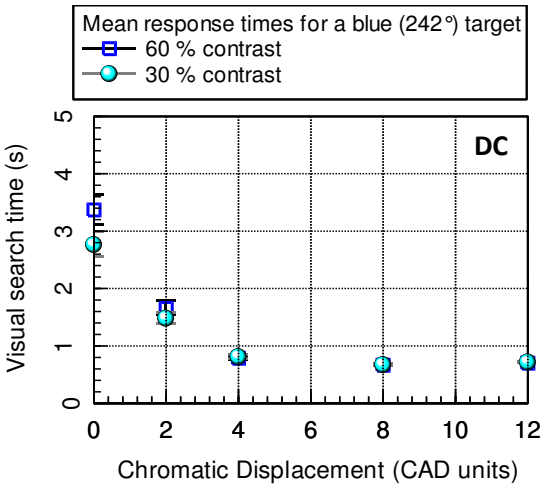




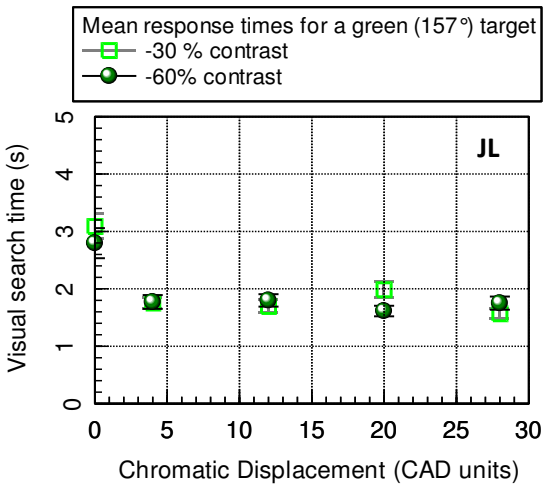


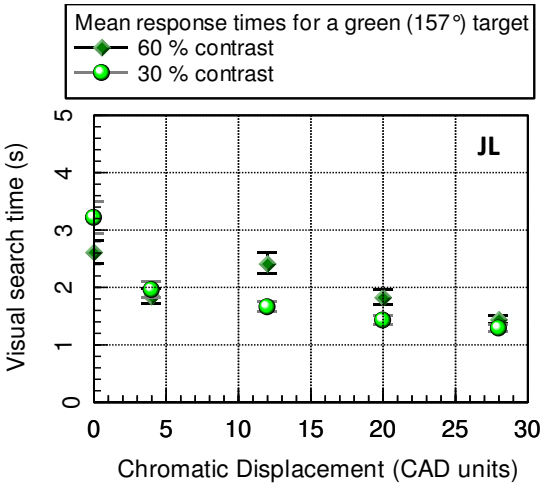


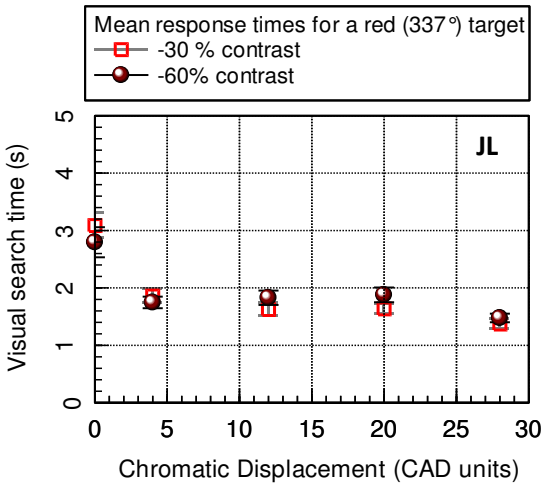


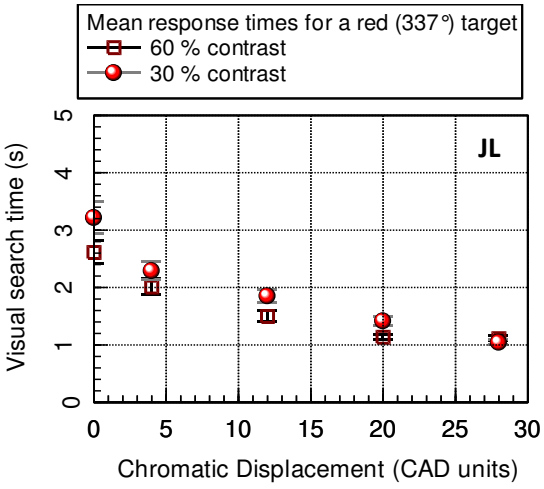


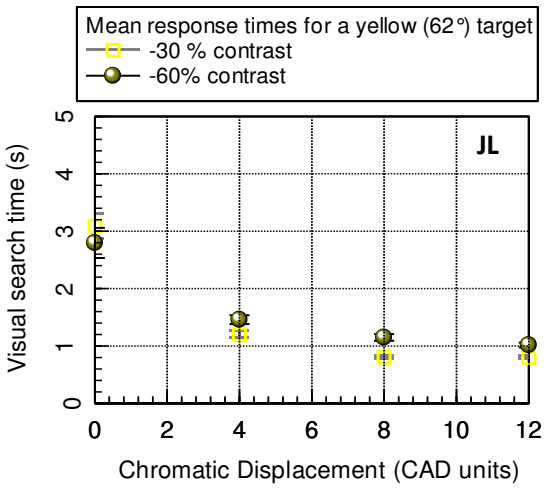
Visual search times, averaged from 90 presentations per combination of saturation and luminance contrast, for deutan subject JL for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

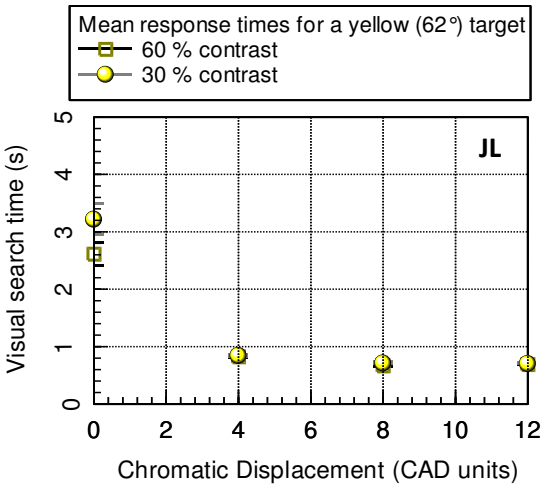

Mean response times for a green (157°) target
-30 % contrast
-60% contrast
JL
Visual search time (s)
Chromatic Displacement (CAD units)

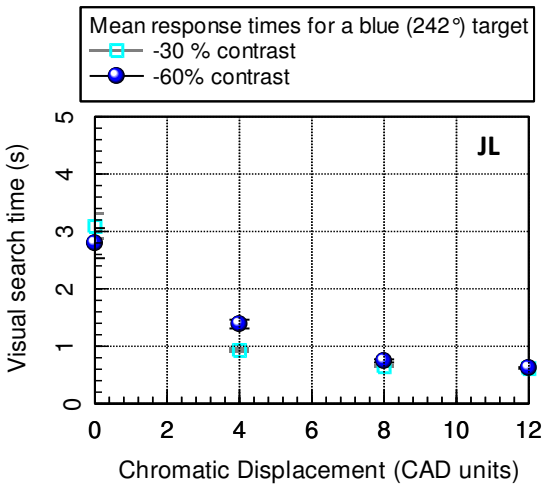

Mean response times for a green (157°) target
60 % contrast
30 % contrast
JL
Visual search time (s)
Chromatic Displacement (CAD units)

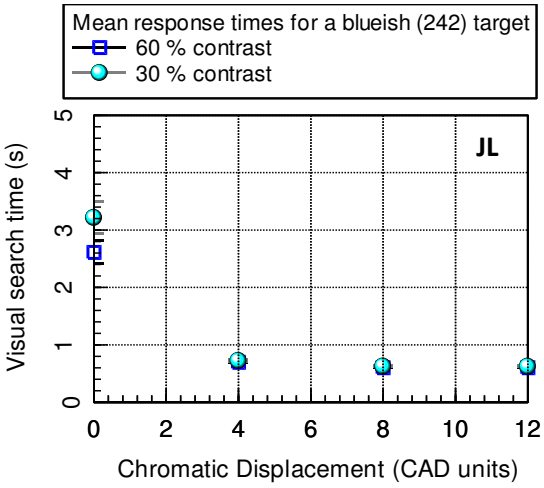

Mean response times for a red (337°) target
-30 % contrast
-60% contrast
JL
Visual search time (s)
Chromatic Displacement (CAD units)


Mean response times for a red (337°) target
60 % contrast
30 % contrast
JL
Visual search time (s)
Chromatic Displacement (CAD units)

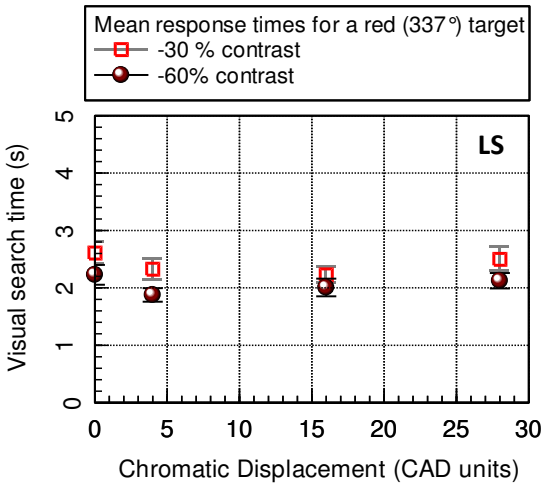

Mean response times for a yellow (62°) target
-30 % contrast
-60% contrast
JL
Visual search time (s)
Chromatic Displacement (CAD units)

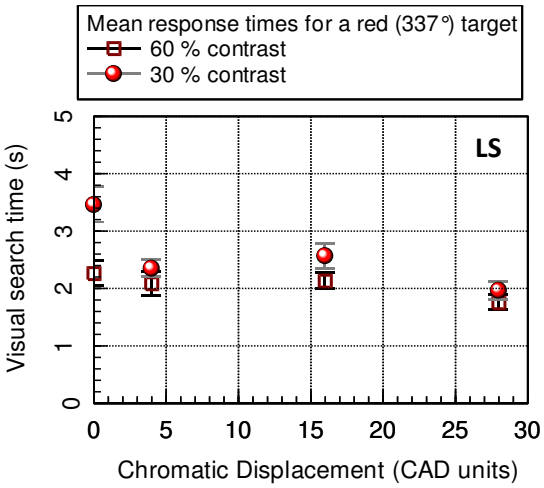

Mean response times for a yellow (62°) target
60 % contrast
30 % contrast
JL
Visual search time (s)
Chromatic Displacement (CAD units)

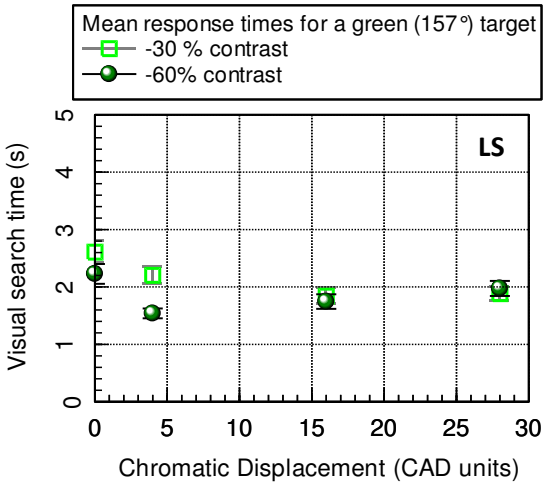


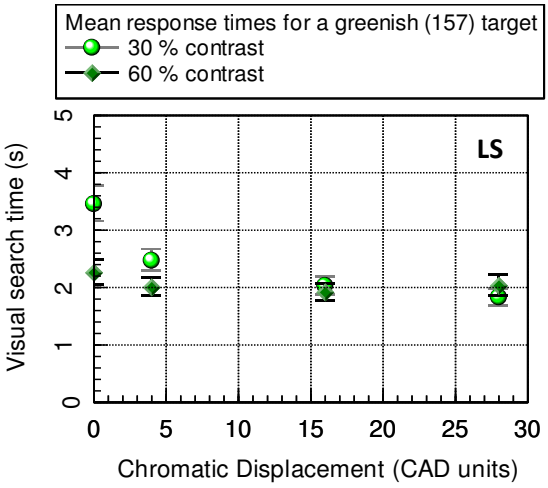


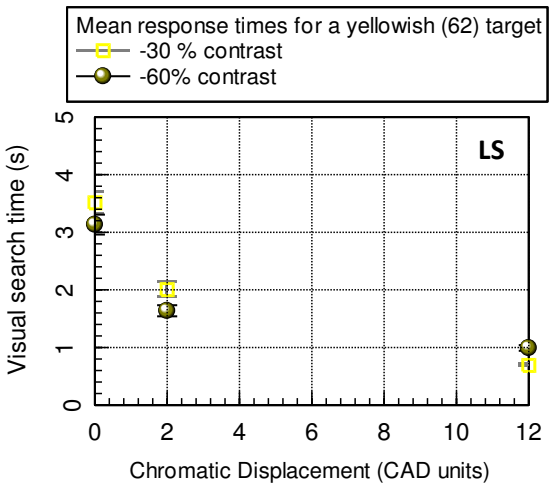
Visual search times, averaged from 90 presentations per combination of saturation and luminance contrast, for deutan subject LS for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

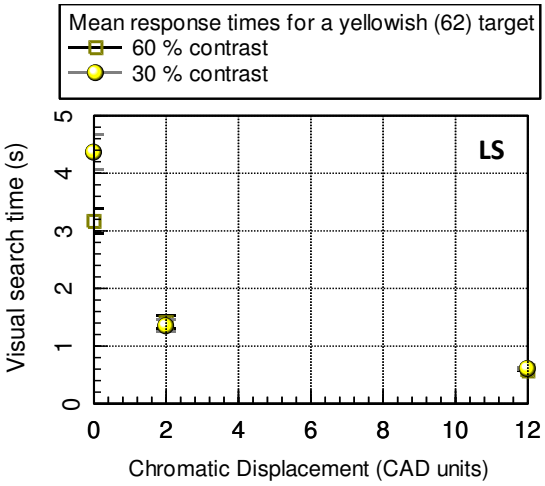


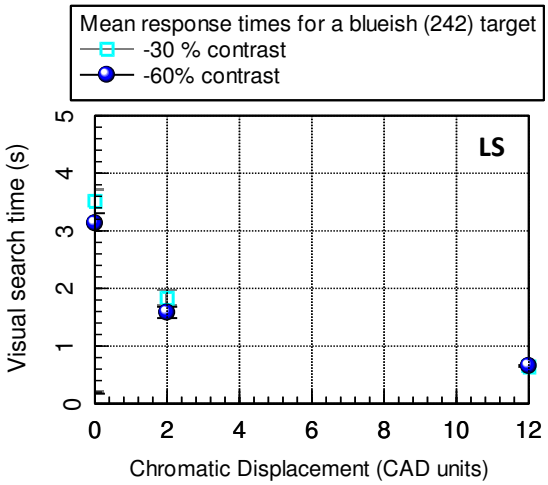


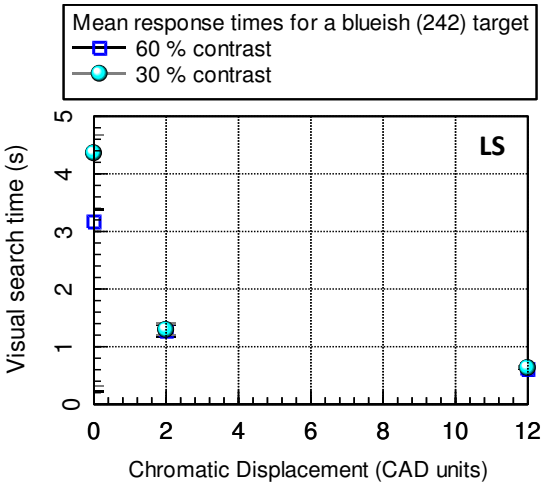




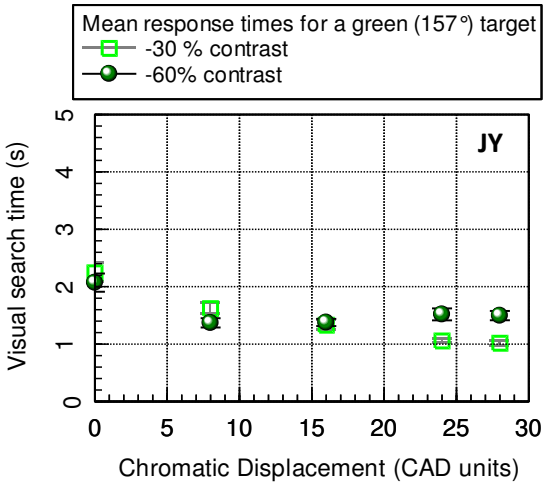


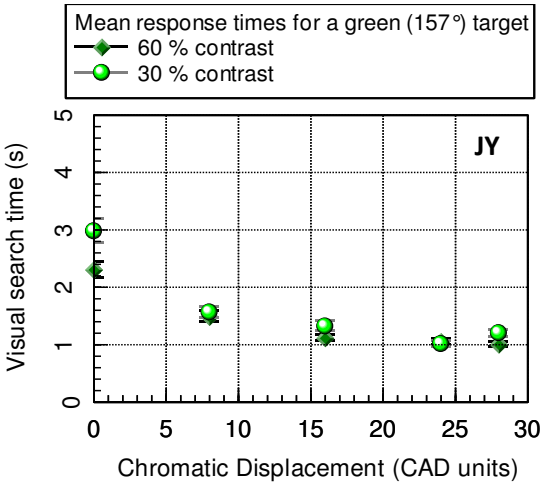


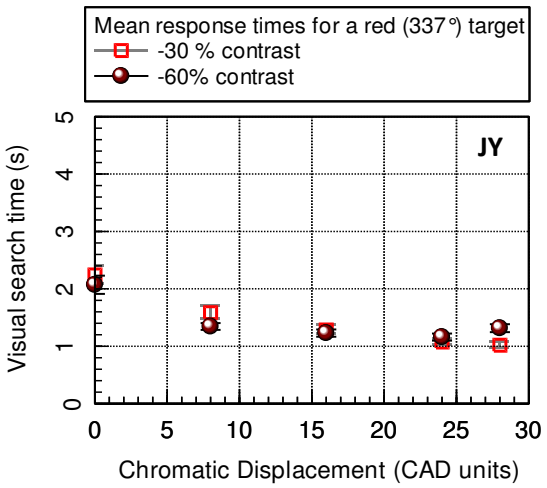


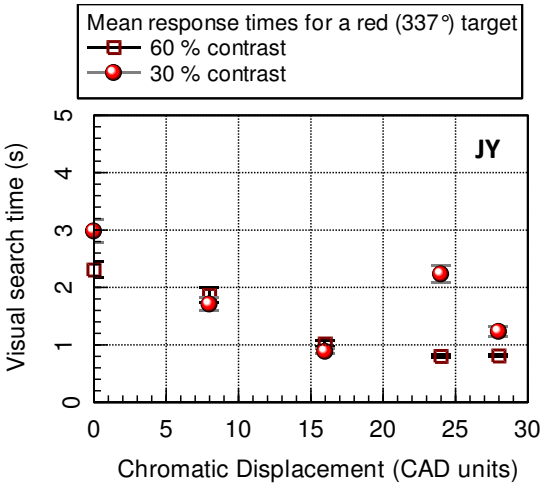


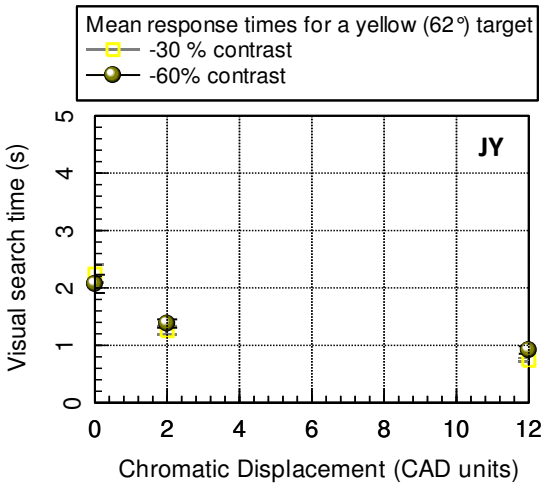
Visual search times, averaged from 90 presentations per combination of saturation and luminance contrast, for protan subject JY for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

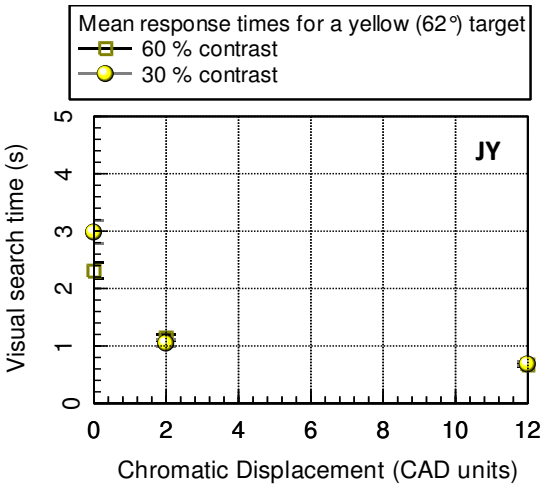


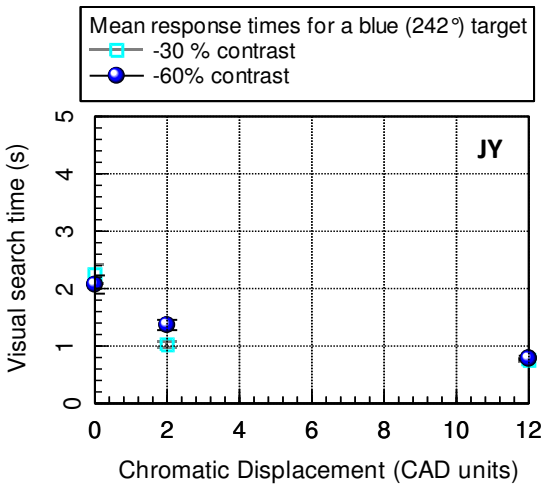


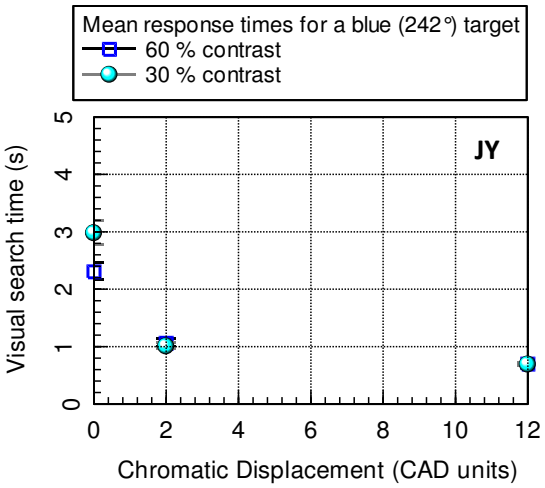

Mean response times for a red (337°) target
-30 % contrast
-60% contrast
JY
Visual search time (s)
Chromatic Displacement (CAD units)


Mean response times for a red (337°) target
60 % contrast
30 % contrast
JY
Visual search time (s)
Chromatic Displacement (CAD units)


Mean response times for a yellow (62°) target
-30 % contrast
-60% contrast
JY
Visual search time (s)
Chromatic Displacement (CAD units)


Mean response times for a yellow (62°) target
60 % contrast
30 % contrast
JY
Visual search time (s)
Chromatic Displacement (CAD units)


Mean response times for a blue (242°) target
-30 % contrast
-60% contrast
JY
Visual search time (s)
Chromatic Displacement (CAD units)


Mean response times for a blue (242°) target
60 % contrast
30 % contrast
JY
Visual search time (s)
Chromatic Displacement (CAD units)

6.8 APPENDIX I: ANOVA RESULTS FOR COLOUR DEFICIENT VISUAL SEARCH TIMES AS A FACTOR OF LUMINANCE CONTRAST (337 AND 157 DEGREES)

Note that the standard error given is the standard error of the mean difference between the comparison groups, rather than the standard error used in calculating the significance of the post-hoc tests, and hence is always the same.

One way ANOVA results for subject DC:

337 degrees (I) luminance contrast		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	-.63270	.38638	.378	-1.6986	.4332
	3.00	-.27976	.38638	.887	-1.3456	.7861
	4.00	-.38296	.38638	.756	-1.4488	.6829
2.00	1.00	.63270	.38638	.378	-.4332	1.6986
	3.00	.35293	.38638	.798	-.7129	1.4188
	4.00	.24973	.38638	.916	-.8161	1.3156
3.00	1.00	.27976	.38638	.887	-.7861	1.3456
	2.00	-.35293	.38638	.798	-1.4188	.7129
	4.00	-.10320	.38638	.993	-1.1691	.9627
4.00	1.00	.38296	.38638	.756	-.6829	1.4488
	2.00	-.24973	.38638	.916	-1.3156	.8161
	3.00	.10320	.38638	.993	-.9627	1.1691

157 degrees (I) luminance contrast		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	-.23095	.15878	.479	-.6690	.2071
	3.00	-.43257	.15878	.054	-.8706	.0055
	4.00	-.42741	.15878	.058	-.8654	.0106
2.00	1.00	.23095	.15878	.479	-.2071	.6690
	3.00	-.20162	.15878	.590	-.6396	.2364
	4.00	-.19646	.15878	.610	-.6345	.2416
3.00	1.00	.43257	.15878	.054	-.0055	.8706
	2.00	.20162	.15878	.590	-.2364	.6396
	4.00	.00516	.15878	1.000	-.4329	.4432
4.00	1.00	.42741	.15878	.058	-.0106	.8654
	2.00	.19646	.15878	.610	-.2416	.6345
	3.00	-.00516	.15878	1.000	-.4432	.4329

One way ANOVA results for subject JL:

337 degrees (I) LC		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	-.21094	.25998	.848	-.9828	.5609
	3.00	-.18668	.25998	.888	-.9585	.5852
	4.00	-.29739	.25998	.671	-1.0693	.4745
2.00	1.00	.21094	.25998	.848	-.5609	.9828
	3.00	.02426	.25998	1.000	-.7476	.7961
	4.00	-.08646	.25998	.987	-.8583	.6854
3.00	1.00	.18668	.25998	.888	-.5852	.9585
	2.00	-.02426	.25998	1.000	-.7961	.7476
	4.00	-.11071	.25998	.973	-.8826	.6611
4.00	1.00	.29739	.25998	.671	-.4745	1.0693
	2.00	.08646	.25998	.987	-.6854	.8583
	3.00	.11071	.25998	.973	-.6611	.8826

157 degrees (I) LC		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	.29842	.18845	.423	-.2611	.8579
	3.00	.13019	.18845	.899	-.4293	.6897
	4.00	.14481	.18845	.867	-.4147	.7043
2.00	1.00	-.29842	.18845	.423	-.8579	.2611
	3.00	-.16823	.18845	.809	-.7277	.3913
	4.00	-.15361	.18845	.846	-.7131	.4059
3.00	1.00	-.13019	.18845	.899	-.6897	.4293
	2.00	.16823	.18845	.809	-.3913	.7277
	4.00	.01462	.18845	1.000	-.5449	.5741
4.00	1.00	-.14481	.18845	.867	-.7043	.4147
	2.00	.15361	.18845	.846	-.4059	.7131
	3.00	-.01462	.18845	1.000	-.5741	.5449

One way ANOVA results for subject LS:

337 degrees (I) LC		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	-.52583	.24962	.206	-1.2669	.2153
	3.00	-.35880	.24962	.502	-1.0999	.3823
	4.00	-.00386	.24962	1.000	-.7450	.7372
2.00	1.00	.52583	.24962	.206	-.2153	1.2669
	3.00	.16703	.24962	.907	-.5741	.9081
	4.00	.52197	.24962	.211	-.2191	1.2631
3.00	1.00	.35880	.24962	.502	-.3823	1.0999
	2.00	-.16703	.24962	.907	-.9081	.5741
	4.00	.35494	.24962	.510	-.3862	1.0960
4.00	1.00	.00386	.24962	1.000	-.7372	.7450
	2.00	-.52197	.24962	.211	-1.2631	.2191
	3.00	-.35494	.24962	.510	-1.0960	.3862

157 (I) LC		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	-.39281	.30757	.593	-1.3060	.5203
	3.00	-.07977	.30757	.994	-.9929	.8334
	4.00	.18138	.30757	.933	-.7318	1.0945
2.00	1.00	.39281	.30757	.593	-.5203	1.3060
	3.00	.31304	.30757	.743	-.6001	1.2262
	4.00	.57419	.30757	.292	-.3390	1.4873
3.00	1.00	.07977	.30757	.994	-.8334	.9929
	2.00	-.31304	.30757	.743	-1.2262	.6001
	4.00	.26115	.30757	.830	-.6520	1.1743
4.00	1.00	-.18138	.30757	.933	-1.0945	.7318
	2.00	-.57419	.30757	.292	-1.4873	.3390
	3.00	-.26115	.30757	.830	-1.1743	.6520

One way ANOVA results for subject JY:

337 degrees (I) LC		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	-.44607	.39306	.674	-1.5706	.6785
	3.00	-.08420	.39306	.996	-1.2087	1.0403
	4.00	-.06730	.39306	.998	-1.1918	1.0572
2.00	1.00	.44607	.39306	.674	-.6785	1.5706
	3.00	.36188	.39306	.794	-.7627	1.4864
	4.00	.37877	.39306	.771	-.7458	1.5033
3.00	1.00	.08420	.39306	.996	-1.0403	1.2087
	2.00	-.36188	.39306	.794	-1.4864	.7627
	4.00	.01689	.39306	1.000	-1.1076	1.1414
4.00	1.00	.06730	.39306	.998	-1.0572	1.1918
	2.00	-.37877	.39306	.771	-1.5033	.7458
	3.00	-.01689	.39306	1.000	-1.1414	1.1076

157 degrees (I) LC		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.00	2.00	-.22401	.35420	.920	-1.2374	.7894
	3.00	-.06142	.35420	.998	-1.0748	.9519
	4.00	-.17591	.35420	.959	-1.1893	.8375
2.00	1.00	.22401	.35420	.920	-.7894	1.2374
	3.00	.16259	.35420	.967	-.8508	1.1760
	4.00	.04810	.35420	.999	-.9653	1.0615
3.00	1.00	.06142	.35420	.998	-.9519	1.0748
	2.00	-.16259	.35420	.967	-1.1760	.8508
	4.00	-.11449	.35420	.988	-1.1279	.8989
4.00	1.00	.17591	.35420	.959	-.8375	1.1893
	2.00	-.04810	.35420	.999	-1.0615	.9653
	3.00	.11449	.35420	.988	-.8989	1.1279

6.9 APPENDIX J: PERCENTAGE OF CORRECT RESPONSES FOR ALL SUBJECTS IN EXPERIMENT 4.1 FOR EACH COLOUR AND LUMINANCE CONTRAST

The percentage of correct responses, averaged from 90 presentations per combination of saturation and luminance contrast, for subject JL for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

62°	Saturation (SNU)			
LC (%)	0	4	8	12
60	100.0	100.0	97.8	98.9
30	100.0	97.8	100.0	100.0
-30	97.8	100.0	100.0	98.9
-60	100.0	100.0	100.0	100.0

242°		Saturation (SNU)		
LC (%)	0	4	8	12
60	100.0	98.9	97.8	100.0
30	100.0	100.0	95.6	98.9
-30	97.8	100.0	97.8	98.9
-60	100.0	100.0	97.8	100.0

157°	Saturation (SNU)				
LC (%)	0	4	12	20	28
60	100.0	98.9	98.9	100.0	98.9
30	100.0	100.0	98.9	95.6	100.0
-30	97.8	98.9	100.0	100.0	100.0
-60	100.0	100.0	97.8	97.8	98.9

337°	Saturation (SNU)				
LC (%)	0	4	12	20	28
60	100.0	98.9	100.0	98.9	100.0
30	100.0	98.9	98.9	98.9	98.9
-30	97.8	98.9	98.9	100.0	100.0
-60	100.0	100.0	100.0	100.0	100.0

The percentage of correct responses, averaged from 90 presentations per combination of saturation and luminance contrast, for subject DC for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

62°	Saturation (SNU)				
LC (%)	0	2	4	8	12
60	100.0	98.9	98.9	100.0	100.0
30	100.0	98.9	100.0	98.9	98.9
-30	100.0	98.9	100.0	98.9	100.0
-60	100.0	100.0	98.9	100.0	100.0

242°	Saturation (SNU)				
LC (%)	0	2	4	8	12
60	100.0	98.9	100.0	100.0	100.0
30	100.0	98.9	100.0	98.9	100.0
-30	100.0	97.8	98.9	100.0	100.0
-60	100.0	98.9	97.8	98.9	100.0

157°	Saturation (SNU)							
LC (%)	0	4	8	12	16	20	24	28
60	100.0	100.0	100.0	100.0	100.0	97.8	100.0	100.0
30	100.0	100.0	100.0	100.0	98.9	100.0	100.0	97.8
-30	100.0	100.0	98.9	100.0	100.0	100.0	100.0	100.0
-60	100.0	100.0	98.9	100.0	100.0	98.9	100.0	98.9

337°	Saturation (SNU)							
LC (%)	0	4	8	12	16	20	24	28
60	100.0	100.0	100.0	97.8	100.0	100.0	100.0	98.9
30	100.0	100.0	98.9	97.8	98.9	100.0	100.0	100.0
-30	100.0	100.0	100.0	100.0	98.9	100.0	100.0	100.0
-60	100.0	100.0	100.0	100.0	100.0	98.9	97.8	100.0

The percentage of correct responses, averaged from 90 presentations per combination of saturation and luminance contrast, for subject HGG for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

62°	Saturation (SNU)				
LC (%)	0	2	4	8	12
60	100.0	98.9	100.0	98.9	100.0
30	100.0	100.0	97.8	100.0	100.0
-30	100.0	100.0	98.9	100.0	100.0
-60	98.9	96.7	98.9	98.9	98.9

242°	Saturation (SNU)				
LC (%)	0	2	4	8	12
60	100.0	98.9	100.0	100.0	98.9
30	100.0	100.0	98.9	98.9	98.9
-30	100.0	100.0	100.0	100.0	100.0
-60	98.9	97.8	97.8	100.0	98.9

157°	Saturation (SNU)								
LC (%)	0	2	4	8	12	16	20	24	28
60	100.0	100.0	96.7	97.8	97.8	100.0	98.9	95.6	98.9
30	100.0	97.8	100.0	95.6	100.0	100.0	97.8	100.0	100.0
-30	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.9
-60	98.9	97.8	100.0	100.0	100.0	97.8	98.9	100.0	98.9

337°	Saturation (SNU)								
LC (%)	0	2	4	8	12	16	20	24	28
60	100.0	97.8	100.0	100.0	100.0	97.8	100.0	97.8	100.0
30	100.0	91.1	96.7	97.8	100.0	100.0	98.9	100.0	100.0
-30	100.0	100.0	100.0	100.0	97.8	100.0	100.0	100.0	100.0
-60	98.9	95.6	98.9	98.9	97.8	100.0	100.0	100.0	98.9

The percentage of correct responses, averaged from 90 presentations per combination of saturation and luminance contrast, for subject JH for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

242°	Saturation (SNU)						
LC (%)	0	2	4	6	8	10	12
60	100.0	98.9	95.6	94.4	95.6	95.6	96.7
30	100.0	96.7	96.7	95.6	95.6	97.8	94.4
-30	100.0	98.9	97.8	98.9	95.6	94.4	96.7
-60	100.0	97.8	97.8	96.7	97.8	96.7	95.6

62°	Saturation (SNU)						
LC (%)	0	2	4	6	8	10	12
60	100.0	100.0	97.8	96.7	98.9	98.9	94.4
30	100.0	98.9	97.8	98.9	97.8	92.2	88.9
-30	100.0	97.8	97.8	98.9	97.8	97.8	98.9
-60	100.0	98.9	97.8	95.6	97.8	97.8	98.9

157°	Saturation (SNU)													
LC (%)	**0**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**24**	**28**	**30**
60	100.0	96.7	97.8	100.0	97.8	97.8	97.8	91.1	97.8	95.6	91.1	96.7	98.9	96.7
30	100.0	98.9	97.8	100.0	97.8	100.0	97.8	97.8	100.0	95.6	93.3	95.6	91.1	98.9
-30	100.0	98.9	98.9	100.0	100.0	100.0	95.6	97.8	95.6	100.0	97.8	98.9	98.9	97.8
-60	100.0	100.0	98.9	97.8	95.6	97.8	93.3	93.3	95.6	95.6	100.0	98.9	97.8	97.8

337°	Saturation (SNU)													
LC (%)	**0**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**24**	**28**	**30**
60	100.0	97.8	100.0	97.8	97.8	97.8	97.8	100.0	100.0	97.8	97.8	97.8	93.3	97.8
30	100.0	100.0	100.0	97.8	100.0	93.3	100.0	100.0	100.0	95.6	97.8	93.3	95.6	95.6
-30	100.0	100.0	97.8	100.0	97.8	100.0	95.6	97.8	97.8	97.8	100.0	95.6	95.6	100.0
-60	100.0	97.8	100.0	100.0	100.0	97.8	97.8	100.0	97.8	97.8	95.6	100.0	95.6	97.8

The percentage of correct responses, averaged from 90 presentations per combination of saturation and luminance contrast, for subject BH for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

242°	Saturation (SNU)				
LC (%)	**0**	**2**	**4**	**8**	**12**
60	97.8	100.0	100.0	100.0	100.0
30	100.0	100.0	97.8	97.8	100.0
-30	97.8	100.0	100.0	100.0	100.0
-60	100.0	100.0	100.0	100.0	100.0

62°	Saturation (SNU)				
LC (%)	**0**	**2**	**4**	**8**	**12**
60	97.8	97.8	100.0	100.0	97.8
30	100.0	100.0	100.0	100.0	100.0
-30	97.8	100.0	97.8	100.0	100.0
-60	100.0	95.6	95.6	97.8	97.8

157°	Saturation (SNU)						
LC (%)	0	2	4	8	12	20	28
60	97.8	100.0	100.0	97.8	97.8	100.0	100.0
30	100.0	100.0	100.0	97.8	100.0	95.6	100.0
-30	97.8	100.0	100.0	97.8	97.8	100.0	100.0
-60	100.0	97.8	100.0	100.0	100.0	100.0	97.8

337°	Saturation (SNU)						
LC (%)	0	2	4	8	12	20	28
60	97.8	100.0	97.8	100.0	95.6	100.0	100.0
30	100.0	100.0	97.8	97.8	95.6	100.0	100.0
-30	97.8	100.0	97.8	97.8	95.6	97.8	97.8
-60	100.0	100.0	97.8	100.0	97.8	100.0	100.0

The percentage of correct responses, averaged from 90 presentations per combination of saturation and luminance contrast, for subject JY for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%:

242°	Saturation (SNU)		
LC (%)	0	2	12
60	100.0	97.8	100.0
30	100.0	98.9	98.9
-30	100.0	97.8	100.0
-60	100.0	97.8	97.8

62°	Saturation (SNU		
LC (%)	0	2	12
60	100.0	98.9	98.9
30	100.0	100.0	97.8
-30	100.0	96.7	98.9
-60	100.0	97.8	98.9

157°	Saturation (SNU)				
LC (%)	0	8	16	24	28
60	100.0	95.6	100.0	100.0	98.9
30	100.0	98.9	96.7	97.8	98.9
-30	100.0	96.7	98.9	100.0	100.0
-60	100.0	95.6	98.9	97.8	98.9

337°	Saturation (SNU)				
LC (%)	0	8	16	24	28
60	100.0	96.7	98.9	100.0	98.9
30	100.0	98.9	100.0	85.6	97.8
-30	100.0	98.9	100.0	100.0	97.8
-60	100.0	98.9	98.9	100.0	100.0

The percentage of correct responses, averaged from 90 presentations per combination of saturation and luminance contrast, for subject LS for red, green, yellow and blue coloured targets in experiment 4.1, at luminance contrasts of +/-30% and +/60%

242°	Saturation (SNU)		
LC (%)	0	2	12
60	100.0	100.0	100.0
30	100.0	98.9	100.0
-30	100.0	100.0	100.0
-60	100.0	100.0	100.0

62°	Saturation (SNU)		
LC (%)	0	2	12
60	100.0	100.0	100.0
30	100.0	100.0	100.0
-30	100.0	100.0	100.0
-60	100.0	98.9	100.0

157°	Saturation (SNU)			
LC (%)	0	4	16	28
60	100.0	100.0	100.0	100.0
30	100.0	100.0	100.0	100.0
-30	100.0	100.0	100.0	98.9
-60	100.0	100.0	100.0	100.0

337°	Saturation (SNU)			
LC (%)	0	4	16	28
60	100.0	100.0	100.0	100.0
30	100.0	100.0	100.0	100.0
-30	100.0	98.9	100.0	100.0
-60	100.0	100.0	100.0	98.9

6.10 APPENDIX K: CORRELATION COEFFICIENTS FOR VISUAL SEARCH TIMES IN EXPERIMENT 4.3 VERSUS AGE

Population	R^2 for 22°, +45% LC	R^2 for 22°, -45% LC	R^2 for 109°, +45% LC	R^2 for 109°, -45% LC	R^2 for 198°, +45% LC	R^2 for 198°, -45% LC	R^2 for 293°, +45% LC	R^2 for 293°, -45% LC
Overall	0.02	0.04	0.02	0.01	0.03	0.03	0.08	0.02
Normal	0.07	0.19	0.09	0.04	0.14	0.12	0.18	0.04
Deutan	0.01	0.02	0.12	0.09	0.04	0.11	0.28	0.24
Protan	0.19	0.41	0.29	0.24	0.06	0.34	0.18	0.05

Correlation coefficients for the overall population of subjects, and for normal trichromat, deutan and protan observers, for visual search times of the four colour directions and two luminance contrasts employed in experiment 4.3 versus the age of observers.

6.11 APPENDIX L: CORRELATION COEFFICIENTS FOR VISUAL SEARCH TIMES IN EXPERIMENT 4.3 VERSUS CAD RG AND YB THRESHOLDS

Population	R^2 for 22°, +45% LC	R^2 for 22°, -45% LC	R^2 for 109°, +45% LC	R^2 for 109°, -45% LC	R^2 for 198°, +45% LC	R^2 for 198°, -45% LC	R^2 for 293°, +45% LC	R^2 for 293°, -45% LC
Overall	0.37	0.46	0.40	0.39	0.32	0.49	0.19	0.25
Normal	0.26	0.44	0.28	0.32	0.35	0.22	0.34	0.30
Deutan	0.20	0.36	0.44	0.29	0.04	0.39	0.05	0.39
Protan	0.01	0.10	0.01	0.03	0.25	0.04	0.05	0.00

Correlation coefficients for the overall population of subjects, and for normal trichromat, deutan and protan observers, for visual search times of the four colour directions and two luminance contrasts employed in experiment 4.3 versus CAD RG thresholds.

Population	R^2 for 22°, +45% LC	R^2 for 22°, -45% LC	R^2 for 109°, +45% LC	R^2 for 109°, -45% LC	R^2 for 198°, +45% LC	R^2 for 198°, -45% LC	R^2 for 293°, +45% LC	R^2 for 293°, -45% LC
Overall	0.35	0.31	0.15	0.24	0.19	0.22	0.21	0.11
Normal	0.25	0.35	0.19	0.22	0.28	0.17	0.27	0.29
Deutan	0.59	0.48	0.19	0.60	0.09	0.28	0.29	0.30
Protan	0.80	0.85	0.43	0.79	0.67	0.68	0.31	0.21

Correlation coefficients for the overall population of subjects, and for normal trichromat, deutan and protan observers, for visual search times of the four colour directions and two luminance contrasts employed in experiment 4.3 versus CAD YB thresholds.

6.12 APPENDIX M: CAD THRESHOLDS FOR SUBJECTS IN EXPERIMENT 4.3

Subject	CAD RG	CAD YB
AA	1.03	1.31
AW	1.44	1.46
BN	1.59	2.06
FW	1.43	1.68
GB	0.93	1.22
GC	1	0.98
JH	0.79	0.71
LC	1.05	1.28
MC	1.34	0.96
EL	1.14	1.08
EU	1.61	2.38
HGG	1	1.02
GJ	1.17	1.48
AH	1.1	1.14
DT	1.35	1.69
TB	1.3	2.5
SEH	1.05	1.37
IC	1.04	0.88
PH	1.03	1.41
BH	1.28	1.56
SBS	0.85	1.1
WB	0.67	0.67
AM	0.95	1.13

CAD thresholds for normal trichromats in experiment 4.3.

Subject	CAD RG	CAD YB
BY	6.09	1.15
IP	3.69	1.06
PB	21.52	1.02
RC	13.39	1.51
SH	5.69	1.02
RF	5.06	1.77
BB	2.96	0.84
CDM	3.15	1.14
RM	2.53	0.73
SS	18.37	1.65
DB	2.91	1.13
CB	2.18	1.01
CP	3.53	1.36
PM	7.47	0.82
SMM	20.87	2.33
SK	17.53	1.27
MH	7.08	0.95
JHU	11.95	1.05
MAL	9.58	1.18
AAL	8.41	1.16
EB	16.9	1.02

CAD thresholds for deutan observers in experiment 4.3.

Subject	CAD RG	CAD YB
SM	8.62	0.99
MJ	6.02	1
MG	17.85	0.8
NO	20.5	3.39
IA	7.7	1.18
WK	9.24	0.98
LK	19.81	0.75
AC	19.97	2.47
CR	19.76	1.01
JG	16.16	0.95
SW	23.74	1.95
JD	15.12	1.05

CAD thresholds for protan observers in experiment 4.3.

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