Defining Acceptable Colour Tolerances for Identity Branding in Natural Viewing Conditions

By

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Abstract

Graphic arts provide the channel for the reproduction of most brand communications. The reproduction tolerances in the graphic arts industry are based on standards that aim to produce visually acceptable outcomes. To communicate with their target audience brands, use a set of visual cues that may include the definition of a single or combinations of them to represent themselves. The outcomes are often defined entirely by their colour specification without an associating it to target parameters or suitable colour thresholds. This paper researches into the feasibility of defining colour tolerances for brand graphical representations. The National Health Service branding was used as a test case borne out of a need to resolve differences between contracted suppliers of brand graphics.

Psychophysical evaluation of colour coded navigation used to facilitate wayfinding in hospitals under the varying illuminances across the estate was found to have a maximum acceptable colour difference threshold of $5\Delta E_{00}$. The simulation of defined illumination levels in hospitals, between 25-3000 lux, resulted in an acceptable colour tolerance estimation for colour coded navigation of $3.6\Delta E_{00}$.

Using ICC media relative correction an experiment was designed to test the extent to which substrate white points could be corrected for colour differences between brand proofs and reproductions. Branded stationery and publications substrate corrections to achieve visual matches had acceptable colour difference thresholds of $9.5\Delta E^*_{ab}$ for solid colours but only $2.5\Delta E^*_{ab}$. Substrate white point corrections on displays were found to be approximately $12\Delta E^*_{ab}$ for solids and $5\Delta E^*_{ab}$ for tints.

Where display media were concerned the use of non-medical grade to view medical images and branded content was determined to be inefficient, unless suitable greyscale functions were employed. A STRESS test was carried out, for TC 1-93 Grey-scale Calculation for Self-Luminous Devices, to compare DICOM GSDF with Whittle's log brightness. Whittle's function was found to outperform DICOM GSDF. The colour difference formulas used in this research were tested, using near neutral samples judged by observers using estimated magnitude differences. The CIEDE2000 formula was found to outperform CIELAB despite unexpected outcomes when tested using displays. CIELAB was outperformed in ΔL* by CIEDE2000 for displays.

Overall it was found that identity branding colour reproduction was mostly suited to graphic arts tolerances however, to address specific communications, approved tolerances reflecting viewing environments would be the most efficient approach. The findings in this research highlights the need for brand visualisation to consider the adoption of a strategy that includes graphic arts approaches. This is the first time that the subject of defining how brands achieve tolerances for their targeted visual communications has been researched.

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This research was borne out of a smaller body of work for the NHS during my employment with the Department of Health. I took on the project on the suggestion of my manager Rosie Meredith who I thank for making sure I had all the support it required for me to get this far. I also thank the NHS brand managers and the Web team - especially Daniel O’Byrne, Francis Babayemi, Raj Mohindra, Andrew Pearce, and Rothna Dev Modak who participated in every psychophysical test I conducted. I owe an additional thanks to the graphic designers Jimmy Fang, Kate Summers, Ann Harezlak, Ken Chow, Jatinder Gill and Olivia Campbell. I was fortunate to have a few external brand managers namely Richie Woode, Charles Brown, and Paul Campbell, of Francisca Management, NHS Service Delivery and Back Rock respectively, participate in all psychophysics.

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I dedicate this to my Mum and Dad
(Robert Kwame Baah and Victoria Baah)

…….and my wife
(Donna Stephenson-Baah)

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Chapter 1 – Introduction

This chapter provides an introduction of the motivation behind the research, objectives, scope and a description of how the thesis is structured. The research uses a test case that generated the initial research question, and this is introduced in this chapter.

1.1. Motivation and objective

In identity branding the achievement of both consistency and uniformity of colour, across different media, is desirable (**Martenson 2007**). Brand colours are quite frequently reproduced on many types of media to satisfy a range of communication channels. Detailed in their visual identity or toolkit document will be all the different permutations of how the colours are to be used. Having defined each colour specification, the brand expects that the reproduction of any colour viewed in one condition will match another reproduced in an alternate medium. The real-world experience is such that anticipated brand colours are often not achieved for several reasons. Brand consultants employ the use of colour to strengthen visual associations with products and services to strengthen their existence in a consumer’s memory through the development of an associative memory network (**Aslam 2006**). This necessitates the need for suitable metrics of agreement in appraisal. For example, appraisal by a print purchaser would typically be conducted as a side by side comparison where printed samples are judged between proof and reproduction. The branding approval workflow however, introduces another level of appraisal where client engagement may also require additional judgment based on memory of the visual stimulus (**Singh et al 2012**). NHS staff uniforms are colour coded based on discipline and engagement levels as depicted in Figure 1, nurses uniform colours correspond to their roles. With multiple suppliers of such branded products brand managers would often judge their approval of supplies based on recalled memory matching. As such they are often influenced in their judgments by a preference for slightly saturated colours (**de Fez et al. 1998**). More recently as part of a digital first drive non- medical grade displays have been used to display branded information as well as medical images for clinicians. The requirements for medical grade image assessment is not likely being met by implementing general displays as part of such remote workflows.

Figure 1: NHS identity branded targets of stationery, male nurse uniform, and NHS building site uniform. Proof to production approval workflow will likely differ for each case. [Crown © copyright 2012].

In a bid to achieve unique identity branding, as depicted in Figure 1, the NHS has developed a guide that specifies colours to be used for developing all their communications by design companies and external suppliers. Their brand statement associates these colours with an expectation; “Our identity is important. It is largely formed by what we do - treating illness and promoting health. But our communications are important in forming our identity too” (**NHS Identity 2003**). This guide provides a series of colours for its branding across different media. What is not apparent is the acceptable representation of brand colour for the target media in its domain of use which is representative of a targeted appearance match. The process appears to be based entirely on non-correlated subjective assessments for output acceptance. This leads to changes in branding, in a bid to achieve a range of acceptable results across the defined media ranges and is continually evolving. The approach is to create an authentic characteristic appearance that presents a universal visual attraction which potentially leads to a level of trust and expectation. The question that arises from such frequent re-appraisal of identity branding is whether graphic arts standards and related research can address issues of brand colour consistency. Further to this all NHS clinical buildings are built and furnished per CIBSE (Chartered Institution of Building Services Engineers) lighting specifications that include designated lamps, location illumination levels, colour temperature and colour rendering indices for each domain. Whilst the specifications centre on the specific task requirements, they also attempt to inform design to embrace a balanced vertical surface luminance, spatial colour and architectural intent (**CIBSE SLL LG2 2008**).

In graphic arts, variants of colour appearance models can facilitate the prediction of changes in a colour across different viewing conditions for different media (**Luo 2002**) and, through managed transformations in reproduction, colour consistency is achievable. It is feasible however, for one media to have target viewing conditions that are variable for a single reproduction in identity branding. Others might even have mixed variations between target location and media. Thus, an overall assessment method is required to arrive at an acceptance metric.

In determining tolerances for identity branding that achieve perceived branding visual consistency as defined by an output and target environment, this research seeks to fulfil the following objectives:

- To determine the tolerances for colour reproduction across a range of media for identity branding together with factors that influence the judgement of colour appearance acceptance;
- To develop, by way of simulation, a feasible method that predicts acceptable colour reproduction appearance across media for target environments.
- To design a psychophysical approach for assessing colour reproduction for identity branding that includes the measurable parameters of the target viewing environment.
- To test findings by implementing the process in an organisation.

In the National Health Service (NHS) brand colour coding of internal and wayfinding signage is used to aid directions within hospitals and larger health clinic buildings. This consists of a primary corporate colour and a secondary print palette of 13 colours with 10 tints for each colour. Selections of colours used are intended to help people navigate NHS buildings easier and know when they have reached the room or department they are looking for.

Directional signs have to clearly indicate direction and safety signs have to comply with standards for safety colours. Wayfinding in the NHS is used to describe the process that people go through to find their way around any of the NHS environments. Additionally, the NHS wayfinding colours further classify the various medical specialties as colour coded locations (**NHS Identity 2008**). Each of these NHS environments conforms to the Chartered Institution of Building Services Engineers (CIBSE) Lighting Guide 02: Hospitals and Health Care Buildings. The guide illustrates varying ways of lighting the modern hospital environment and makes illumination recommendations in line with European Standards on lighting which, varies between 25-3000 lux. The exception is within theatre cavities' where illumination levels may far exceed 10,000 lux.

Hidayetoglu et al. (**2012**) considered that the successful use of colour and light positively affects wayfinding. The usefulness of the colour coded information, in facilitating easy navigation, depends on its colour appearance which in turn is influenced by changes in illumination levels. The extent to which visual perception of colour is impacted by illumination level changes can be a significant enough to result in perceived colour differences (**Nayatani 2007**). Nayatani (**2007**) found that high illumination increases the colour appearance of objects with low brightness and colourfulness. Consequently, they will be perceived to be brighter and more colourful than another object with higher brightness and colourfulness but under low illumination. Hunt (**1952**) found in his study of the effects of light and dark adaptation on colour perception that, as an object's illumination level increases its perceived colourfulness also increases. In another experiment by **Stevens and Stevens** (**1963**), in which observers estimated the magnitude of stimuli brightness across different adapting conditions, it was shown that increased illumination enhanced lightness contrast. Light colours appeared lighter and dark colours darker thus increasing perceived contrast. More recently Ishida (**2002**) examined observer efficiency in searching for pre-named colours from sample sets under illumination levels of 0.1 – 1000 lux. Each observer had to locate and evaluate each sample based on colour identification data. It was found that the performance of the observers declined with decreasing illumination. At 1 lux observer judgement errors occurred between orange and pink as well as green and blue with high frequency. Based on previous experiments illumination at 1 lux would be expected to result in colourfulness and perceived contrast being significantly reduced.

Real world judgements of colour reproductions in end-use environments inevitably involve illumination levels different to that specified for production. Therefore, it may be useful to consider modifying the appearance of colour stimuli depending on purpose (**Favre and November 1979**). End-use viewing environments can be expected to change colour perception and as such possibly lead to differing visual interpretations (**Choi et al. 2010**). Product and company branding are such instances where colour perception is of critical importance and may require such modification to preserve colour appearance. Different levels of illumination have been shown in the research of Hunt (**1952**), Stevens and Stevens (**1963**), Ishida (**2002**) and Nayatani (**2007**) to have impact on observer perception and location of colour. In this research the perceived colour differences, under illumination levels of 25 – 3000 lux, for visitor navigation wayfinding in NHS hospitals and clinics are determined.

1.2. Scope

The fundamental concept behind this research was the science of the human visual system which encounters a series of phenomena as an interaction with colour reproduction. Such interactions lead to the challenges described in this introduction. These challenges are because of the changing configurations between media, illuminant, and environment conditions that colour science seeks to model and simulate in reproduction assessment:

- ISO 3664:2009 *Graphic technology and photography - Viewing conditions* provides the baseline for all target stimulus environments for which parameters are scaled to reflect criterion of change;
- Psychophysical assessment techniques are an extension of original work developed by Johnson and Green (**1999**);
- The research outcome is focused on tolerance for uniform colour as employed in identity branding as part of a visual identity.

The determination of whether colour tolerance in graphic arts is entirely suited to what is considered acceptable for identity branding, or not, should provide a pathway to modelling a workflow that performs well for branding. Additionally, the viewing configurations must consider targeted environments of the productions if the achievement of a suitable proof-to-production appraisal is to be established. In all cases the baseline of defining appraisal, media properties or viewing configuration is anchored on a series of ISO standards for graphic arts technology.

1.3. Contributions

The context of this research has resulted in the following contributions:

1. **Perceived acceptability of colour matching for changing substrate white point.**
Baah, K., Green, P.J., Pointer, M., (2013) Proc. SPIE 8652, Color Imaging XVIII: Displaying, Processing, Hardcopy, and Applications, 86520Q, © (2013) COPYRIGHT Society of Photo-Optical Instrumentation Engineers (SPIE).;

2. **White point adaptation issues in colour management.**
Green, P.J., Baah, K., (2012) China Academic Conference on Printing and Packaging, China Printing and Packaging Study. vol. 4 (6).

3. **Colour perception with changes in levels of illumination.**
Baah, K., Green, P.J., Pointer, M., (2012) Proc. SPIE 8292, Color Imaging XVII: Displaying, Processing, Hardcopy, and Applications, 829207. © (2012) COPYRIGHT Society of Photo-Optical Instrumentation Engineers (SPIE).

4. **Psychophysical evaluation of grey scale functions performance**
Baah, K., Green, P.J., Pointer, M., and Carter, R., (2016) Results to enhance confidence in the recommended self-luminous neutral-scale calculation in TC 1-93: Calculation of self-luminous neutral scale, CIE © CIE 2000 - 2017 | Babenbergerstraße 9/9A, A-1010 Vienna, Austria.

1.4. Thesis Outline

Chapter 2 introduces some fundamental concepts of colour science and techniques for managing colour to produce consistency in reproduction, namely human colour vision, colorimetry, colour difference, colour management and viewing conditions. In Chapter 2a branding is defined in general terms and a description of the specific parameters that use colour as a cue is presented. The NHS brand is used as a test case in this research, so the manner in which they use their brand colour to communicate, which necessitates consistency, is described. The chapter explains how branding uses colour to generate variable responses from customers, and how it relates to colour tolerance. Subsequently, the chapter explains the NHS use of colour specifications to illicit customer interaction with their identity through brand colour. Chapter 3 defines methods for determining colour tolerance in relation to this research based of configuration of stimuli, detection of quality and how best to solicit useful judgments from observers. This is the main subject of this research, which is colour tolerance for the reproduction of brand colours. The chapter introduces well known techniques for determining colour tolerance, methods designed to test the efficiency of such techniques, and statistical methods used to estimate tolerance efficiencies from acquired data. The discipline of psychophysics provides the techniques for testing observer responses to colour judgements. In this research category judgement and estimation magnitude scaling, discussed in this chapter, are the main psychophysical methods employed. Chapter 4 is a summary that explains why specific experiments in this research has been carried out, by outlining the areas of identity branding engagement that result in possible colour tolerance departure from graphics arts. Chapters 6-9 present all the experiments that test configurations of colour, media and illuminants to arrive at a suitable model for assessing identity branding colour tolerance. Chapter 10 summarises the results from the experiments and discusses what future work might prove useful. The conclusions are presented in chapter 11 and the references for this research and a glossary follow on in sequence. The key datasets produced by the various experiments are included as appendices in the final sections.

Chapter 2 - Theory and literature survey

This chapter introduces the concept of colour, factors that influences its appearance and calculating colour differences. The second half of the chapter describes how colour is managed in a generic workflow. This considers parameters for reproducing colour and appraising the output media.

2.1 Background and related work

The graphical representation of brand identity that uses colour to create associations relies on connections that individuals make, mostly for events that occur in a given environment (**Shimp 1991**). This research considers the metrics of perception and acceptance of such associations in response to brand colours. Human physiological and psychological responses to colour have been well researched and findings that interlink the representation of colour and responses provide the foundations of making this study possible. However, it is important to be aware that, when there is a perception of brands sharing the same colour, consumers will often develop a secondary cue of association. This is because of colour specific context (**CIE 15:2004**), so the perceived acceptable tolerance is not a standalone cue of recognition.

2.2 Visual stimulus

The colour properties of objects are not fixed but rather a sensation of their perceived visual stimulus. Colour results from an interaction between light and materials or objects to arrive at a relational eye-brain combination outcome (**CIE 15:2004**). This perception is a function of light falling on the eye, physiological factors and psychological biases. The spectral characteristics for reflected or emitted radiance can be equated to quantities derived from their measurements. Subsequently, changes in any of these factors will lead to perceived differences in colour. Light is electromagnetic radiation for which wavelengths vary between 380-780nm that can be detected by the human visual system (**CIE 1987**). The colours perceived along the different electromagnetic wavelengths fall into broadly described intervals of blue, green and red regions shown in Figure 2.

Figure 2: Electromagnetic wavelengths showing regions of visible colours.

These regions are considered to approximately correlate to the three kinds of cones, Figure 3, in the human visual system and can further be described by their spectral power distribution (SPD) and a set of weighting functions for each of the three receptors. This concept has led to the colour-matching functions which can be used for the calculation of the tristimulus values of the different spectral compositions of a colour.

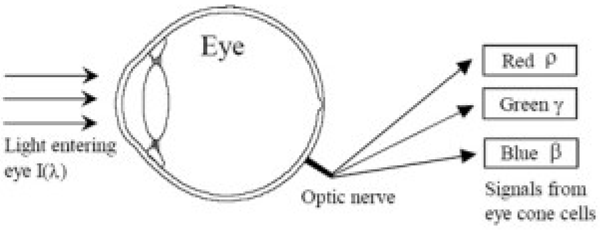

Figure 3: Representation of the 3 types of receptors.

Where a pair of colours has equal tristimulus values it indicates that the colour appearances of the two colours match, under the same viewing conditions. Alternatively, if the pair visually match but have different spectral compositions they are considered to be a metameric match, and this forms the basis for nearly all commercial colour image reproduction.

In 1931, the Commission Internationale de L'Eclairage – the International Commission on Illumination (CIE) agreed the basis of establishing a set of functions that were the description of human colour vision as a set of numerical values. These functions were derived from the mean results of visual experiments separately carried out by W.D. Wright (1928-9) and J. Guild (1931). The human colour perception in these functions are described by the three sets of cone-response related values **(Schanda 2007**). CIE colorimetry seeks to determine the extent to which a test colour stimulus matches a reference stimulus and by no means attempts to describe what an observer sees but rather model the human perception of colour. Consideration of the visual field led to the 1931 Standard Colorimetric Observer and later, the 1964 Standard Colorimetric Observer (**Stiles and Burch 1959**) for defining the matching functions for the discrimination of colour samples subtending to 2° **(**$\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$**)** in Figure 4 and 10° **(**$\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$**)** respectively (**CIE 1986**). Variations in the visual field of the retina were found to reduce discrimination for a 2° field when the field size changed beyond 4°, so the 1964 model was developed. It was considered that detail in vision extended over a visual angle of only 2° in the centre of the visual field. In the colour-matching functions the combined perceived luminance, represented by the $\bar{y}(\lambda)$ wavelength function, is a linear transformation of the cone characteristics and their actual responses. The $\bar{y}_{10}(\lambda)$ for the 10° field however, has no photometric significance as exists in 2° fields (**Hunt 1998**). "The colour matching functions are the curves that represent the amounts of R, G and B that is required to match a constant amount of power for each minimal wavelength interval at each wavelength spectrum" (**Hunt 1998**).

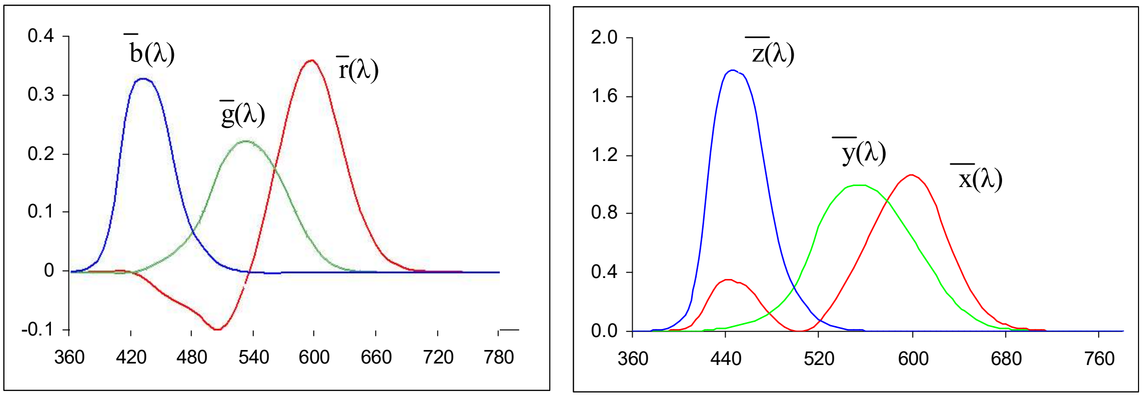

Figure 4: Spectral tristimulus values for CIE RGB monochromatic primaries is on the left and the negative part of the curves indicate a matching of those spectral colours requiring only R and G amounts. The CIE 1931 standard colorimetric observer matching functions are on the right. The CIEXYZ 1931 model was developed to eliminate negative values and adopt the CIE 1924 photopic luminous efficiency function $V(\lambda)$.

Tristimulus values for red, green, and blue were considered by the CIE to be unsuitable for creating a standardized colour model. Therefore, the CIE developed a mathematical formula to convert existing RGB data to a system resulting in only positive integer values. The reformulated tristimulus values were denoted as XYZ and quantify the trichromatic characteristics of colour stimuli as approximations of red, green, and blue. The Y tristimulus, a luminance value, is equal to the curve that represents the total power of a light source and for any given Y value. Therefore, the XZ plane will contain all possible chromaticities at that luminance. The CIEXYZ values for an object is characterised by either its spectral reflectance or transmittance and illumination of a light source. The light source itself is characterised by its spectral distribution which is the relative proportion of radiant power at each different wavelength in that light. The summation of the products of the distributions of the spectral power, reflectance and colour matching functions over the visible wavelengths 380nm to 780nm is sued to calculate X, Y and Z values of an object.

$$X = k\sum_{780}^{380} S(\lambda)R(\lambda)\bar{x}(\lambda) \qquad Y = k\sum_{780}^{380} S(\lambda)R(\lambda)\bar{y}(\lambda) \qquad Z = k\sum_{780}^{380} S(\lambda)R(\lambda)\bar{z}(\lambda)$$

The X, Y and Z values are the CIE tristimulus values; $S(\lambda)$ is the spectral power distribution of the illumination source; $R(\lambda)$ is the spectral reflectance or transmittance of the object and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$and $\bar{z}(\lambda)$ are the CIE 2° Observer colour matching functions, all depicted in Figure 5. A normalising factor k is applied and set to keep Y = 100 when a perfect diffuser is assumed as the object.

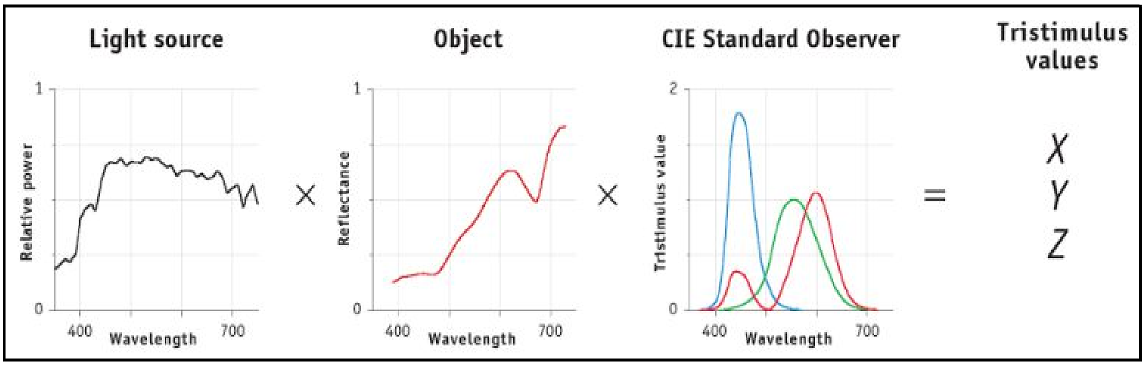

Figure 5: Image showing the spectral distribution of an illuminant, the spectral reflectance of an object and the CIE 2˚ Observer colour matching functions. The summation of the products these distributions over the visible wavelengths of 380-780nm is used to calculate the CIEXYZ.

A generalised approach for calculating the $CIERGB$ tristimulus values of a stimulus with the spectral power of distribution $\phi(\lambda)$ is given as;

$$R = \int_{\lambda} \phi(\lambda)\bar{r}(\lambda)d\lambda \qquad G = \int_{\lambda} \phi(\lambda)\bar{g}(\lambda)d\lambda \qquad B = \int_{\lambda} \phi(\lambda)\bar{b}(\lambda)d\lambda \qquad (1)$$

Where $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, and $\bar{b}(\lambda)$ are the matching functions represented on the left in Figure 5. $CIEXYZ$ colour-matching functions are similar to that of $CIERGB$ except for the use of a normalising constant employed in the XYZ model (**Fairchild 2005**).

$CIEXYZ$:

$$X = k\int_{\lambda} \phi(\lambda)\bar{x}(\lambda)d\lambda \qquad Y = k\int_{\lambda} \phi(\lambda)\bar{y}(\lambda)d\lambda \qquad Z = k\int_{\lambda} \phi(\lambda)\bar{z}(\lambda)d\lambda \qquad (2)$$

In graphic arts and other colour reproduction industries, CIE XYZ colorimetry is in some instances used for normalising tristimulus values to substrate white and not the perfect reflecting diffuser (**Fairchild 2005**). This allows the substrate to assume a Y value of 100 to preserve it as the lightest colour in an image when transformations between different substrates are required. In colour management media-relative colorimetry in colour reproduction helps to maintain target colour detail despite differences between original and reproduction media (**ICC.1:2010**).

$$\begin{bmatrix} X_{rel} \\ Y_{rel} \\ Z_{rel} \end{bmatrix} \begin{bmatrix} X_{illum}/X_{mw} & 0 & 0 \\ 0 & Y_{illum}/Y_{mw} & 0 \\ 0 & 0 & Z_{illum}/Z_{mw} \end{bmatrix} \begin{bmatrix} X_{abs} \\ Y_{abs} \\ Z_{abs} \end{bmatrix} \qquad (3)$$

The $X_{\mathrm{abs}}Y_{\mathrm{abs}}Z_{\mathrm{abs}}$ produced by the output device is normalised by the media white point to the perfect reflecting diffuser defined white point for which $X_{\mathrm{w}}Y_{\mathrm{w}}Z_{\mathrm{w}}$ correspond to the illuminant in the workflow, and $X_{\mathrm{mw}}Y_{\mathrm{mw}}Z_{\mathrm{mw}}$ the media white point. From this point all subsequent retargeting is performed using these media relative colours (**Theodoridis and Chellappa 2013**).

2.2.1 Luminance

Luminance is the amount of visible light leaving a point on a surface in a given direction that passes through or is emitted at a given solid angle (**Tarrant 2002**). The CIE defines luminance as the integrated radiance of a source denoted as:

$$L_v = k_m \int_{360nm}^{830nm} L_{e,\lambda} V(\lambda) d(\lambda) \qquad (4)$$

$L_{e,\lambda}$ is weighted by the spectral luminosity $V(\lambda)$ of the CIE Standard Observer, $d\lambda$ represents the perfect diffuser, k_m is a constant of 683 lm/W known as the maximum spectral luminous efficacy for photopic vision and is calculated as 683 x V(555.000 nm)/V(555.016 nm) = 683.002 lm/W (**Bass 2010**). “The value of k_m is given by the 1979 definition of candela that defines the spectral luminous efficacy of light to be 683 lm/W at the wavelength 555.016 nm.”

A measure of luminance is expressed as candela per square metre which is abbreviated as cd/m^2 and, for example, most walls in household rooms have luminance values between 30-100cd/m^2. The amount of light falling on a unit area of a surface is the illuminance, measured in lux $E = \lim_{s \to 0} F / s$ where *E* is illuminance produced by luminous flux of one lumen on a square metre of an area. Colour discrimination is significantly influenced by the level of luminance (**Pridmore and Melgosa 2005**) and as luminance increases the detection of colour difference increases up to a point. Where colour targets are presented as luminance increments relative to a background luminance, the scaling relationship between the luminances is a power function referred to as Stevens' Law (**Nundy and Purves 2002**). Stevens’ power law is a proposed relationship between the magnitude of a physical stimulus and its perceived intensity. Conversely Brown (**1951**) showed that as luminance decreased the chromaticity reduces and as such their corresponding tolerance ellipses grew larger, indicating depreciation in discrimination. Hurvich and Jameson (**1957**) determined that the processing of colour and luminance contrasts in the human visual system was consistent with second stage mechanisms that were opponent colour cone inputs of red-green, blue-yellow and an additive achromatic process.

In the human visual system, the rods and cones are essential for the visual function of the eye for which the rods serve vision at low luminance levels whereas the cones serve vision at higher luminance level (**Fairchild 2005**). The fovea is an area of the retina where images formed by the eye lens are centred and the fovea is also the area where there is the highest level of spatial resolution and colour vision sensitivity. The rods and cones perform separate functions with differing spectral sensitivities. There is a transition between rod and cone vision that allows the visual system to work across a wide range of luminance levels. Only one type of rod exists in the human eye and the rods are responsible for light and dark vision, referred to as scotopic vision. The photosensitive pigment in the rods is continuously created which compensates for the fact that it is destroyed by photo bleaching under normal daylight conditions and other high levels of illumination – thus only small amounts are present in such conditions. Figure 6 is a pictorial representation of the impact of luminance and illumination on colour vision acuity.

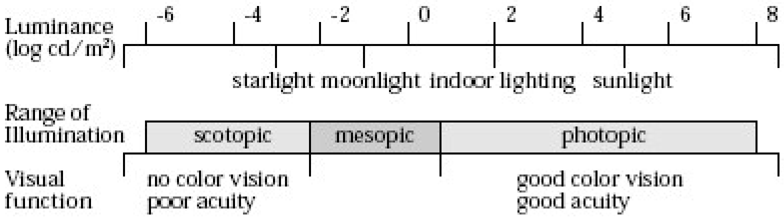

Figure 6: Effect of luminance on colour vision acuity in natural conditions **(Ferwerda 1996**).

2.2.2 Colour appearance phenomena

For the average observer two colour stimuli with identical CIE XYZ tristimulus values will match in appearance where factors such as surrounds, backgrounds, object surface properties, size, shape, along with retinal area of stimulation, luminance level and subtending angle are the same. However, in practical situations the influence of viewing conditions must be considered in order to appreciate the appearance of a colour stimuli. These phenomena underpin the definition of colour appearance for most practical situations. The changes that occur to the surround, luminance level, illumination colour and cognitive responses/interpretation that influence the appearance of a stimulus result in the various phenomena that are considered to be "breaking" the simple XYZ tristimulus colour system (**Fairchild 2005**).

Such phenomena include:

- simultaneous contrast, crispening and spreading that are related directly to colour stimuli spatial structure;
- a change in the hue when a change in luminance occurs;
- changes in hue with colorimetric purity;
- brightness dependency on luminance and chromaticity;
- colourfulness increasing with luminance;
- increasing of contrast with luminance;
- changes in image contrast with changes in the surround;
- discounting the illuminant;

The perceived colour of an object has a direct relation to its spatial structure so if the background of the object is changed a shift in colour appearance will occur. This is referred to as the simultaneous contrast phenomenon, a colour shift which follows the theory of opponent colour (**Albers 1963**). Subsequently a pair of similar colour stimuli will appear to have a different magnitude of colour difference with different backgrounds, an effect known as crispening (**Semmelroth 1970**). If the spatial frequency of stimuli is increased, the impact of simultaneous contrast will be replaced by spreading where there is an apparent mixing of the colour stimuli with its surround; billboard posters (halftone) are often produced with this sort of spatial frequency so that the dots cannot be resolved at a typical viewing distance.

When the level of luminance is increased, the perceived colourfulness of the stimuli becomes more apparent (**Hunt 1952**), a phenomenon referred to as the Hunt effect. Similarly, the same condition of increased luminance results in a greater perception of contrast increase, often referred to as the Stevens effect (**Stevens and Stevens 1963**). The Bezold-Brücke hue shift phenomena indicates that there is a perceived shift in hue observed for stimuli when luminance changes. However, Hunt (**1989**) highlighted that this is not the case for related colours – colour seen in relation to their surround, as is the case for most surface colours. Further to this effect of hue shift from a change in luminance, a mixing of monochromatic light with white light will also cause a hue change known as the Abney effect. This mixture alters the colorimetric purity and causes the appearance of hue shift (**Robertson 1970**). Perception of brightness is best confirmed by the phenomenon known as the Helmholtz-Kohlrausch which indicates that this depends on luminance and chromaticity. This effect identifies perceived brightness to become more apparent when a stimulus becomes more chromatic at constant luminance.

The background of a colour stimulus will also influence the colour perceived if the surround changed from dark to dim to light. Bartleson and Breneman (**1967**), from their experiment results in testing image contrast changes with surround, determined that with a dark surround dark colours appeared lighter. The impact of different surrounds is present for television images that are typically viewed with a dim surround, photographic prints with a light surround and transparencies with a dark surround. The visual system will also allow an observer to interpret colour stimuli independent of an illuminant. This phenomenon is referred to as discounting-the-illuminant and is of importance where comparisons are being made across different media.

2.2.3 Chromatic induction

Chromatic induction occurs when a visual stimulus influences the perceived colour of another stimulus within the same visual field (**Krauskopf et al. 1986**). For the subject of this study, this is consistent with a colour presented on a chromatic background; typical with brand logo representation. The foreground colour stimulus appears to be tinged with its complementary colour. Krauskopf et al. (**1986**) considered induction as implying that the effects of a stimulus falling on one part of the retina are modified by stimuli falling on another part of the retina at some level in the visual system. The extent of colour induction (**Kinney 1962**) increases relative to the inducing field, the luminance ratio between the inducing and the induced fields and to some extent relational to the purity of the inducing colour. Alternative to this type of chromatic induction, which is simultaneous contrast, there is chromatic assimilation where a colour shifts its perceived colour appearance towards that of a nearby source of light. This type of induction is considered to include wavelength independent spread light, wavelength-dependent chromatic aberration and neural summation (**Cao and Shevell 2005**).

2.2.4 Adaptation and adoption

Adaptation describes the processes where the visual system adjusts its operating properties in response to changes in the environment (**Clifford 2007**). The immediate visual response to a continuous stimulus is not the same several seconds thereafter. In resolving colour, the human visual system adapts to conditions within the viewing environment. This is a process for the visual system to alter its sensitivity to a colour stimulus in response to changing conditions of stimulation (**Fairchild 2005**). When describing how luminance impacted visual acuity it was highlighted in Figure 5 that three categories existed namely, scotopic, mesopic and photopic. Scotopic is vision in dark conditions where rod vision is predominant from about 0.01 cd/m^2, less than 1 lux, which evokes dark adaptation. The little cone activity there is at this state is non-existent once luminance reaches 0.001 cd/m^2 and colour vision is gone. Photopic vision evokes light adaptation where cone photoreceptors are most dominant. This occurs at approximate luminances of 3 cd/m^2 and higher. This type of vision results in the majority of trichromatic colour perception. Mesopic vision is a transition between light and dark adaptation. Dark adaptation is a change in visual sensitivity when a current state of illumination level is significantly reduced (**Aubert 1865**) as would be the case when illumination is reduced from 500 lux to below 1 lux (**Boiko et al. 2006, Brown and Braley 2011**). Figure 7 is a depiction of dark adaptation as a function of log intensity and time in the dark.

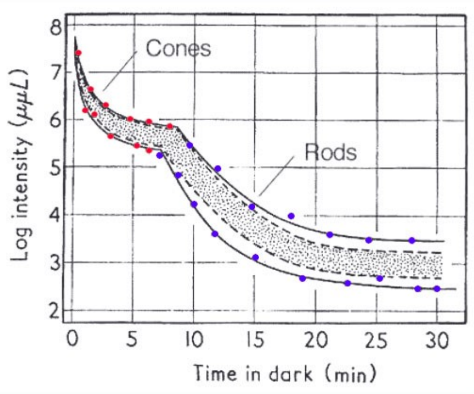

Figure 7: Dark adaptation curve. The shaded area represents 80% of the group of subjects. Hecht and Mandelbaum’s data from From Pirenne M. H., Dark Adaptation and Night Vision. Chapter 5. In: Davson, H. (ed), The Eye, vol 2. London, Academic Press, 1962.

The visual system then adjusts to become more sensitive to accommodate the lack of illumination as would occur when an observer moves from a well-lit room into a dark one. In dark adaptation there are two stages (**Hecht et al 1937**) of adjustments as a result of the engagement of both rods and cones. First there is a rapid cone adaptation lasting about 2 minutes (**Fairchild and Reniff 2005**) which is then followed by rod adaptation with a significantly longer duration of change over a duration of about 30 minutes (**Hecht et al 1937**). The colour of the illuminant in the viewing environment and the retinal coverage determines the maximum intensity range covered by the rods and cones. The reverse of dark adaptation leads to light adaptation but with different visual functional changes shown in Figure 8. Light adaptation requires the visual system to become less sensitive in order to produce useful perceptions in an environment with higher level of illumination. The process of adaptation is reversed and takes about 5 minutes.

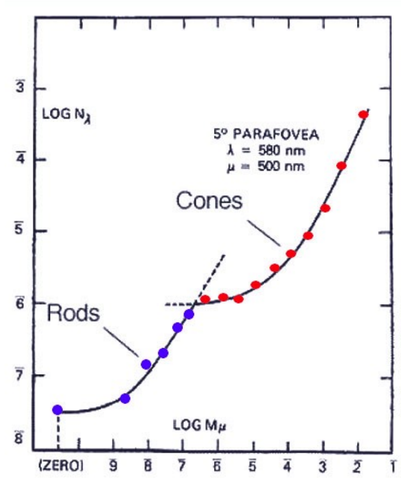

Figure 8: Light adaptation curve plotted as increment threshold versus background luminance. The plot shows increment threshold (N_λ) and background luminance (M_μ). Light of two different wavelengths are used in this case (580 nm for the test and 500 nm for the background). Stiles’ data from Davson (Davson’s Physiology of the Eye, 5th ed. London: Macmillan Academic and Professional Ltd, 1990).

The inability to perceive the presence of stars in the sky during a clear summer day, despite the fact that they are present, typifies light adaptation. The high level of luminance induces a reduction in visual sensitivity to their presence. Various colour appearance models account for these various adaptations because they do have a profound effect on colour vision and hence colour appearance.

Work by Helson and Grove (**1947**), Helson, Judd and Warren (**1952**) and Hunt (**1952**) has shown that numerous pairs of colours that look alike when viewed by eyes adapted to different kinds of light can be elaborated by the law of coefficients proposed by Von Kries (**MacAdam 1970**) to account for such results. This is referred to as chromatic adaptation which occurs when the visual system discounts a change in illumination source to preserve the appearance of colour stimuli. This type of adaptation is very critical to colour appearance models because of the preservation of perceived colours with changes to illumination. Images viewed on a CRT monitor will have a bias towards blue and thus cause white areas to have a blue tinge. The viewer will partially adapt to this and perceive the white as being whiter than blue. However, this same image will be perceived to have the same white colour when the image is reproduced on different media where the illuminant differs (**Henley and Fairchild 2000**). Chromatic adaptation is essential to developing colour appearance models and in cross-media reproductions. Transformation models are used to predict how adaptation acts on cone response signals. Recent chromatic adaptation models are related to the von Kries model which describes a relationship between an illuminant and visual sensitivity in compensating for the illumination change based on scaling of the cone responses (**Süsstrunk et al 2001**). Fairchild’s modern interpretation of the von Kries hypothesis of a chromatic adaptation model is as follows (**Fairchild 2005**).

$$L_{adapt} = k_L L \quad (5) \qquad M_{adapt} = k_M M \quad (6) \qquad S_{adapt} = k_S S \quad (7)$$

L_{adapt}, M_{adapt} and S_{adapt} are the cone signals after adaptation, k_L, k_M and k_S are initial cone signals coefficients scaling factors and *L*, *M* and *S* the initial cone signals. This can also be described as a matrix:

$$\begin{vmatrix} L_{adapt} \\ M_{adapt} \\ S_{adapt} \end{vmatrix} = \begin{matrix} k_L L & 0 & 0 \\ 0 & k_M M & 0 \\ 0 & 0 & k_S S \end{matrix} \begin{vmatrix} L \\ M \\ S \end{vmatrix} \qquad (8)$$

In imaging systems chromatic adaptation transforms provide a pathway to map the appearance of an image defined in terms of its colorimetry to the corresponding colorimetry under any different illuminant.

2.3 Colorimetry

In graphic arts, quantifying the surface colour of a substrate and establishing an appropriate tolerance level, supported by visual judgements, is highly desired. There is also an expectation that the resulting colour can be consistently reproduced across various media for specified target conditions. For this reason, reproduction, measurement and assessment of colour must have a reasonable correlation to visual perception (**Billmeyer 1988**). Using colorimetry provides the ability to measure colour that is reflective, emissive or transmitted in order that the question of matching between a test and reference colour can be determined (**Rich 2002**). Through the development of models of colour appearance, it has also become possible to describe colour in terms of a viewing condition and determine differences that reflect visually perceived changes.

From the CIE 1931 XYZ tristimulus a two-dimensional chromaticity diagram can be derived. The diagram itself represents colour perception by the CIE standard observer in terms of *x* and *y,* or can be represented with a luminance factor *Y* to result in *xyY*. The chromaticity coordinates of the spectral colours are distributed around the edge of the diagram.

The chromaticity coordinates are calculated by:

$$x = \frac{X}{(X+Y+Z)} \quad y = \frac{Y}{(X+Y+Z)} \quad z = \frac{Z}{(X+Y+Z)} \qquad (9)$$

where $x + y + z = 1$

The tristimulus values and two-dimensional chromaticity diagrams however, do not address the representation of perceptual uniformity that would show a useful correlation of colour attributes with regards to proportionally perceived differences between two colours. In an attempt to correct for perceptual uniformity a new chromaticity diagram was developed with defined axes (**Hunt 1987**):

$$u' = 4X/(X+15Y+3Z) \; ; \; v' = 9Y/(X+15Y+3Z) \qquad (10)$$

Where there is an interest in the discriminability of colours it is useful to use this diagram to show the relationship between them. However, as chromaticity diagrams in themselves only show proportions of tristimulus values they are applicable only to colours with the same luminance. To account for the luminance, factor the CIE recommended the use of the 1976 L*u*v* colour space (CIELUV) or the 1976 CIE L*a*b* (CIELAB) colour space. Both are reasonably uniform colour spaces that also take into account the tristimulus values of the reference white which could either be a perfect diffuser or defined by the media white (transmissive or reflective), using the guidance of ISO 13655. CIE L*u*v* and CIE L*a*b* colour spaces are defined as follows:

$$L^* = 116\, f(Y/Y_n) - 16$$

$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

Where

$$f(X/X_n) = (X/X_n)^{1/3} \qquad \text{if } (X/X_n) > (6/29)^3$$

$$f(X/X_n) = (841/108)\ (X/X_n) + 4/29 \qquad \text{if } (X/X_n) \le (6/29)^3$$

CIE 1976 u, v saturation $$s_{uv} = 13[(u' - u'_n)^2 + (v' - v'_n)^2]^{1/2} \tag{11}$$

CIE 1976 u, v chroma $$\Delta C^*_{uv} = (u^{*2} + v^{*2})^{1/2} = L^* s_{uv}$$

CIE 1976 u, v hue angle $$h_{uv} = arctan[(v' - v'_n)/(u' - u'_n)] = arctan(v^*/u^*)$$

Where L* represents approximation of lightness correlation, u* redness-greenness, v* yellowness-blueness, C^*_{uv} the chroma, h_{uv} hue, with u'_n and v'_n the reference white. The notation Y, u', v' describes the colour stimulus considered for which $Y_n, u'_n\ and\ v'_n$ is the reference white.

$$L^* = 116\, f(Y/Y_n) - 16$$

$$a^* = 500[f(X/X_n) - f(Y/Y_n)]$$

$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$$

where $$f(X/X_n) = (X/X_n)^{1/3} \qquad \text{if } (X/X_n) > (6/29)^3$$

$$f(X/X_n) = (841/108)\ (X/X_n) + 4/29 \qquad \text{if } (X/X_n) \le (6/29)^3$$

and $f(Y/Y_n) = (Y/Y_n)^{1/3}$ if $(Y/Y_n) > (6/29)^3$

$f(Y/Y_n) = (841/108)\ (Y/Y_n) + 4/29$ if $(Y/Y_n) \leq (6/29)^3$

and $f(Z/Z_n) = (Z/Z_n)^{1/3}$ if $(Z/Z_n) > (6/29)^3$

$f(Z/Z_n) = (841/108)\ (Z/Z_n) + 4/29$ if $(Z/Z_n) \leq (6/29)^3$

CIE 1976 a, b chroma $\Delta C^*_{ab} = (a^{*2} + b^{*2})^{1/2}$ (12)

CIE 1976 a, b hue angle $h_{ab} = arctan(b^*/a^*)$

Where L^* represents approximate correlate of lightness, a^* redness-greenness, b^* approximate yellowness-blueness, ΔC^*_{ab} the 1976 a, b chroma, h_{ab} hue angle. The notation X, Y, Z describes the colour stimulus considered for which X_n, Y_n and Z_n is the reference white.

The perceptual attributes that are predicted by CIELUV and CIELAB above can be defined (**Fairchild 2005 and Hunt 1995**) as:

- **Lightness** is the brightness of a colour relative to the brightness of the reference white (with brightness being the attribute of visual perception according to which an area appears to transmit more or less light);
- **Hue** is the attribute of a visual perception according to which an area appears to be similar to one, or to proportions of two, of the perceived colours red, yellow, green and blue.
- **Chroma** is the colourfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or clearly transmitting.

- **Saturation** is the colourfulness of an area judged in proportion to its brightness.
- **Colourfulness** is the attribute of a visual perception according to which an area appears to exhibit more or less of its hue.

Uniform colour spaces are intended to apply to object colours of similar dimensions that are viewed in identical white to mid-grey surroundings (**Hunt 1998**) where the observer is photopically adapted to a field of chromaticity close to average “daylight”. CIE colour spaces are independent of any device and do not depend on any particular input or output such as a scanner, camera, monitor, printer or transparency. CIELUV colour space is best suited for use in applications where additive colour mixing is required and also for the lighting, television and display industries. CIELAB on the other hand is currently used by the colorant and graphic arts industries as well as for other applications of subtractive mixing like the surface colour industries. A key difference between these two colour spaces is that CIELAB has no real association with the chromaticity diagram and saturation is not defined due to the non–linear nature of the formula defining a* and b*.

2.3.1 Colour Appearance

For a given colour stimulus its appearance will depend on the context in which it is seen and not its physical properties (**Luo 2002**). CIEXYZ accounts only for the quantities derived from the physical properties of the stimulus, so in order to derive the perceptual attributes of the stimulus, and account for the impact of the contextual viewing environment, a colour appearance model is required. The models themselves can be grouped into two steps where initially there is a chromatic adaptation transform to account for the chromatic adaptation of an observer to the viewing condition where a stimulus is presented and secondly the colour appearance attributes of lightness, chroma, hue, brightness, saturation and colourfulness are defined. Memory has also been considered to influence colour appearance (**Hansen et al 2006 and Olkkonen et al 2008**). This typifies the colour as an integral and expected property of an object due to past experience (**Bartleson 1960**) therefore modulating the colour appearance of the objects' actual colour through psychological bias. The effect creates strong object associations with a typical colour based on a level of familiarity.

2.3.2 Colour difference

An estimation of magnitude for the perceived difference between two colours under a specified viewing condition (**CIE2007**) is commonly required in many practical situations concerning colour reproduction. CIE colorimetry and its progressive developments provide quantitative methods for expressing such differences by Euclidean distances. The results correlate closely to human visual judgments but differing requirements for different industries led to several colour-difference formulas being developed. CIELAB and CIELUV colour-difference formulas, 1976 Uniform Colour Spaces, can be used to represent the difference between two colours as the Euclidean distance between their coordinates. However, in both colour spaces there is a significant level of perceptual non-uniformity which renders it unsuitable for a number of applications where a single value is required to define colour tolerance throughout it. These two colour spaces are still widely used successfully for many instances and most advanced versions of colour-difference formulas are based on the transformation of CIELAB coordinates (**Green 2002**). The terms of expressing the formulas are CIELAB ΔE^*_{ab} and CIELUV ΔE^*_{uv} for which differences can calculated for each predictive attribute namely lightness, chroma, hue, and so on thus denoted as:

$$\Delta E^*_{ab} = [\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}]^{½} \quad (13)$$

$$\Delta E^*_{uv} = [\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2}]^{½}$$

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta C^*_{ab})^2 + (\Delta H_{ab})^2]^{½}$$

$\Delta H_{ab} = [(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*_{ab})^2]^{½}$ an alternative method for calculating the hue difference:

$\Delta H_{ab} = 2\sqrt{C^*_{ab,r} C^*_{ab,s}} \sin\left(\frac{\Delta h_{ab}}{2}\right)$ where subscripts r and s are the reference and sample.

Despite the intention of the colour spaces to have colour differences that were perceptually uniform throughout this does not really exist. A colour difference of ΔE^{*}_{ab} 1.0 for a pair of red stimuli would for example, be perceived to be equal in magnitude of estimation to that of a pair of grey stimuli with the same ΔE^{*}_{ab} 1.0 but this is not the case. It is important to note that viewing conditions and media surface characteristics are not accounted for and these aspects could impact the capability of quantifying differences suitably. In situations where tolerance factors are required for a magnitude of acceptability it has been found that the perceptual components of ΔL^{*}, ΔC^{*}_{ab} and ΔH_{ab} colour differences provide better correlation of colour shifts.

Industrial requirements for a suitable pass/fail evaluation led to the development of colour difference metrics that employed weighting functions to correct for the non-uniformity found in CIELAB and CIELUV colour spaces. The CMC (*l:c*) (**Clarke et al. 1984**) equation was designed for the textile industry and seems to provide better uniformity and BFD (*l:c*) (**Luo et al. 1987**) introduced hue-chroma interaction, $\Delta H / \Delta C$. The inclusion of a new term R_T designed to control rotation of tolerance ellipses, maximizing in blue samples with high chroma. The CIE later developed a new equation that resulted from a study of the industrial colour-difference formula called CIE94 (**CIE 1995**), which was considered to be much simpler to implement than CMC. This equation introduced a much-simplified set of weightings as parametric factors k_L, k_C and k_H which are the same as l, c, and h in the CMC($l:c$) formula (**McDonald and Smith 1995**). In the CMC($l:c$) formula l and c are factors that result in relative tolerance changes to ΔL^*, ΔC^*_{ab} and ΔH^*_{ab} through modification of the relevant ellipse semi-axis. However, in CIE94 the parametric factors k_L, k_C and k_H (named as such to differentiate them from the acceptability tolerance influencing l and c) are designed to allow independent adjustments to colour difference components. Essentially, the parametric parameters can be used to correct for any deviation from the reference conditions caused by component-specific visual tolerance variations. This can be seen when assessments of textile pairs where an adjustment of $k_L = 2$, and $k_C = k_H = 1$ gives a better correlation between CIE94 predicted results and visual assessments.

Berns *at el* [**1989,1991**] in collaboration with the DuPont company also conducted visual assessments based upon glossy paint samples using the pair comparison method. A data set, named RIT-DuPont, including 156 pairs (19 colour centres) perceptually equivalent to a near-grey anchor pair of 1 CIELAB ΔE unit was generated. The data was used to derive a relatively simple colour difference equation, named CIE94, which was recommended for field trials by CIE in 1994. The chromatic ellipses for the 19 colour centres were also fitted by Melgosa et al [**1997**] and are plotted in Figure 9.

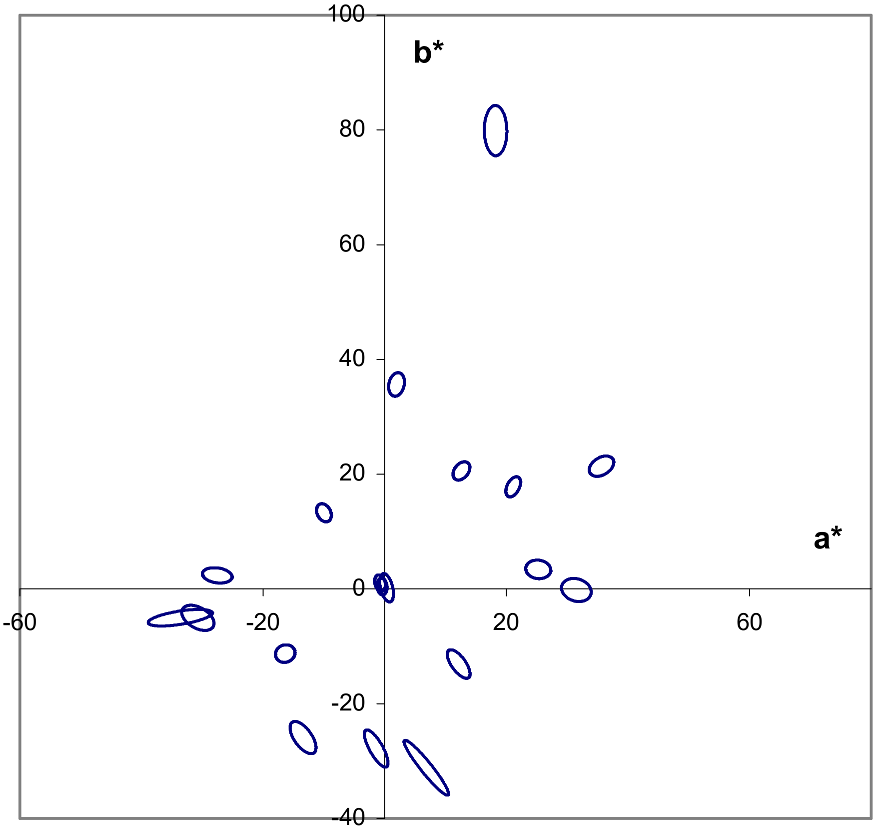

Figure 9: RIT-DuPont colour discrimination ellipses plotted in a* b* diagram (Luo 2000).

This colour difference formula, also based on colour tolerance, was developed as a result of the success of the CMC equation. It was derived from visual observations of automotive paints on steel panels. Like the CMC equation, it is based on the CIELAB color metric and uses the position of the standard in CIELAB color space to derive a set of analytical functions that modify the spacing of the CIELAB space in the region around the standard. Its weighting functions are much simpler than those of the CMC equation.

Improving upon CIE94, the CIE Technical Committee 1-47 developed new functions S_L and S_H. The CIEDE2000 (**Luo et. al. 2001**) does perform better than its predecessors CMC (*l:c*) and CIE94 where it extends to include a hue-chroma interaction variable to improve performance in the blue region thus correcting for perceived constant hue nonlinearity. Further adjustments include improved performance for low chroma colours and a hue dependent function to resolve perceived hue differences.

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{k_L S_L} \right)^2 + \left(\frac{\Delta C'}{k_C S_C} \right)^2 + \left(\frac{\Delta H'}{k_H S_H} \right)^2 + R_T \left(\frac{\Delta C'}{k_C S_C} \right) \left(\frac{\Delta H'}{k_H S_H} \right) \right]^{1/2} \qquad (14)$$

S_L is the lightness weighting function:

$S_L = 1 + 0.015(L'_m - 50)^2 / \left[20 + (L'_m - 50)^2\right]^{1/2}$ with $L'_m = (L'_1 + L'_0)/2$

S_C is the chroma weighting function which is the equivalent to that in CIE94:

$S_C = 1 + 0.045 C'_m$ with $C'_m = (C'_1 + C'_0)/2)$

S_H is a hue function as in the CIE94 formula but includes a *T* function to cope with the complex hue angle dependence: $S_H = 1 + 0.015 C'_m T$ with

$T = 1 - 0.17\cos(h'_m - 30) + 0.24\cos(2h') + 0.32\cos(3h'_m + 6) - 0.20\cos(4h'_m - 63)$ and $h'_m = (h'_1 + h'_0)/2$

R_T is a multiplicative function that corrects for the anomalies in the blue region of the CIELAB colour space with regards to the hue angle and chroma interaction (**Schanda 2007**):

$R_T = -\sin(2\Delta\Theta)R_C$ with $\Delta\Theta = 30\exp\left[-\left((h'_m - 275)/25\right)^2\right]$ and $R_C = 2\left({C'_m}^7/\left({C'_m}^7 + 25^7\right)\right)^{1/2}$

K_L, K_C and K_H are parametric weights which can be set if they are known, otherwise a value of 1.0 is used. For most imaging applications, they are unknown values and are therefore set to 1.0.

Luo et al. **(2006**) introduced a series of colour-difference formulas based on the CIECAM02 colour appearance model. The CIECAM02 appearance model is a result of improvements made on the earlier CIECAM97s model and it led to a simpler and more effective model. It can predict all of the appearance phenomena that CIECAM97s deals with and includes correlates of relative and absolute appearance attributes. It is well suited to being applied to a large range of luminance levels and states of chromatic adaptation. CIECAM97s itself was born out of an industrial demand for a single colour appearance model of standardised approach. Some requirements of the model were for it to be comprehensive enough to suit various applications, cover a wide range of stimulus and adapting intensities, cover a wide range of viewing conditions, provide a varied range of adaptation and have the capability of being reversible in operation.

$$\Delta E' = \sqrt{(\Delta J'/K_L)^2 + \Delta a'^2 + \Delta b'^2}$$

$$J' = \frac{(1 + 100c_1)J}{1 + c_1 J}$$

$$M' = (1/c_2)\ln(1 + c_2 M) \qquad (15)$$

$$a' = M' cos(h)$$

$$b' = M' sin(h),$$

where the CIECAM02 lightness, colourfulness and hue angle values are J, M, h respectively. The difference between a reference and a sample for J', a' and b' is represented by ΔJ, $\Delta a'$ and $\Delta b'$. This colour difference approach has coefficients K_L, c_1 and c_2 for three types of configurations namely:

- large colour difference,
- small colour difference,
- uniform colour space.

This is tabulated as follows in Table 1 for each version of uniform colour space:

Table 1: Colour-difference coefficients for CAM02-LCD, CAM02-SCD and CAM02-UCS

Versions	CAM02-LCD	CAM02-SCD	CAM02-UCS
K_L	0.77	1.24	1.0
c_1	0.007	0.007	0.007
c_2	0.0053	0.0363	0.0228

In this thesis, the concern is to identify the attributes of colour differences between uniform stimuli that influence observer judgment when a sample and reference are compared. The resulting data is then used to represent colour tolerances that describes, statistically, the limits of colour differences as an end goal for colour reproduction workflows.

2.4 Colour management

In graphic arts achieving high quality colour reproductions is of primary concern from pre-production right through to final reproduction. Achieving this depends on the efficient interaction between devices and output media. Each device in a colour workflow has its own characteristics in capturing or reproducing colour information and their range of reproducible colours may also differ (**Johnson 1996**). As a result, there is a requirement for a global framework to manage these colour variations. Colour management provides methods by which adjustment and control of colour images reproduced on different devices for various media can be achieved with some visual consistency. Also, designers of artwork and facilitators of image capture systems involved in graphic arts do not often predefine target media or viewing conditions. Employing colour management goes some way to guarantee colour accuracy in the transfer of such colour information along the colour imaging chain (**Fraser et. al 2005**).

Colour reproduction is achieved by additive light mixing or subtractive methods using inks represented in Figure 10. Mostly, in the additive light process, colour is produced by a combination of different intensities of red, green and blue primary colour light sources. Additive colour represents a weighted summation of the spectra for each primary and in display monitors this is a relationship between the digital input and the luminance of each colour channel (**Choi et. al. 2002**). The subtractive process involves depositing a number of ink films, typically cyan, magenta, yellow and black, on a substrate to subtract spectrally from its whiteness to achieve the required colours. In this manner, the light wavelengths are either absorbed or transmitted to produce colour.

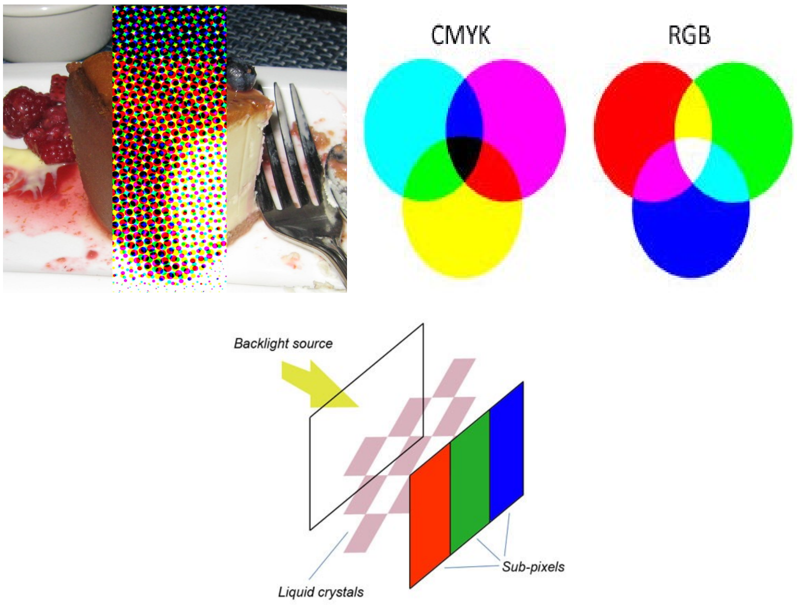

Figure 10 : CMYK halftone dots highlighted for a printed image and an LCD displays monitor showing sub pixels of RGB, liquid crystals and backlight source by http://www.bit-tech.net/.

Device specific colour models produce different colours for the same set of RGB or CMYK values on different devices or for different substrates on a printer. To produce the same colour on different devices for RGB or CMYK their values require adjustment according to the device. These differences could result from RGB photo-detector sensitivity, algorithms, and luminance. Where CMYK colour is concerned technologies for depositing colorants on substrates differ and likewise their interaction with substrate whiteness. None of these representations give any information about their colour appearance which is a function of device characteristics and the viewing conditions of a resulting reproduction (**Sharma 2004**). Using CIEXYZ and CIELAB colour spaces it is possible to independently define colour characteristics of such devices and translate information between them. Figure 11 is an example of a colour management workflow. In colour management systems a module, the Colour Management Module or CMM, performs such transformations (**Green 2010**).

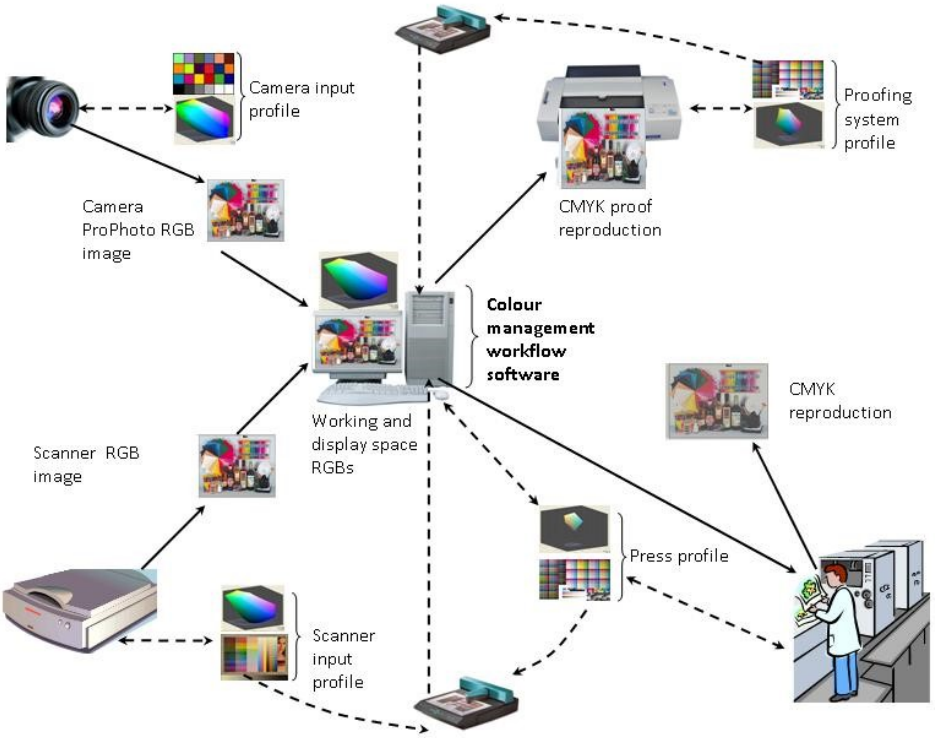

Figure 11: Generic RGB colour management workflow.

The procedures of calibration and characterisation define the techniques intrinsic in matching colours (**Johnson 1996**) between different media or devices.

2.4.1 Calibration

Calibration is the setting up of a device or process so that it gives repeatable data. It defines a relationship between input signals for a device and the colorimetric data that will form the output. Several models of calibration exist for colour workflow devices based on techniques such as the Neugebauer equations for predicting the colour generated by a permutation of print halftones, the Beer's law analytical model of colour prediction or one based on a colorimetric technique that uses a matrix of colour patches and interpolations to assume smoothness for relational input-output (**Hung 1993**).

2.4.2 Characterisation

Characterisation defines the relationship between the device colour space and the CIE system of colorimetry, be it XYZ or CIELAB. Once calibration is completed characterisation will establish the relationship between the signals sent to the device and the colours reproducible. Characterisation methods usually depend to a large extent on the device targeted. There are other characterisation approaches such as visual neural networks and polynomial transforms (**Cheung et. al. 2005**). Full characterisation and masking equations that can be used for any device (**Johnson et al. 1998**) are another method. The characterisation of a device will only hold true for the state in which it was characterised so the importance of calibration as an initial setup process is very significant to ensure that the device performs to a known colour specification.

To achieve efficient colour management, the data structure for the model of a device needs to include characterisation, colour appearance modelling, gamut mapping and a defined intermediate device-independent colour space. At the level of implementation, the device operation system is required to handle different profiles and manage colour transformations. The ICC (International Color Consortium) colour management framework extends a computers' operating system to route application program calls to enable access to profiles and colour management modules (CMM). The profile defines the device model as a relationship between the device coordinates and that of the reference colour space. The CMM connects together profiles to produce transformations between device colour spaces for source (input) devices and destination (output) devices whilst also carrying out any required interpolation. The operating system then handles user required colour transformations through application program calls (**Wallner 2002**). By using a common intermediate communication base, the ICC profile provides data necessary to transform the colours of an image from the colour characteristics of one device to those of another.

2.4.3 Colour reproduction and media

Primarily colour reproduction systems often objectively fulfill the requirement of achieving faithful colour matching of multiple stimuli. It is common for the reproduction of colour to be intentionally different from its original as a way of improving perceived image quality and adjust for media dynamic range (**Viggiano and Wang 1992**). Colour reproduction in this manner is designed to systematically map image differences from capture to reproduction in order to avoid mismatches resulting from the production of colorimetric matches between source and destination target media (**Viggiano and Moroney 1995**). Such mismatches are due to variations in the viewing conditions between the original image and output media, therefore faithful reproductions require appearance matching (**Morovic and Pei-Li 2002**). Some key principles that are set to be achieved in colour reproduction quality are:

- Mapping of reference colours such as skin tones, natural content and the like. Whilst the match may not be precise there must be perceptual recognition;
- Suitable mapping of media white and neutral grey of the overall image;
- Efficient tone reproduction as a mapping of contrast and brightness to preserve image detail. This is designed to compensate for differences between output and input medium luminance ratio capability (**Holm et. al 2002**). It applies to reproduction processes that start and end with a visible image and not the defining characteristics of an input or output device individually.

2.4.4 Colour Gamut

The efficient prediction of colour appearance, through an appearance model, only goes part of the way to satisfy the requirement of image reproduction. The ranges of colours that can be reproduced on each media and output by imaging devices are known as their colour gamut. Being able to map the gamut of devices and media is essential in achieving a satisfactory stimulus representation for a desired outcome. In this study colour gamut mapping will not be investigated but it is necessary to highlight the importance of having a suitable method for its mapping between images and an imaging device (**Fairchild 1994**). For lighter colours the gamut of a monitor exceeds that of a printer whereas in the darker areas the printer exhibits a larger gamut. When comparing the gamut of a monitor to that of most printers in a two-dimensional representation, the monitor will often show a larger range. This will however not be reflected in a three-dimensional representation. The third dimension of colour space shows that often the gamut of a printer extends beyond that of the monitor (**Fairchild 2005**).

Adjusting the colours of an image to enable its representation by another device is known as gamut mapping. The mapping process may require compression of colour in one area or conversely expansion in another, but ultimately depends on whether the desired colour falls either outside of the required region of a device. It may also be that there is no need to fully utilise the complete gamut of the said device. Several techniques have been suggested over the years for gamut mapping, but no individual mapping is generally in use. It is however important to adopt a gamut mapping strategy within a colour management framework that appropriately satisfies the required appearance output. Johnson (**1979**) proposed maintaining of the hue, linear compression of perceived lightness (using Bartleson–Breneman Lightness (**Bartleson and Breneman, 1967**) and linear compression of perceived colourfulness. Laihanen (**1987**) proposed the maintaining of colour appearance as much as possible so that changes between monitor and print were not too noticeable. Lightness compression is carried out towards the centre its axis (L*=50), with the rate of compression independently determined along each individual step. Gordon, Holub & Poe (**1987**) opted for achieving a faithful reproduction between two media, based on CIELUV colorimetry, which was defined such that the neutrals of the original and the reproduction media mapped onto each other and colour differences in the reproduction were equal to colour differences in the original scaled by a constant scale factor. CIELUV was used because of the range of colour increase in L*u*v* with lightness. Berns & Choh (**1995**) proposed a gamut mapping focused on colour appearance modelling where gamut clipping was the preferred option as it minimised the colour difference ΔE_{ab}. Fairchild (**2005**) suggests that an approach for pictorial images with linear scaling of the lightness value to attain a match between black and white points whilst keeping the mid-grey constant at $L^* = 50$, then clip the chroma to the gamut boundary. Another option is to clip out-of-gamut colours so that only that which lies within the boundaries remain, but this may not suit instances such as that of branding where the importance is the preservation of a chosen colour and its appearance. In this situation, the preservation of the chroma elements with minor hue shift may be the appropriate measure to preserve acceptable colour appearance. Morovic (**2003**) proposed a gamut mapping algorithm method based on different levels of resolution, lightness compression and spatial colour which intends mostly to preserve the spatial information of an image. The algorithm works on different spatial frequency bands, with lightness compression and gamut mapping transformations for each frequency band. An evaluation of the algorithm psychophysically performed similarly to previous published gamut mapping algorithms proposed to preserve spatial luminance variations (**Bala et al. 2001**).

2.4.5 Colour Reproduction Criteria

Brand image reproduction is required to conform to a perceived set of representations that preserves its appearance. This is based on a set of criteria that is often influenced by cross-media reiterations including spatial, dynamic range and reproducible gamut. Image content is produced once and repurposed for various media on inter-platform and inter-device permutations (**Veglis 2007**). Objective criterion for output could invariably be assigned to any of the following reproduction target requirement outcomes:

- Spectral reproduction (**Hunt 1970**) attempts to match the spectral reflectance curves of the original scene by aiming to reproduce colours identical in spectral value. Despite evolving technology in colour science reproduction colorants such ink pigments are different in spectral composition from the colorants of other methods. The dyes in textile colour reproduction are spectrally different and would result in metameric mismatching under differing illuminants.

- An exact reproduction would require that the original and reproduction have the same chromaticities and absolute luminance level. Such reproductions would result in equal appearance between the original and reproduction as long as the observers’ adaptation is the same for both. Virtually reality employs this type of reproduction.

- If the original and reproduction have the same chromaticities and the same relative luminances it is considered as a colorimetric reproduction. This is a suitable approach where reproduction is relative to the white point of an original scene. The suitability of this method depends on the importance of colour appearance matching because hue errors are likely to occur so a choice between perceptibility and acceptability has to be made. This is in most cases suitable, for example, for photocopying;

- Corresponding reproduction is defined as having chromaticities and relative luminances of the original and reproduction having an appearance illuminated to produce the same average absolute luminance levels. It is considered the most appropriate for general use because of the relation of both the original and the reproduction to a reference white. This allows for different white reference points and surrounds. Typically, a scene lit by daylight reproduced as a print viewed under tungsten light, which although is much yellower can be largely compensated by visual chromatic adaptation.

- Preferred reproduction looks dissimilar compared to the original but satisfies the visual preference of the observer. It is a reproduction in which the colour appearance departs from the original relative to a reference white. This is common in reproductions of the sky and grass where observers tend to prefer a more saturated blue or green respectively. In holiday brochures, it is common to have skin tones made to look more tanned. Such changes arise from a perceptual colour memory association with scenes.

For cross media, especially in branding, preferred reproduction the most likely candidate for the colour rendering intent. The ranges of media have a much larger variation in gamut representation so for the most part reproduction that exhibits dissimilarity prevails. Where cross media may have, a gamut overlap for specific colours either corresponding or equivalent reproduction could suffice. Through colour management a further set of rendering intentions are defined which primarily are aimed at complex images:

- Perceptual mapping where source colours are altered but relationships between colours are maintained. The alterations of colours are either compressed or expanded whilst preserving grey balance.
- Saturation mapping results in colours being scaled to increase saturation at the expense of changes lightness and hue.
- Absolute mapping reproduces exact colorimetric values of the original colours but results in the clipping of out-of-gamut colours.
- Relative colorimetric mapping preserves chromaticities and relative luminances such that colours that fall outside the gamut are replaced with relative colours within the target gamut to preserve lightness and hue.

2.4.6 Cross Media

In its simplest terms media are physical channels of communication that are used to facilitate communications between audiences. However, in this context it refers to physical channels that are used to communicate colour images restricted to printing substrates and displays. Surface reflectance or emission of media depends on the reflectance or emissive properties, conditions of illumination, viewing conditions and surface texture. Where there is surface uniformity in texture and colour the viewing condition illumination yields relative consistency with changes across the media (**Fleming et al. 2003**). Visually resolving a sense of uniformity on the surface of any media depends on the structure of colorants and intended viewing distance, such that there is no ability for the observer to resolve these structures (**Pointer 1980**). Additionally, media the white point is considered to be an indicator of the quality of colour reproduction achievable.

Channeling the generation of a colour stimulus for reproduction from a single source and output to two or more combinations of media is considered as cross-media reproduction. An example of cross media is the creation of a brand logo with a specific colour using a computer and then reproducing that original image on paper, vinyl, TV, cinema and mobile phone. The ensuing workflow will involve different colorants, colour gamuts and target viewing condition. MacDonald (**1993**) depicts the cross-media reproduction workflow as suitably categorized into five stages of colour reproduction modelling, shown in Figure 12. The stages are further grouped into three essential categories:

- the reproducible gamut of each media,
- the characterisation of each device involved in the reproduction
- and the modelling of colour appearance.

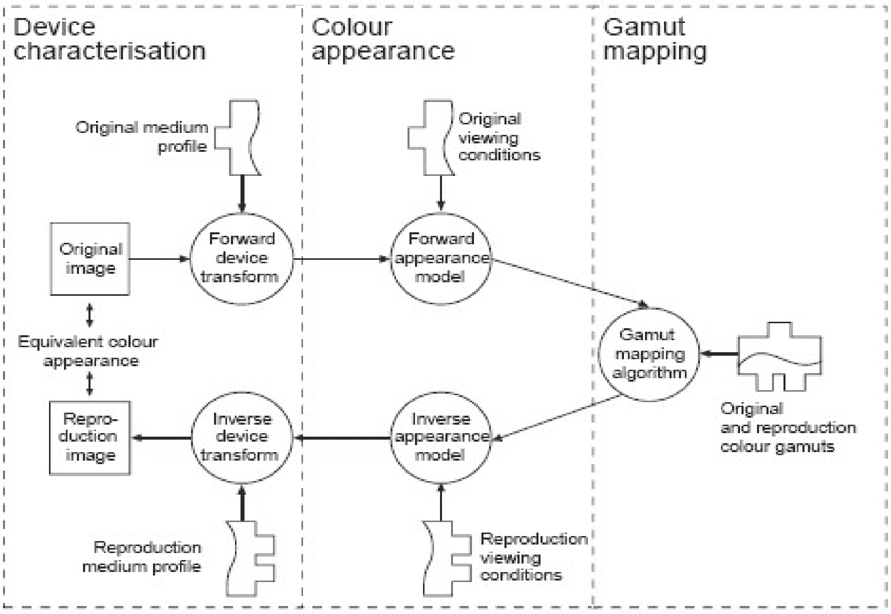

Figure 12: Five stage colour reproduction system with data–flow for calculating the original and reproduction gamuts indicated by arrowed lines (**MacDonald 1993**).

2.5 Viewing conditions

The visual field has a direct impact on the appearance of a stimulus (**Lotto and Purvis 2002**). The interpretation of a given stimulus and its perceived colour is dependent on the configuration of the four main components, which are the stimulus, the proximal field, the background and the surround. Primarily this classification of parameters clearly deals with a uniform colour stimulus, but is also successfully used in appearance modelling of individual colours in complex images because it accounts for some of the key elements that impact on colour appearance.

2.5.1 Target viewing environment

According to the definitions within the Hunt colour appearance model, the proximal field is the immediate area around the stimulus that extends for about 2˚ from its edge and distinguishes the stimulus form the background. Its definition enables the modelling of effects such as chromatic induction, crispening, or spreading. For a large number of practical situations, it is not often easy to define this parameter of the visual field.

Extending for about 10˚ from the edge of the stimulus is the background or. if the proximal field is defined, this then extends beyond this field. In imaging, the background is often considered as the surrounding area because its precise specification for imaging applications would require a complex point to point calculation. The assumption is often one of it being constant with medium chromaticity and luminance factor such as neutral grey with 20% luminance factor (**Fairchild 2005**). Careful consideration will be required for the background of test images in this research because of the evaluation of a uniform colour stimulus.

Outside of the background is the surround field where practical situations will often require an entire room or viewing location to be defined as the surround of the stimulus. At least some of this area is still within the visual field and typically video displays are considered to have a dim surround, printed images are usually viewed in an average illuminated surround whilst projected transparencies have a dark surround. This is essential when modelling overall contrast effects (**Bartleson and Breneman 1967**) and the impact of flare on a stimulus. A further component of the visual field is that of the adapting field of the complete environment of the stimulus extending to the limits of vision. The degree of adaptation ranges from 0 to 1, based on whether adaptation to the adopted white point occurs completely or not. A dark surround would in practice have a value not less than 0.65 and converge to 1 exponentially for an average surround with the values of the luminance of the adapting field largely increasing.

The perception of colour results from interactions of the illumination with the objects present in the viewing environment (**Judd 1961**). To some extent colour perception will remain stable across changes in illumination and thereby enable the observer to identify an object as having a well-defined colour (**Delahunt and Brainard 2004**). It is believed that the mean light reflected from the viewing environment determines the perception of a colour (**Buchsbaum 1980**) and in the presence of surrounding colours their variance will affect the perceived target colour. For identity branding the understanding of these interactions with illumination changes is important to predict so that stability of visual acuity can be determined.

Crawford (**1973**), in his paper that investigated the colour difference perceptibility relative to level of illumination for museums and art galleries, determined that 30 lux was the practical lower limit of illuminance, after which the appreciation of displays degrades in observer experience. At this level of illumination colour perception was deemed as acceptable for viewing items on display within the referred environment of museums and art galleries. Recent research (**Ravi 2010**) gives a clear indication that a change in illumination levels has a direct impact on the noticeable colour differences for which the correlation coefficient consistently showed differences corresponding to illumination levels.

2.5.2 Proofing of media

In the colour reproduction workflow proofing provides an accurate estimation of how a reproduction is likely to look for specific media. The media types can broadly be classified as softcopy, which is display technology, and digital hardcopy produced on special digital presses. Media differences can often present challenges when trying to achieve appearance matching as a result of differences in device colour gamut used in reproduction so where possible it is highly desired that the media have the same gamut (**Norberg and Andersson 2003**). Through colour management techniques it is feasible to manage the representation of a proof to meet expected visual criteria of reproduction devices. In soft proofing of media, chromatic adaptation and colour visual appearance variations exist since a softcopy is on self-luminous media and hardcopy is a reflective image. ISO 3664:2009, 12647:2013 and ISO 12646:2008 provide recommendations for configuration of viewing conditions and proofing processes.

- ISO 3664:2009 specifies viewing conditions for images on reflective and transmissive media, transparencies and images displayed in isolation on colour monitors.
- ISO 12646:2008 specifies the minimum requirements for the properties of displays used for soft proofing and their conforming parameters.
- ISO 12647-7:2013 specifies requirements for systems used to produce hard-copy digital proof prints intended to simulate a printing condition defined by a set of characterization data and recommend appropriate test methods associated with these requirements.

ISO 3664:2009 recommends that the viewing conditions for prints, where a more practical appraisal is required, should be under a light source which is approximate to the CIE D50 standard illuminant and the maximum illuminance at the viewing surface should be 500 lux - 125 lux. If assessment is for critical comparison the level of illumination should be 2000 lux. Prints are to be viewed against a matt surround that is neutral and should have a luminous reflectance of less than 20% and extend beyond the material being viewed on all sides by at least 1/3 of their dimension. The standard requires that the light source used must provide a near accurate simulation of the CIE D50 Illuminant within the UV range. Therefor the metamerism index (MI) should be less than 1.5. The colour rendering index prescribed by ISO 3664:2009 is set to 90. The colour rendering index (CRI) is a quantitative scale which measures the quality of colour of a specified illuminant. The CRI scale range is from 0 to 100 where higher CRI values are considered to show better colour quality.

Where softcopy is of consideration ISO 3664:2009 recommends a viewing configuration, such that appraisal is done in isolation, conforming to a white point set to chromaticities similar to those of CIE D65 illuminant with a luminance level between 80-120cd/m^2. The level of ambient illumination should have a colour temperature equal to or less than the white point of the display. The level of illumination measured at the face of the monitor or plane between monitor and observer should be less than 64 lux and preferably be below 32 lux. Any sources of reflection and glare should be avoided with the surround for the image dark and neutral as this will minimise flare.

ISO 12646:2008 deals with the recommendations for softcopy proofing displays where a monitor is used to simulate a hard copy proofing system. The specifications require uniformity in size, resolution, convergence and refresh rates, luminance levels and viewing conditions. The white point of the display should be set to a chromaticity of CIE D50 illuminant and the luminance level should be as high as practical but in the least and should be greater than 80cd/m^2. The black point shall have a luminance that is less than 1% of the maximum luminance. The resolution of the display shall be sufficient to display an image of 1280 x 1024 pixel without interpolation. All luminance values should be within 5% of the luminance of the centre and the ambient illumination level, when measured at the face of the monitor, shall be less than 32 lux. The surrounds should be no more than 10% of the maximum luminance of the screen.

2.6 Brand Theory

The use of branding as a communication tool is described in this chapter as a name, term, design, symbol, or any other feature that identifies it. The definitions covered relate entirely to interactions with brand colour that elicits judgment. Following on from this the test case brand is placed into the context of this research.

i. Branding

Marketing concerns itself with defining products and services in terms of their likeness or difference from that similar to it. There may also be an occupation of the same social space relative to prospective consumers (**Slater 2002**). Through the use of attractive displays marketers seek to influence salience to generate consumer familiarity with branding constructs (**Alba, Hutchinson and Lynch 1991**). These marketing concerns therefore provide the requirements for branding which includes recognisable visual identity by its target audience. The early stages in the development of the modern consumer culture and the brand are shown to be born out of the aggressive competition. This started to develop when markets extended into multinational spaces with its corresponding circulation, distribution and economic rivalry (**McClintock 1995**). Whilst highlighting the importance of branding as the identity of an entity, through reviewed literature, this study primarily focuses on defining an approach for preserving the visual identification of a brand image when reproduced for different viewing conditions.

Prior to the 1980s a brand was commonly considered as a fast-moving product at a specified point of sale with a specific customer appeal. This has extended to include corporations as they presented themselves to their target audience and now a brand typically embraces the corporation as well as its products and services (**Olins 2008**). The mixed representation of what makes up branding extends tangible and intangible attributes that define the products and/or services of an entity to create a self-image representation that is required to have consistency.

Generically named products such as soap took on brand names in England post 1884. The use of brand signatures such as Pears appeared in the marketplace whereas previously all wrapped soap was labeled as “Soap”. From this period onwards named corporate logos have continued to be used to promote products and services as seen with the likes of Rowntree’s Fruit Pastilles, Quaker Oats cereal, TESCO, Kellogg’s, Campbell’s soup and the like. Coca-Cola, which was branded in 1886, started life in the United States as a medicinal product but post 1890 was being promoted as a national drink (**Lury 2004**). This was an example of branding being used to speak directly to the consumer by way of visual presentation, packaging and other media definitions with time.

Branding is thus a design, marketing, communication and resource tool, which intends to influence the organisation and its entire audience continuously. It seeks to act as a co-coordinating resource to make the corporation’s activities coherent and visually present its strategy in an easy-to-perceive manner for all audiences. Olins (**2008**) implies that the visibility of a brand consists of a combination of a graphical representation, inscription, and colour which, in certain circumstances includes sound, music or smells. The precise mix is determined by what the entity considers as the best representation of their aims, what they do, own, and produce. This puts a significant emphasis on creating a consistent visual appearance of the identity of a brand across their different media destined for various targets. In the context of this study the physical colour stimulus of the brand representation that results in visual identification of its presence is considered as identity branding.

vi. Brand image and visual identity

It is easy to confuse the concepts of brand image and brand visual identity as the same thing by definition. A brand image is considered as a translation of visual representation whilst brand visual identity is a set of cues for communicating the physical presence of a brand that will include one or more brand images. A brand image is typically linked to memory or to representations of visual phenomena and not to imagination (**Christensen and Askegaard 2001**). Where there is a coherent look and feel of a brand image that reflects the values of a corporate brand its visual presentation carries with it an impact. TESCO’s store branded products in its early days of trading did not attract much purchasing attention because it was then considered to be of lesser quality when compared to well-known and established brands. However, TESCO achieved a more positive image when their store branded products were considered as giving value for money. This assisted an increase in its sales (**Martenson 2007**). Within retail, carrying popular manufacturer brands also help to increase image and equity acknowledgement (**Ailawadi and Keller 2004**) and where a store has a positive representative brand image the consumer perception is further enhanced.

The visual identity batches the various cues that are part of its communication policies, which seek to empower targeted audiences to identify them (**Balmer and He 2007**). These cues will include any permutation of a logo, slogan, nomenclature, strap line in relation to a graphic design. This is part of what makes up the brand image of the entity, which includes consideration of the identity mix (strategy, structure, communication and culture) and its management thereof (**Balmer 2001**). Van Riel and van den Ban (**2001**) highlighted the importance of visual identity in an evaluation of the benefit of corporate logos. In 1999, Melewar and Saunders' research in Malaysia concluded that it was essential to have standardised visual identity when entering a new market more so because its recognition in the first instance was key to providing an effective platform for communicating what the organisation stood for. Society is saturated with images (**Baudrillard 1981; Ewen 1988**) so in the quest for visibility and credibility, it raises the importance recognition of brands by their identity and as such, there is the need for the focusing of attention on symbolic dimensions (**Christensen and Cheney 1994; Cheney and Christensen 1999**). The buying public is faced with a wide choice of designs and features of products that are very similar with little price difference. This means that most of their purchasing decisions are likely to be influenced by brand identification that is aligned with a perception of reputation (**Kennedy 1977**).

The research of Louis Cheskin in the 1930s suggested that there was a "Principle of Sensation Transference" (**Kathman 2002**) where consumers' assigned expectations about using particular products based on design, colour and shape of packages. This effectively placed the promise of taste, efficacy and quality in the realms of visual appearance appreciation. Cognitive psychologists also believe that the strength of memory association with brand images decay very slowly so favourite ones committed to memory tend to guide the integration of new information of same brand products (**Petty and Cacioppo 1986**). Consumers employ visual selective attention to assess stimulus display regions of brand stimuli and there is a tendency to fixate some regions more than others (**Loftus 1972**). This enables visual identification through comparisons with referenced memory knowledge and observed visual patterns.

vi. The brand design

As an example, The Body Shop brand focuses on environmentally friendly cosmetic and toiletry products that ethically sourced. The distinctiveness of its brand ties in with a specific identity and values that are represented in its visual cues. The brand’s dark green colour, shown I Figure 13, seeks to connote a message of environmental and ethical awareness. However, in another account (**Kent and Stone 2007**), the brand’s dark green colour was chosen because of its ability to hide patches of damp in the original store (**www.worldaware.org.uk**). This theme of visual representation of the brand is carried throughout its product packaging and advertisements with a view to continually presenting a uniform message.

Figure 13: The body shop logo.

The packaging communicates the personality of the brand through visual element combinations that infer by associations such as environmental, nostalgia, prestige and the like. The advertising presents a single symbolic resource that mediates experience (**Lindssay 1977**).

iv. Brand recognition

Corporations intend for their brand image to be recognisable irrespective of where they are seen by consumers and as such the consistency. In recognizing, brand consumers are confirming a perceived set of attributes that differentiate it from other products or services. Quite often this leads to the interchangeable definition of identification as a trademark or brand, where the former is a definition assigned by manufacturers or sellers, often as a legal terminology, and the latter used by marketing scholars (**Peterson et al. 1999**). Both instances intend to serve the purpose of identifying and differentiating one brand from another (**Keller 1998**) or just the latter. Trademarks in their true sense will comprise any of the following attributes in a manner that provides a unique descriptive of an entity that makes it identifiable from others: -

- A form of logo for which in some circumstances are abstract shapes such as the Nike swoosh;
- Marks that are capable of graphical representation with distinctive marks;
- A set of words that present a strength of mark, such as Kodak and Sony, or even ‘Just do it’ as used by Nike;
- More recently some companies have succeeded in the inclusion of a colour within a specified context.

Physical characteristics are not the sole factors of evaluation for a consumer and during the process of choice, brand perception will be an important sign of quality reflected through its packaging. The visual information on packaging can serve to attract the attention of consumers and set their expectations of its content, thereby serving as an advance information organiser for the textual content of the packaging (**Alesandrini 1982 and Houston et al. 1987**). This highlights the problem of so-called “new” products that are really innovative imitations (**Gatignon and Robertson 1991**), essentially re-creations with minor modifications. The greater the similarity between the brand image appearance the more likely the possibility of a consumers thinking they are made by the same company (**Loken et al. 1986**) which, leads to ecognizedion of quality and performance from the original to the imitator (**Ward et al. 1986**). The similarity is predominantly focused on the stimulus presented by the imitation to appear like the original product. The less the original is known the more likely it is that the imitation will be considered as the actual original (**Foxman et al. 1990**).

Publicised legally pursued cases of brand image imitations are indicative of this:

- United Biscuits “Penguin” versus Asda’s “Puffin” (United Biscuits, UK Ltd v. Asda Stores Ltd [1987] RPC 513;).The product are dipicted in Figure 14.

Figure 14: The court case resulted in acceptance that the name Puffin and the upright dark-coloured bird with a white front was likely to be seen as having a possible association between the ASDA product and United Biscuits Penguin [**http://newlegalreview.cpaglobal.com/room-resemblance-battle-brands/**].

Neutrogena versus Neutralia (Neutrogena Corp. v. Golden Ltd [1996] RPC 473) These products are shown in Figure 15 below.

Figure 15: In court, it was suggested that confusion between Neutrogena and Neutralia only occurs in a minority of cases and did not impact on the former's market share. [R.P.C. (1996) 113 (16): 473-506. doi: 10.1093/rpc/1996rpc473].

The Marriott hotel chain uses its brand logo across different hotel ranges that have an array of budget level prices. Mariott, Renaissance, Courtyard or Fairfield Inn all carries the brand image representation of the chain, but each is distinctive in their pricing. However, the lower costing accommodations do not impact on the image of the more expensive ones because the perceived quality of the higher end carries through via the identity branding (**Rotfield 2008**) of the complete chain. Wayne D Hoyer and Steven P Brown (**1990**) conducted a couple of experiments to determine the degree to which brand recognition affected consumer choice. Using a brand of peanut butter, shown in

Figure 16, that was highly rated as being significantly better than another in a pre-test, they established that without labeling the higher quality sample out of three was identified 59% of the time. When participants did random guessing they only achieved a 33% success rate, which meant that a difference in taste could actually be identified.

Figure 16: Hoyer and Brown brand comparison experiment. Decision Science News – http://www.dangoldstein.com/dsn/archives/2006/02/recognition_can.html).

When a lower quality brand was labelled as a nationally known better brand that sample was chosen only 20% of the time. The preference for the recognized brand despite it tasting of lower quality was chosen 73% of the time. Even when all three samples had exactly the same contents, the ecognized brand still achieved 75% selection as shown in Figure 17.

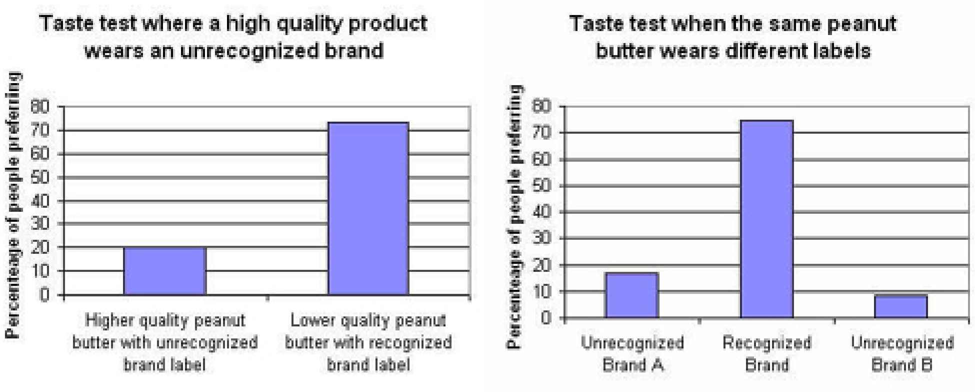

Figure 17: Hoyer and Brown brand comparison results. Decision Science News – http://www.dangoldstein.com/dsn/archives/2006/02/recognition_can.html

The unsuccessful recognition of a brand can also have adverse effects where product-line extension strategies and retailer labels can result in customer confusion (**Burke and Srull 1988**). Surveys reveal that 22 per cent of British consumers have at one time or another purchased the wrong product (**Supermarketing 1997, Rafiq and Collins 1996**).

v. Brand awareness

When a consumer is able to identify a brand under different target conditions brand awareness becomes apparent (**Keller 2003**), often as a result of a combination of the recognition and recall process. There is an assumption that the consumer has had prior exposure to the brand in order to create a perceptive mapping to the cues received from the brand's presentation. This implies that the brand holds a strong position in the consumer's mind. The NHS Brand is the sample brand that will be used in the test scenarios generated for this study. This brand responds to all attributes of branding with the exception of being marketed for commercial appreciation. Being a nationwide service provider of health does actually extend its remit beyond what which any commercial enterprise encounters. There are however several private sector health entities that are in direct competition with it with regards to service efficiency. The NHS Brand in creating awareness of its brand engages in increasing its familiarity through repeated exposure of their products and services, which are intended to result in unique consumer experience. Using visual and verbal cues through advertising consumers are expected to retain a memory (**Keller 2003**) of the brand and its comprehensive purpose. The brand seeks to perform an array of functions for the consumers (**Lambin 2002, Varey 2002, Pickton and Broderick 2001**) where it serves as a signal of its characteristics and function, a guarantee of providing trust and consistency in delivery and mitigating risk.

The key identifiable elements presented by the NHS brand are its logo, font and colour palette which serves as its identity branding signature. The primary representation of the logo is a fruitger font with "NHS" in white, surrounded by the NHS Blue. The NHS blue is specified as an RGB value of 0, 114, 198 with transformations specified in

Pantone reference and CMYK. A secondary colour palette of 13 colours and 10 tints for each have also been defined as brand colours intended to help maintain recognition and trust in the NHS brand communications. To improve recognition and recall each colour has been assigned a two or three-word description, Pantone colour reference, CMYK values, RAL values, BS480: 2011 Colour Chart number and RGB values.

vi. Brand Summary

Lury (**2004**) provides evidence of the consideration of a brand as an object where this object is not entirely tangible as it also includes processes and a set of relations between products and services in time. However, it is important to complete the acceptance of this definition with Olins' (**2008**) comment that the brand also includes a signature that carries its communication to its intended audience. A suitable definition would hence be that "a brand is an object that has a set of relations between products and services in time with a characteristic brand signature". For this instance, the comprehensive representation of the brand is not within scope. The paper focuses on the recognition of the brand signature, as a consistent visual phenomenon. As such the signature is expected to remain perceptually stable through colour reproduction on different media and across varied target viewing environments.

vii. Natural viewing condition

The natural viewing condition that is referred to for identity branding in this thesis is the media used to present brand imagery and target location. Brand imagery may be applied on carriers such as stationery, printed documents, adverts, digital virtual resources, vehicles, buildings, and even on corporate clothing. Identity branding guidelines are perceived to attain visual consistency by applying a singular brief in commercial messages, or packaging (**van Riel, 2000**). Using a specific name, logo, colors or palette, and fonts aim to deliver consistency (**Melewar and Saunders, 1999**). The guidelines help to reduce customer anxiety when engaging with products or services, whilst shaping identification for each carrier for each target (**Kapferer 1994**). Weak visual identity associations across targets can be considered as corporate malaise (**Baker & Balmer, 1997**). The coherence amongst various design elements, namely colour consistency, is desirable.

Figure 18: The NHS logo artwork on the left and as targeted for NHS response vehicles. Compared to the original artwork the branded targets here are likely to exhibit changes due to viewing condition differences.

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viii. Identity branding

Identity branding is the highly distinctive visual outward expression of an entity where its values, promise and personality are conveyed with an aim of creating instant recognition. The representation of this is encapsulated in a well-defined colour palette and design. They are visual differentiating cues that facilitate encoding and retrieval of differences in brand quality or acknowledging it (**Warlopa et al. 2005**). A common use of identity branding in the NHS is to distinguish between its employees at hierarchy and team levels. In this sense, its visual equity provides derived value from this look-and-feel through brand recognition (**Lightfoot and Gerstman 1998**) and carries intrinsic meaning that becomes central to the brand's identity (**Schmitt and Simonson 1997**). It enables consumers of this identity to use colour cues to make evaluative decisions (**Crowley 1993**). Figures 18 and 19 depict NHS colour coded staff uniforms that translates to specific disciplines and NHS product branding.

Figure 19: In the NHS hospitals and clinics staff uniforms are categorized and notated through the use of colour coding. The ranges of colours used are derived from their nominated colour palette.

A logo is central to a brand's identity and its colour quite often extends to other contexts such as package design, advertising or even intrinsically linked to the brand. The colour can appropriate a symbolic and associative meaning about the brand as previously highlighted with The Body Shop's assumed green credentials (**Hine, 1996**). The nature of such identity associations creates an overlay of direct sensory experience of colour response (**Garber, Hyatt, and Starr, 2000**).

Figure 20: NHS branded products exclusively for the operating theatre and registered pharmacies.

The NHS brand colours consist of a blue logo (Pantone® 300) in Figure 20 which is defined as their corporate colour. It is intended to represent their primary colour when any communication materials are designed. The NHS Blue, as it called has, is considered by the NHS brand manager to have high recognition and identification presence amongst its targeted audience. Such communications include wayfinding communications, uniforms for their staff and printed materials. A secondary set of 13 colours with graded tints are included in the NHS brand colour palette, shown in Figure 21, to help make communication designs stand out and appeal to different audiences. To accommodate display devices each colour has been specified in hexadecimal for such media. For each colour in the palette there is a descriptive name prefixed by "NHS" Pantone reference, RGB value, CMYK print value and hexadecimal value. An example the descriptive names are NHS dark blue, NHS aqua, NHS green, and NHS light green.

Figure 21: NHS identity brand colour palette for communications.

In using the primary and secondary colours on their communication media the intention is to maintain visual consistency and aid recognition. However, without suppliers' adherence to a specific set of standards for reproduction across the different media, maintaining visual consistency is a challenge for their target locations. Each targeted location represents an NHS natural viewing condition which have a set of illumination specifications. In the branding guidelines, like most brands, tolerances for reproductions of communication materials are dependent on brand manager viewing subjectivity. No media white points are specified by the brand and there is no anchoring of reproductions to any set of standards as such the concept of working to a set of tolerances is non-existent.

In this study, it is proposed that a selection of the brand colours, including the primary NHS blue colour, are used to test for acceptable tolerances for display and hardcopy media using psychophysical methods. Perturbations of this selection of NHS colours were reproduced in order of increasing and decreasing lightness, chroma and hue. Each colour represented a reference and the corresponding perturbations samples to be judged for tolerance acceptability for varying illuminances and white points. The samples varied from their references in the order of 0-10ΔE^*_{ab}.

viii. Identity branding colour tolerance

Brands often specify their logo and nominated palette colours as Spot Colours, CMYK, RGB, sRGB and hexadecimal values. Brand managers expect that such approaches in themselves facilitate visual consistency when reproduced for various purposes. Whilst reproduction methods are able to faithfully reproduce these requirements to tight tolerances they may not achieve visual approval for a number of reasons including:

- Significant differences may exist in the estimating of visual tolerances by brand managers in comparison to the rest of the stakeholders. This is because colour tolerance is considered as the maximum acceptable variations of sample colours from a standard colour for a defined purpose (**McAdam 1939**) that is relative to the observer.
- Brand managers largely judge their brand colours based on memory associations from an agreed artwork or proof. Such recollections are enhanced in chroma and luminance (**Perez-Carpinell et al. 1998**) relative to colorimetric purity of the reference colour;
- Cross-media reproduction in identity branding extends to the various media used in presenting a brand’s colour identity. Each media has a different white point chromaticity (**Henley and Fairchild 2000**);
- When proofing is conducted using simulated target conditions there is no estimation of the impact of illumination level variability on the resulting colour appearance (**Fleming et al. 2003**);

- Modern colour-difference formulas are considered to achieve an accuracy of about 65-75% in predicting observer perceived colour differences (**Huang et al. 2015, Kuehni 2008**). However, the efficiency of some colour-difference formulas used to assess the relationship with perceived colour differences may not be suitable. As such it is essential to employ the formula that best fits the specified purpose.

ix. NHS Branding

The NHS introduced a single brand for their corporate identity for in 1999 to replace over 600 logos within the organization (**http://www.nhsidentity.nhs.uk/ 2011**). Their identity branding is used extensively across their estate and services in the form of logos or colour sequences on letterheads, websites, documents, signage, uniforms, medical products and displays. Their logo, shown in Figure 22 below, carries their primary colour and secondary colours are assigned for other uses, namely backgrounds. There are also specifications for the secondary colours as tints and web safe colours. A solid colour, referred to in this experiment, is a colour that does not have any gradations in printed terms. A tint on the other hand is a colour that has been changed by adding whiteness to result in a lighter appearance. Brand optimization in the NHS hospitals and clinics conform to specific building regulations which includes the specification of task lighting for designated areas. The guidelines, Lighting Guide 02: Hospitals & Health Care Buildings, were developed by CIBSE (**2008**) to provide task efficient illumination for public and specialist areas throughout the NHS estates. Illumination levels recommended for navigational areas for a typical hospital extends from 20-1000 lux for lighting specifications previously detailed in this chapter. Operating theatre cavities have an estimated illumination of 40,000 – 160,000 lux and is not accounted in this research. Brand-influenced colour coded navigation in NHS hospitals have target environments with approximate illumination levels of 20 – 1000 lux. Approval of the navigational colour-coded signage is commonly based on graphic arts standards at a supplier's location. Graphic arts suppliers produce signage for such navigation and proofing would be expected to conform to ISO 3664:2009.

Figure 22: (a) NHS logo and colour description as specified by NHS Identity. (b) The magazines show how the NHS logo is used on publications. (http://www.nhsidentity.nhs.uk/ 2011)

Using colour as a coding component in an environment can be a powerful navigation tool in aiding people to find their way around a building. It aids memory recalling of shapes and patterns. In using it as part of signage coding it provides a sense of direction, aid wayfinding by enabling decision making and successful negotiation of a building easier. The NHS colour coded signage presents a visual system to simplify navigational decision making, divides hospital spaces into broad areas and sets out cues that provide information for its users to understand elements environments.

Colour coded design plays a big part in helping NHS users to find their bearings and understand the spatial layout of hospitals and clinics. Users note areas have colour coded information about key routes to recognise their arrival at their desired destination. Once a route is selected by users they access textual information and colour coded visual cues to aid their movement around and through the building to their desired destination. The consistency of the communication material, including colour, contrast and text are as such critical (**Dalke et al. 2004**).

The various branded products that carry the NHS identity are engaged with across the NHS estate (**Dalke et al. 2004**):

- Reception (200-500 lux) depending on the size of the room and whether there is mixed lighting induced by daylight;
- Clinical assessment and observation in the ward (300 lux) at theoretical pillow position.
- Intensive therapy units (400 lux) however, may be adjusted to 1000 lux for critical examination;
- Wards (300 lux at reading points and 100-150 lux in between with an average of 5-10 lux at floor level at night) are predominantly illuminated by daylight during the day;
- Nurses stations (30-200 lux) allows the reduction of light levels at night to but providing sufficient lighting for required tasks;
- Corridors (150 lux) pathway finding is aided by signage and colour coded directional markings;
- Stairwells (25-50 lux);
- General treatment rooms (750 lux);
- Labs (750-1000 lux);
- Operation theatres (1000 lux) where during surgery an operating cavity has 10,000-100,000 Lux;
- Offices (300 lux);

For areas where illumination levels are up to 400 lux a colour rendering index of Ra80+ is expected for illumination sources. All other areas of 500 lux or more should have Ra90+ colour rendering index. The recommended colour temperature across the estate is 4000K. All the NHS Hospitals and healthcare facilities use colour coding to aid internal and external way-finding (**Enterprise IG 2005**). There is an expectation that people would be able to use the colour coding to assist their navigation around NHS environments successfully despite differing illumination levels.

xi. Brand summary

It has been established that a brand colour represents an important element of the brand's visual identity. As previously discussed colour facilitates memory recall, differentiates a brand from competitors or even serves as a signal through psychological meaning. This necessitates the need to ensure consistency in the reproduction of brand colours. As such this depends on defining methods that would in some way preserve the visual identification of a brand image. Such a method would result in acceptable representation of a brand colour when reproduced for different viewing conditions. In graphic arts, acceptable representations of colour is often judged based on a tolerance which, is an acceptable variation in either measured or observed colour. Brands in establishing their presence produce a wide array of communications that employ their brand colours in some context for multiple target environments. The question therefore arises as to whether colour tolerances employed in the graphic arts industry can satisfy the requirements of identity branding.

To test this, question a national brand was used to develop the research process. The NHS is the brand used in the research because it is a widely-known brand and uses a vast array of colour branded communications. The brand has multiple specifications that are intended to be replicated across their estate, such as lighting specifications for designated areas of hospitals and clinics, colour coding of hospital navigation (pathway finding), use of multiple displays in various locations, and shortlisted numbers of print suppliers that produce branded communications across the country through visual identification guides. All brand commissioning and actual decisions on colour acceptability approval is the remit of the various brand managers at regional and centralised locations.

2.7 Colour Tolerance

In the context of this research colour tolerance is considered as the permissible visual colour difference that is deemed as acceptable in colour-matching terms. Brand related colour reproduction requires multi-stage approval by brand owners, artwork developers, pre-press proofers, and production minders. Along this trail of colour auditing there are several matching judgments carried out to achieve the limits of tolerance. When conducting such assessments, observations are carried out based on pass/fail criteria where each decision is a preferred colour-difference. Each colour stimulus is defined in colorimetric terms so that an association between stimulus and observation can be established (**Bunkall and Quinn 1969**) as units of a psychological scale. The scale defines an estimation of generally accepted colour differences across all samples, a measure of standard and a sense of distance, in Euclidean terms, between reference and samples (**Boring 1939**). Colour tolerance pass/fail assessment leads to the establishment of boundaries for the values of CIELAB between a reference and samples. Samples that are adjudged to fall within these boundaries are within tolerance as correlates of visual assessment. Figure 23 shows an example of a tolerance ellipse denoting a pass criterion with rejected samples outside of the ellipse.

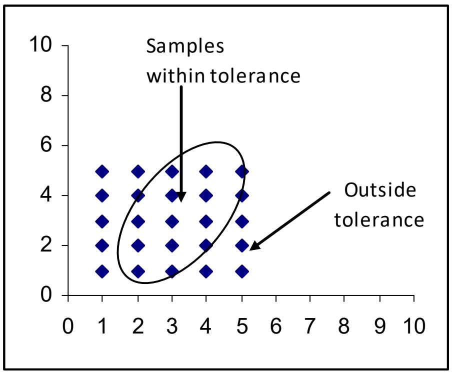


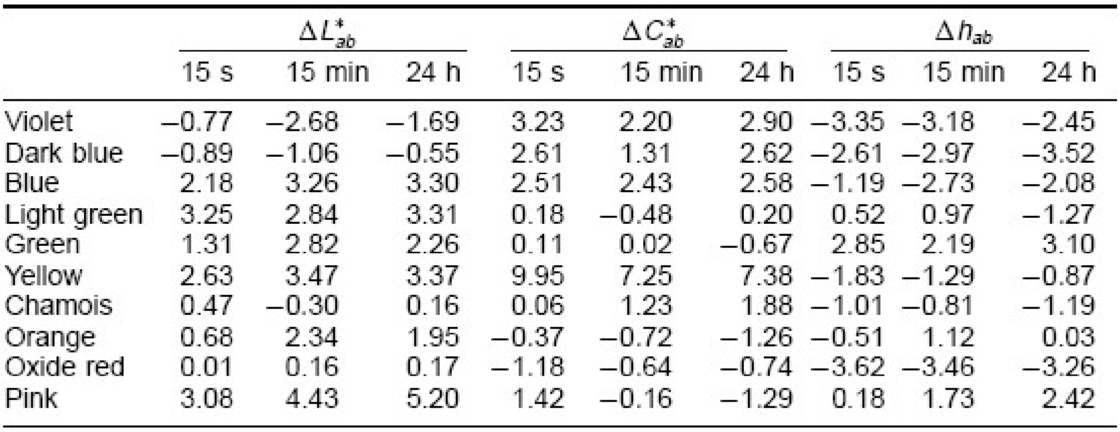
Figure 23: Rejected sample fall outside of the ellipse.

In the packaging of branded products, the aim is to avoid perceived visual variations because consumers establish a relationship between colour packaging and expected sensory characteristics (**Wei et al. 2012**). As such the ability to derive a visual tolerance provides a tool for quality assessment and marketing purposes.

2.7.1 Configuration

Colour-matching configurations are commonly defined by two well-known methods referred to as simultaneous and successive. The key differential is the time lapse between the presentation of reference and sample stimuli. Simultaneous matching is the presentation of a reference and sample as an adjacent pair. It has been well researched that the human visual system detects small colour-differences efficiently when colour stimuli are presented adjacently (**Kaiser and Boynton 1996**). Successive matching is more commonly referred to as memory matching. In memory matching, there is time lapse so observers make judgments based on what can be remembered. It is also not inconceivable to conduct memory as recollected matching in entirely different viewing conditions. Memory matching is part of daily life activities that evoke gaze shift when purchasing items to match or even locating known products in a supermarket (**Bartleson 1960**). Colour memory study was found by Bartleson to present varying results depending on observers' associated familiarity with the object in question. Additionally, Katz (**1999**) noticed that remembered colours stressed the chromatic attributes with increased saturation and lightness increments. There was clearly affirmation of exaggeration in the salient aspects of an object colour for which the key changes in the recalled resided in the dominant wavelength and colorimetric purity (**Pérez-Carpinell et al. 1998**). In the L*a*b*space seen in Table 2 yellow, light green, blue and pink showed an important shift with mean colour difference higher than seven CELAB units, except blue and pink at 15 seconds **(M D de Fez et al 1998)**.

Table 2: Lightness, chroma, and hue colour differences between the colour matching and the colour test in the CIELCH space (**M D de Fez et al 1998**).



	ΔL^*_{ab}			ΔC^*_{ab}			Δh_{ab}		
	15 s	15 min	24 h	15 s	15 min	24 h	15 s	15 min	24 h
Violet	−0.77	−2.68	−1.69	3.23	2.20	2.90	−3.35	−3.18	−2.45
Dark blue	−0.89	−1.06	−0.55	2.61	1.31	2.62	−2.61	−2.97	−3.52
Blue	2.18	3.26	3.30	2.51	2.43	2.58	−1.19	−2.73	−2.08
Light green	3.25	2.84	3.31	0.18	−0.48	0.20	0.52	0.97	−1.27
Green	1.31	2.82	2.26	0.11	0.02	−0.67	2.85	2.19	3.10
Yellow	2.63	3.47	3.37	9.95	7.25	7.38	−1.83	−1.29	−0.87
Chamois	0.47	−0.30	0.16	0.06	1.23	1.88	−1.01	−0.81	−1.19
Orange	0.68	2.34	1.95	−0.37	−0.72	−1.26	−0.51	1.12	0.03
Oxide red	0.01	0.16	0.17	−1.18	−0.64	−0.74	−3.62	−3.46	−3.26
Pink	3.08	4.43	5.20	1.42	−0.16	−1.29	0.18	1.73	2.42

The greater variability in matching of surface colours is considered to exist in successive configuration than in simultaneous matching (**Newhall et al. 1955, Nilsson and Nelson 1981**), suggesting that long intervals degrade colour appearance recall. The work of Pérez-Carpinell et al. (**1998**) highlighted the tendency of diminishing discrimination from about 15 seconds was previously found by Hanawalt and Post (**1942**) to show consistent recall of colour descriptors up to 15 minutes despite the occurrence of slightly increased saturation and reduced lightness (**Hamwi and Landis 1955**).

2.7.2 Quality

The quality of colour stimuli is often an estimation of objective mathematical assessment that models the visual perception of a human visual system as an initial step. Subsequently a subjective evaluation of psychophysical assessments, using a standard viewing condition, provides estimates of the color reproduction quality as a visual correlate (**Ludovic et al. 2008**). The most common evaluation of such relational assessments is a difference between the mathematical colour difference ΔE and the visual color difference, denoted as ΔV . The colour-difference metrics may include additional parameters to extend the basic tristimulus model to capture illumination and viewing parameters. There is generally a desire for the reproduction metrology of ΔE to approach values derived from ΔV such that image quality computed metrics could be predicted by the visual differences. There are a series of statistical models designed to test the strength of correlation between ΔV and ΔE namely *PF/3*, STRESS and controversially R^2.

PF/3 is a combined index proposed by Guan and Luo (**1999**) from previous metrics suggested by Luo and Rigg (**1987**) which in turn employed the **γ** parameter. It incorporates *CV* metrics proposed by Alder et al. (**1982**) and the V_{AB} metric proposed by Shultze (**1972**). The *PF/3* equation is as follows:

$$PF/3 = \frac{100[(\gamma - 1) + V_{AB} + CV/100]}{3}$$

A *PF/3* value of zero indicates a perfect agreement between ΔV and ΔE . García et al (**2007**) consider that *PF/3* has a significant shortcoming in its ability to indicate the statistical significance of the difference between colour-difference formulas or spaces. However, research determined that when complemented by F-tests (**Luo et al 2006**), first proposed by Alman (**1989**), determining whether a new colour-difference formula significantly improves a previous one becomes possible.

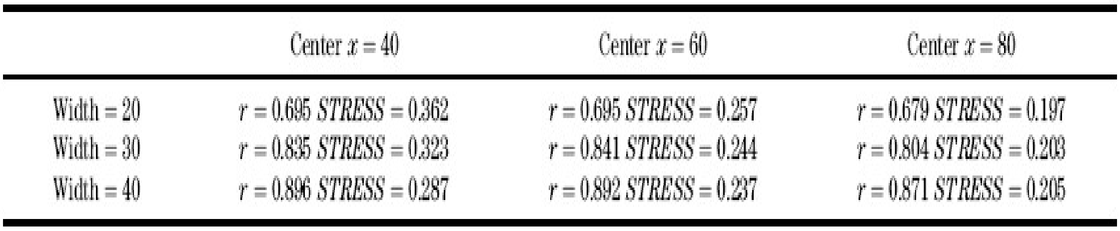
The Standardized Residual Sum of Squares (STRESS) test is multidimensional scaling (**Kruskal 1964 and Coxon 1982**), for which dissimilarities between object pairs are denoted as a coefficient and approximated in distance between corresponding pairs and visually represented (**Garcia et al. 2007**). The resulting loss function is the so-called normalized STRESS or Kruskal's STRESS (**1964**):

$$STRESS = \left(\frac{\sum (\Delta E_i - F_1 \Delta V_i)^2}{\sum F_1^2 \Delta V_i^2} \right)^{1/2}, \quad \text{with } F_1 = \frac{\sum \Delta E_i^2}{\sum \Delta E_i \Delta V_i}$$

STRESS index can be used to calculated data for determining the performance of colour-difference formulas and compare observer variability for colour-matching colour pairs, under specified illumination and viewing condition. The colour pair is represented by ***i*** and perceived colour difference **ΔV_i** with the computed colour difference **ΔE_i** (**Melgosa et al 2011**).

Kirchner and Dekker (**2011**) however, argue for the use of Pearson's correlation coefficient as a measure for goodness of fit for a pair of colour-difference formulas in relation to **ΔV** and **ΔE**. In their argument against the uses of PF/3 and STRESS they explained that the two approaches were sensitive to averaging the colour difference in a data set, which is depicted in Table 3. This was considered to contribute to the varying STRESS values reported by Melgosa et al. (**2008**) in the evaluation between CIELAB and CIEDE2000 for five different datasets.

Table 3: STRESS compared to the correlation coefficient showing less sensitivity to the location of the center of the distribution of data points but more sensitive to changes in the width of that distribution (**Kirchner and Dekker 2011**).



	Center $x = 40$	Center $x = 60$	Center $x = 80$
Width = 20	$r = 0.695$ $STRESS = 0.362$	$r = 0.695$ $STRESS = 0.257$	$r = 0.679$ $STRESS = 0.197$
Width = 30	$r = 0.835$ $STRESS = 0.323$	$r = 0.841$ $STRESS = 0.244$	$r = 0.804$ $STRESS = 0.203$
Width = 40	$r = 0.896$ $STRESS = 0.287$	$r = 0.892$ $STRESS = 0.237$	$r = 0.871$ $STRESS = 0.205$

The main assumption suggested that the STRESS model assumes a starting point of zero which would equate to $(\mathbf{1}\text{-}\boldsymbol{r}^{2})^{½}$ where *r* is based on restricted linear regression going through the origin. In this research, the STRESS model is used for establishing colour-difference formula performance and correlation with the magnitude of the visually perceived difference, which cannot be attained with $\boldsymbol{r}^{2}$. The correlation coefficient is however employed when conducting psychophysical analysis of observer positional ordered perceptual responses.

2.7.3 Judgment

Branding requires the delivery of products with visual cues that exhibit desired colour representation. Where large variations exist, control is required to restrict tolerance to an extent where it is appropriately recognisable by brand managers or consumers and suits their expectations. In the pursuit of acquiring threshold units for colour reproductions determining measures of perceptibility and acceptability provide the most useful metrics. To determine the perceptible, difference a sense of deviation from the intended reproduction target is sought. This is done through psychophysical assessments that elicit observer responses. Acceptability, on the other hand, evokes a tolerable colour-difference that represents a threshold of error averages (**Kim et al. 2011**). The determining of such thresholds is a significant part of colour quality control in the various reproduction processes. It has however, been shown that even if two pairs of colors show the same perceptibility, acceptability judgments can be different from each other (**Berns 2000**) and as such further analysis is necessary.

From the observer response data of the psychophysical assessments a psychometric function can be derived to determine the thresholds and level of uncertainty. This would apply to either to a single observer or entire population of observers, for whom responses fall into a pass or fail category. The psychometric estimation is a function of stimulus intensity for the percentage of a categorised response. The function $\psi(x)$, specifies the relationship between the underlying probability of a correct response ρ and the stimulus intensity x . The curve shape is determined by the parameters {□, □, □, □}, and the observer choice of pass-fail (0,1) denoted by a two-parameter function *F*, which is typically a sigmoid function. The parameter □□gives the lower bound of □ (*x*; □, □, □, □) which can be interpreted as the base rate of performance in the absence of a signal (**Wichmann and Hill 2001)**.

$$\psi(x;\alpha,\beta,\gamma,\lambda)=\gamma+(1-\gamma-\lambda)F(x;\alpha,\beta)$$

The function itself increases from 0 to 1 and a threshold level of 50% is considered as a point at which observers may be guessing. However, results at 75% or higher give an indication of correct detection stimulus intensity 50% of the time. This is essentially a description of an observer’s probability response as a function of stimulus variation (**Wichmann and Hill 2001**).

The most commonly used psychometric functions to fit data are Probit, Logistic or Logit functions. The commonalities between these functions are sigmoidal shape, monotonic increments from 0 – 1 and data fitted parameters (**Berns et al. 1991**).

Probit function

$$f(x\mid\alpha,\beta)=\int_{-\infty}^{\alpha+\beta x}\frac{1}{\sqrt{2\pi}}e^{-z^2dz}$$

Logit function is the inverse of the sigmoidal "logistic" function.

$$\operatorname{logit}(p) = \log\left(\frac{p}{1-p}\right) = \log(p) - \log(1-p) = -\log\left(\frac{1}{p} - 1\right).$$

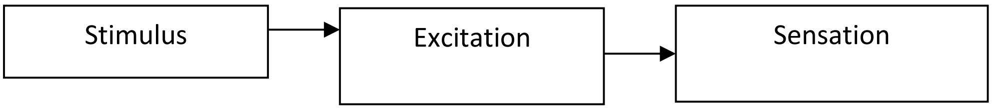
Logistic regression

$$f(x \setminus \alpha, \beta) = 1/[\ 1 + e^{(\alpha + \beta x)}\ ]$$

2.7.4 Psychophysics

Previously, in this research, it was established that the interaction between the human visual system and electromagnetic radiation resulted in the appreciation of the phenomenon of colour. Further to this was the defining of the physical properties of the stimulus and how its perceptual attributes could, in some way, be predicted through measurement: attributes of colour perception being brightness, colourfulness, saturation, chroma and hue. Psychophysics seeks to establish a correlation between the perceptual experience and physical stimuli. To achieve the goal of defining colour tolerances that are deemed as acceptable appearance matches in branding, across the various environments of viewing, it is important to establish a relationship between the physical measurements of the brand stimulus and perceived sensations that arise.

This process of quantifying the mapping between subjective responses to perceptual attributes for an observer to derived measures of perceptual phenomena is termed psychophysics; the scientific study of the relationship between stimulus and sensation (**Gescheider 1997**). Here there is an analysis of perceptual processes by studying the effect it has on a subject's experience or behaviour with the systematic varying of the properties of a stimulus along one or more physical dimensions (**Bruce , Green and Georgeson 1996**). A simple representation of the mapping would be (**Spillmann and Werner 1990**; **Spillmann and Ehrenstein 1996**):



Significant formulation and progression of psychophysics in the modern era was greatly facilitated by the works of Weber (**1834**), Fechner (**1860**) and Stevens (**1961**). E.H Weber in investigating the discrimination of lifted weights established that the size of the difference threshold was a linear function of the stimulus intensity. This relationship between the size of the difference threshold and stimulus intensity level is known as Weber's law. It states that the ratio of $\Delta I/I$ is constant, whereby I is stimulus intensity and ΔI is the change in stimulus intensity required for achieving a just noticeable difference. Fechner (**1966**) introduced techniques for measuring mental events, which enabled the specification of the smallest amount of stimulus energy required to produce a sensation. The ensuing law from Fechner's work states that the relationship between the magnitudes of physical stimuli and resulting perceptions is logarithmic. Stevens (**1953**) law however stated that this relationship is exponential and thus challenged the validity of Fechner's law of logarithmic function. Stevens's law reflects the modern validation of the relationship between stimulus intensity and sensation magnitude.

The modern approach to this subject acknowledges four basic types of measurement scales for perceptions as nominal, ordinal, interval and ratio. Each scale represents varied degrees of correspondence to a number system and property system of events or objects. A nominal scale is a discrete classification of data that reflects qualitative differences, for which either labelling or naming is applied to the data, rather than quantitative ones. In a nominal scale assigned numbers are used to distinguish one thing from another so it important that no two items have the same number. An ordinal scale information is about assigning a magnitude of differences between represented values. The set of measurements characterise the number of objects or events that exist in ranked order. The application of the rule of numbers requires that the rank order corresponds to that of the property being measured. An interval scale indicates quantified differences between amounts of the property measured, as represented by intervals between scale values. A ratio **scale** is an interval scale with a meaningful origin that represents the zero amount of a property. The data construct permits comparison of the differences of values in relation to the origin such as estimating an order of magnitude.

The main psychophysical approach used in this study is the threshold method, to determine the measure of sensitivity to stimulus changes and detection metrics required to achieve a threshold in varying experiment configurations. Visual experiments in psychophysics are grouped into two main categories namely threshold and scaling. Scaling is suited to generating a relationship between the physical and perceptual magnitudes of a stimulus. The scaling technique, **paired comparison**, which is a one-dimensional psychophysical scale, is the preferred method when observer interaction is required for scaling to establish the acceptance of appearance match predictions. In this method of scaling observers are either required to scale samples to perceptually match a reference stimulus or arrange samples in a continuum relevant to a reference.

Thurstone’s law of comparative judgement (1927) presents a psychological scaling method onto which stimuli are mapped and each time a stimulus is presented there is a presumption that it can be represented by a point along a scale. Therefore, Thurstone declared that a given stimulus did not always result in identical observer response due to momentary fluctuations and as such results in a random variable on the psychological continuum. The assumption is that an observer is unlikely to report an exact value of discrimination between moments, so such scaling must be done indirectly **(Zwick 1985)**. It is assumed that the `just noticeable difference' is impacted by the notion that an observer is inconsistent in their comparative judgments from one moment to another. For the same pair of stimuli, the observer gives different comparative judgments on successive occasions hence the discriminal process is not fixed. The psychological continuum is defined to show that the frequencies of the corresponding discriminal processes for any given stimulus form a normal distribution on the psychological scale. **(Thurstone 1927).**

The resulting data can then be transformed into interval scales to give a representation of error-distance between the reference and sample stimulus in terms of confidence in appearance matching. Thurstone's law of comparative judgement (**Thurstone 1927**) provides a suitable means of representing such translation of derived data. Thurstone's Law indicates that the value of the scale difference between any two stimuli in a paired comparison assessment is a random variable that has a probability density function which forms a normal distribution. The mean value of this distribution represents the scale value difference between the two stimuli in being compared:

$y_i - y_j = z_{ij}\sqrt{\sigma_i^2 + \sigma_j^2 - 2p_{ij}\sigma_i\sigma_j}$ where z_{ij} is the normal deviate, z-score, corresponding to the proportion of times stimulus i is judged greater than stimulus j; and $y_i - y_j$ represent the scale values for stimuli i and j, respectively. The notations σ_i and σ_j are standard deviation values for stimuli i and j among observations respectively. The correlation coefficient between stimuli i and j is p and ranges from -1 to 1.

Variations of the law of comparative judgment assume that stimuli are independently compared many times and therefore there is the possibility that observers will use memory of earlier judgments of stimulus pairs if they can be identified. This necessitates the need to control the conditions to eliminate biasing effects by randomising relative positions and orders.

2.7.4.1 Numerical category technique

The numerical category technique used in this research is based on category judgement technique. Numerical values are assigned to verbal responses to elicit perceived judgements of colour differences from observers, based on a 6-point category scale of:

0 = Not perceptible;

1 = Barely perceptible;

2 = Perceptible but acceptable;

3 = Barely acceptable;

4 = Just unacceptable;

5 = Unacceptable.

The category judgement here deals with the subjective assessment of perceived colour reflecting the closeness of match to a reference as well as the ability of the individual to discriminate between JND values (**Laborie et al. 2010**).

Without presenting quantitative information about a pair of colours it is possible to derive observer perceived ratings of their similarities or differences (**Shepard 1980**). Each qualitative response is associated with a binary variable that answers the comparison query of the closeness of the colour pair or other. Observers are known to be better at associating verbal descriptions to assessments as opposed to giving more detailed numerical judgments (**Stewart et al. 2005**). Using the technique as employed by Green and Johnson (**2005**) this research quantifies such responses for brand colours in various viewing configurations. Their decision to use category judgement was borne out of the need to obtain more detailed information about observer judgements whilst facilitating intuitive decision making. Simple pass-fail decisions tend to remove response sensitivity from observer responses which may consider contextual nuances. Shepard (**1966**) stated that ordinal data about the underlying magnitude of difference can be obtained from some judgements and may be used to derive an interval scale.

This research extends the psychophysical technique of assigning descriptive ratings to ordinal data to determine a representative dimension of the objects being judged (**Shepard 1966**). Green and Johnson (**1999 and 2001**) developed a variant of this approach to produce psychophysical methodologies for assessing colour differences in graphic arts. In this research, these techniques are adopted as a psychophysical test method to determine observer assessments. It is known that in categorised judgements observers tend to focus attention towards a biased centre tendency for judgments, which is relevant to each observer’s perception. Their responses gravitate toward a mean magnitude relative to the reference stimulus and as such shorten the range of the dependent variables (**Garner 1953 and Hollingworth 1910**). There is suggestion that this results in sequential dependencies of judgments, so the labelling of the sequential metrics significantly removes elements of bias. Green and Johnson however, noticed some observer tendency to restrict judgements to a limited subset of available categories. They established that real-life judgements of acceptability improve contextual decisions and helps observers to reach decisions with less hesitation, which helps throughput. This manner of assigning labelling to ordinal data also provides more detailed information about the decisions observers made which a pass-fail method could not.

2.8 Summary

The experiment, which is detailed in Chapter 5, assess colour perception with changes in levels of illumination for a selection of NHS brand colours used in such navigation. The work of Crawford (1973) determined that for picture galleries there was a level at which the capability of the human eye in discriminating small colour differences began to deteriorate. Through a series of experiments Crawford found that an illumination level of 30 lux was the minimum desirable, as a practical lower limit of illumination from the point of view of colour discrimination. For expert observers Crawford found that 10 lux was the minimum illuminance. His experiment took into consideration the less-experienced viewers of pictures and complete adaptation with the absence of glare. Observers were required to determine noticeable colour difference between a test and sample areas of a field at different illuminances. In this research experimentation under different illuminances is used to determine colour discrimination like Crawford. However, the range of illuminances are designed to test colour discrimination in relation to a threshold of acceptability when the lux level increases or decreases. The lower illuminance was found to mimic the 30 lux Crawford determined as a suitable practical minimum and reside somewhere between 25-50 lux. It was also determined that an illuminance increase to 3000 lux was the maximum suitable for use in colour coded internal navigation signage.

Ishida (2002) on the other hand researched the use of colour as a visual task aid under different illuminances, which closely aligns with research in using colour for coded navigation as a wayfinding tool. The chosen illumination levels were 1000 lux, 10 lux, 1 lux, and 0.1 lux. Observers were asked to search for colour chips to match a named category. At 1 lux observer identification dropped off significantly. More recently Radonjić et al (2016) Tested for measured sensitivity to changes in illumination for blue, yellow, red, and green. The stimuli were presented to observers in two different scenes. One was a real illuminated scene and the other simulated but closely matched the real one, using hyperspectral imaging. Their outcome showed that observers were able to discriminate fine chromatic changes in illumination for the stimulus scenes used. Having established discrimination efficiency like Ishida (2002) and Radonjić et al (2016) between a wide range of illuminances for colour sets this research determines the colour acceptability threshold for each illuminance used. Whilst there are many papers that research colour discrimination under various illuminances they are not linked with colour tolerance thresholds as found in this research. This provides a more practical use for such research where thresholds are linked with brand colours' visual consistency for target environments.

The main aim of the experiment in Chapter 6 was to determine the extent to which the ICC medial relative correction could be pushed to accommodate changes in white point for solid colours and tints. ISO 12647-2:2007 provides guidelines for retargeting such substrate white point differences that extends to 2.5-3 ΔE^*_{ab}. Tian and Chung (2011) in their paper found that the impact of OBAs (optical brighteners), which result in differences between proof and production was significant. They concluded that the color difference resulting from OBAs in paper was greater than color differences due to measurement backing. They also determined that the colour patches with less ink coverage resulted in larger colour differences. In this thesis using the ICC media relative correction model it was found that a colour patch with less ink coverage could be corrected up to approximately 2.5ΔE^*_{ab}. A colour patch with significantly increased ink, solid, could be corrected for a change in the substrate whiteness in the region of 9.5ΔE^*_{ab}. This result of this experiment was instrumental in the adoption of ICC media relative correction into the ISO print standards.

In Chapter 7 the use of displays for branded content and the complementing of film-based medical imaging with displays is becoming more commonplace across the NHS estate. Medical imaging requires significantly higher intensity to accommodate grey levels that far exceed the 256 shades used in displaying non-medical information. Carter (2013) considers that the increasing penetration of computation and information display in society makes it a high priority for self-luminous greyscale calculation to be realised. Carter and Brill (2014) proposed an alternate approach that could feasibly complement CIE L* and facilitate the increase of JNDs relevant to maximum luminance, that could rival the DICOM GSDF established discrimination levels. The approach was to use Whittle's log brightness function. The assumption is that the display of branded content on multiple displays, with similar viewing conditions, will look broadly the same if all the displays use the same greyscale function and luminance range. The Carter and Brill (2014) hypotheses was tested with psychometric assessments of observer judgments for just-noticeable-differences between near neutral reference targets and their corresponding samples. STRESS test was applied to the data and it was found that Whittle's log brightness function performed slightly better than DICOM GSDF. The full STRESS results have been contributed to the TC 1-93: Calculation of Self-Luminous Neutral Scale draft document.

In Chapter 8 This best fitting colour-difference model between CIELAB and CIEDE2000 was tested using STRESS multidimensional scaling. Recently Cui, Luo et al. (2013) tested the performance of colour-difference formulae for assessing colour differences near the neutral axis. It was determined that CIELAB and CIEDE2000 colour difference model prediction of hue, near the neutral axis, was better than its prediction of lightness, chroma and the chroma-hue interaction. The assessment of CIEDE2000 parametric also showed that the lightness parameter k_L had a greater influence on the balance of an overall colour difference than the k_C factor. In this thesis, it was found that the results were in in line with the findings of Cui, Luo et al. (2013) however for displays CIEDE2000 performed better than CIELAB in ΔL^*.

Chapter 3 – Aims and objectives

Aims

The aims in this research were borne out of a need an NHS branding requirement to deliver a more consistent brand visual appearance for the NHS logo colour across an extended range of white stationery. A secondary requirement to consider tolerances for NHS colour palette used in wayfinding was included. From this set of the following aims were developed:

1. To determine how far changes in the whiteness of a substrate, namely the NHS stationery, leads to an unacceptable change in the appearance of the NHS logo blue. NHS stationery white points extended beyond ISO 12647-2 guidelines.

2. To find out whether colour coded wayfinding in hospitals were easily recognised by observers as designated areas within such environments had varying illumination levels. This was despite the use of illuminants of the same colour temperature and colour rendering index exceeding 80.

3. To consider the consistency of colour appearance of brand colour coded images, primarily NHS blue, delivered by displays of varying illumination within a specific target location.

Objectives

1. To test the acceptability tolerance of a brand colour reproduced on substrates of changing white points a psychophysical experiment was devised. Changes in the white points of was extended considerably beyond ISO 12647-2 guidelines and included displays. Conversions for the simulated changes to the target colours were to be converted using media relative colorimetry.

2. Using a simulation of wayfinding colours commonly used in the NHS hospitals a psychophysical experiment was developed to test 5 distinct NHS illuminances, ISO 3664:2009 practical and critical illuminances. Due to the random nature of wayfinding in relation to target area illumination level the illuminances during the experiment would also be randomized.

3. The approach taken to determine the impact of different illumination on brand colour images was to conduct a psychophysical test, using near neutral brand colours, for a judgment of comparison between a reference and a sample set. Three illumination intensities were set for each series of observations. The results from this test as also applied to a comparison between greyscale distribution for DICOM versus Whittle’s log brightness function.

4. Throughout the various experiments the metric representation of colour differences assessed were calculated using both CIELAB and CIEDE2000 colour difference formulas. It was there essential to test which formula performed best in suitably representing observers’ estimation of differences and tolerances. The data from the greyscale experiment, which was also conducted in hardcopy for a substrate that had very little optical brighteners, was used to test for the most suited colour difference formula.

Experimental procedures

3.1 Colour perception with changes in levels of illumination

This experiment is designed to determine colour perception and tolerance for colour coded navigation. Such coding is used by the NHS to visually segment locations of hospital disciplines and each area is illuminated under different lux levels.

- Using a Verivide viewing booth, with variable illuminance settings, 7 approximate lux levels were preset. The location for displaying target reference and sample colours for judgment is measured with a calibrated lux meter check illumination value;
- Four NHS brand colours used in navigation colour coding are chosen as reference targets, namely brown, blue, pastel green and pastel yellow. Each colour is then varied according to increasing and decreasing lightness, chroma and hue for sample targets.
- Target colours measuring 2.5cm x 2.5cm were then printed out using a characterized HP Deskjet 995c printer. Each sample was measured at 3 random points then averaged for homogeneity.
- Under each illuminance observers were asked to arrange the reference and samples of either increasing or decreasing colour difference values in a continuum. Selected targets were placed in a scrambled manner at the base of the viewing cabinet and observers arranged them on a raised shelf.
- Observers also assessed the magnitude of colour difference between reference and sample targets based on a scale of 0-5 where 0 denoted no perceptible difference and 5 an unacceptable match. Samples were placed next to the reference for judgment in a random manner.
- Observations were initially transformed into pass/fail scores according observation group scores of 0-3 or 4-5 on the category scale. The data was then ordered per the magnitude of the colour difference in the selected metric.

3.2 Perceived acceptability of colour matching for changing substrate white point

When acceptability depends on accounting for the change in paper colour appearance preservation of the original when printed on the production substrate is essential. Using ICC Media-relative Colorimetric rendering intent this experiment determines acceptable colour difference tolerance for substrates that differ in colour.

- The reference substrate CIELAB coordinates was selected from ISO 12647 paper types;
- 14 variants of the reference substrate, differing from the reference by 1-10 CIELAB ΔE^*_{ab} was created;
- Five NHS colour centres of red, green, blue, orange and purple were chosen along with corresponding tints. Target colours measuring 2.5cm x 2.5cm were then printed out using a characterized HP Officejet Pro 8600;
- The surrounding border for target colours was as depicted in Figure 24.

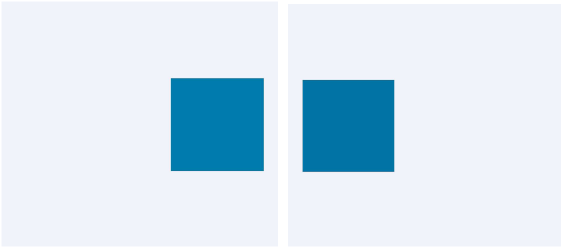


Figure 24: Simulated depiction of target colour layout configuration.

- The hardcopy observer judgments in this experiment was conducted using a Verivide viewing booth with D50 simulating illumination at 500 lux (±25 lux) against a surround with 20% reflectance;
- For display observer judgments, an Eizo colour monitor with a 120cd/m^2 peak white luminance was used. Using a Minolta CS-1000A telespectrophotometer all colours, displayed for observation were measured. The spectral radiance data converted to tristimulus values normalized to the display peak white as L*=100.Three configurations were presented to observers for judgement.

  - Simultaneous hardcopy, where the observer judges a print against a proof on a different paper;
  - Sequential, where the observer judges a print having previously viewed a proof on a different paper;
  - Simultaneous display, where the observer judges a print against a soft copy proof on a display screen.
- Observers are asked to estimate the size of colour difference between reference and sample based on a six-point category scale. Observations were initially transformed into pass/fail scores according observation group scores of 0-3 or 4-5 on the category scale. The data was then ordered according to the magnitude of the colour difference in the selected metric.

3.3 Psychophysical evaluation of grey scale functions performance

A psychophysical experiment was conducted to evaluate the performance of metrics for observer perceived difference detection, for a set of near neutral samples at different luminance levels. The medical imaging DICOM standard function GSDF is mimicked by Whittle's brightness function and used to evaluate observer magnitude estimation. Psychometric assessments by observers are based on judgment of the just-noticeable-differences between reference targets and their corresponding samples.

- a calibrated EIZO ColorEdge CG246 monitor for which approximated peak white point luminance levels of 282 cd/m^2, 229 cd/m^2 and 166 cd/m^2 were set for three phases of experimentation.
- Measuring with a Minolta telespectroradiometer the display black point was determined as having a luminance of 0.22cd/m^2 located at the observation position relative to the screen.

- Display viewing conditions pertaining to ISO 3664:2009 was used with dark surround. The samples were centrally positioned on the screen with observers at approximately 80cm away in distance relative to target size.
- 24 near neutral perturbations were generated respectively for CIELAB L*22, L*52 and L*88 values. A total of 72 observations were carried out each at luminance levels of 282 cd/m^2, 229 cd/m^2 and 165 cd/m^2.
- Observers were initially presented with a colour pair that had a magnitude difference of 1 as a judgment guide. Afterwards they were required to estimate the magnitude of difference between a reference and sample for the 24 near neutral perturbations at each of the display white point luminances.
- The resulting mean data of observer estimations were then used to calculate GSDF and Whittle's JND (just noticeable difference) functions for predicting greyscale differences.

3.4 Near neutral colour parametric weighting for CIEDE2000

This experiment is designed to generate weighting metrics for near-neutral CIEDE2000 colour differences

- Using the CIELAB colour space model two near neutral reference points with lightness variations of L*16, L*52 and L*88 are chosen. Lightness, chroma and hue step intervals of ±6ΔE^*_{ab} from the references are assigned as samples.

- The chosen hardcopy reproduction media is a bright white proofing paper with no optical brighteners in it. The white point of this media is measured as CIELAB data using a white backing.

- For display judgements, the near neutral colours are presented using sRGB profile in an Adobe Flash developed application.

- The reproduction of each stimulus on the chosen media is 3cm x 3cm and the background is 9cm x 8cm positioned so that they are .25cm to one edge as depicted below in Figure 25.

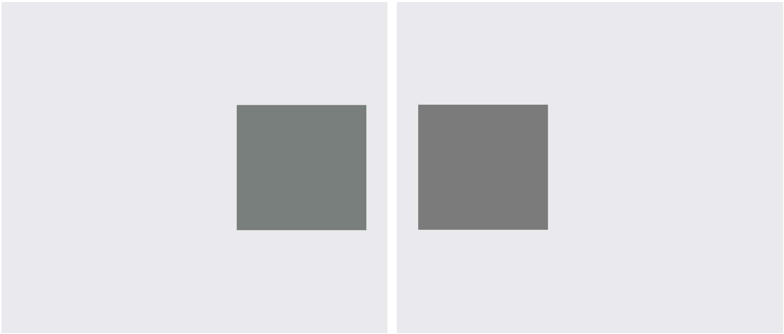


Figure 25: Target configuration showing stimulus and substrate.

- Judgments were made in a Verivide viewing booth that conformed to ISO 3664:2009 and a simulation of the P1 viewing specifications, with an approximation of 2000lux illumination was employed.

- In-situ measurements of all samples, for both experiment configurations, are made using a Minolta Spectroradiometer. Hardcopy reference and sample stimulus are initially measured using a GretagMacbeth Spectrophotometer.

- Initially observers are asked to arrange each set of samples in a continuum, as depicted in Figure 26, along with each corresponding reference for the hardcopy format in the booth. This step was designed to get less experienced observers acquainted to working with near neutral colours.

Figure 26: Near neutral samples ordered in a continuum.

- Each sample was then compared to a reference for which observers made judgements of estimated magnitude of colour difference. Observers were initially presented with a colour pair that had a magnitude difference of 1 as a judgment guide. The same procedure was carried out for the display configuration.

- For each sample observation, the recorded scores gave an indication of error estimation in relation to its magnitude of measured colour difference.

- Analysis of the observer data, using LINEST (least squares method), was carried out to calculate the estimation of weighting metrics for near-neutral CIEDE2000 colour differences.

Chapter 4 - Colour perception with changes in levels of illumination

Having previously established that colour perception significantly depends its viewing condition it would follow that colour coded navigation would be influenced in the same manner. The NHS in using combinations of brand colours as important cues for signage and navigation pathways, shown in Figure 27, require suppliers to adhere to strict colour reproduction tolerances. Typically, such stimuli would be judged using an ISO 3664:2009 standard however in the target environment illumination levels alter from point to point. The effect of such changes may have a significant impact on the navigation experience. To test this hypothesis a series of psychophysical experiments was conducted to determine whether changes in illumination level significantly alter acceptability and perceptibility thresholds of uniform colour stimuli.

4.1 Introduction

Psychophysical experiments were conducted under 7 levels of illumination (25 lux, 50 lux, 250 lux, 500 lux, 1000 lux, 2000 lux, and 3000 lux), using 24 observers of normal colour vision to evaluate the extent to which perceived colour difference altered in observer judgment. Reference colours were derived from the NHS identity colour palette (**http://www.nhsidentity.nhs.uk/all-guidelines/guidelines/independent-sector-treatment-centres/nhs-colours**). Viewing conditions for the experiment were

Figure 27: NHS Hospital wayfinding signage and medical specialities colour coding.

set to conform to ISO 3664:2009, which was described in Chapter 2, as such practical and critical appraisal illuminances were included. Derived samples were organised per hue, lightness and chroma for judgment. The 7 levels of illumination were chosen based on the maximum illuminance of the viewing booth at the location of test and reference stimulus is represented as 3000 lux. The remaining 6 illuminances represent 4 areas in NHS hospitals where coded signage is mostly engaged with by users and the two ISO 3664:2009 recommended viewing standards for graphics appraisal. The reference target comprises 3 colours commonly used for NHS signage and one control colour.

The relationship between metric colour-differences (ΔE) and visual differences (ΔV) was investigated for the viewing conditions used in this experiment. Metric colour-differences were calculated with CIELAB, CIEDE2000 and CIECAM02_UCS to establish the strength of relationship between ΔE and ΔV. A STRESS (standardised residual sum of squares) test was used to select the best fitting colour-difference formula, previously described in Chapter 2.

4.2 Materials and methods

4.2.1 Sample preparation

The colour centres and their perturbation variants provided a total of 144 samples that were varied in lightness, chroma and hue attributes. For each colour centre the numbers of the corresponding samples were

- NHS Blue: 36 sample pairs,
- Brown: 33 sample pairs,
- NHS Yellow: 36 sample pairs and
- NHS Light Green: 35 sample pairs.

The samples were printed on an 80g/m2 inkjet-coated matte office paper using an HP Deskjet 995c printer. The printer was calibrated and characterised to facilitate the colour management of printing reference and sample sets. Each sample was measured in three different locations, noted in Table 4 below using a GretagMacbeth Spectrolino spectrophotometer to determine its uniformity and accuracy with respect to the NHS brand specifications. The physical size of each sample was 2.5 cm x 2.5 cm. The measured mean colorimetric values in CIELab-CIELCh of the reference colour centres are also shown in Table 5

Table 4: Each printed NHS brand reference colour was measured in three places to average out differences across the sample as noted in this table. Colour difference values in CIEDE2000 and CIELAB show difference between expected and reproduction measurements.

Blue	L	a	b	**Brown**	L	a	b
measure 1	51.09	-3.41	-40.04	measure 1	51.60	9.18	16.21
measure 2	50.91	-3.27	-40.46	measure 2	51.06	8.98	15.71
measure 3	51.20	-3.83	-39.93	measure 3	50.91	9.20	15.49
avg	51.07	-3.50	-40.14	avg	51.19	9.12	15.80
ref	49	-5	-43	ref	50	7	15
ΔE_{00}	2.12	ΔE_{ab}	3.83	ΔE_{00}	2.56	ΔE_{ab}	2.36
P. Green	L	a	b	**P. Yellow**	L	a	b
measure 1	75.49	-22.83	14.68	measure 1	88.34	-3.61	21.57
measure 2	75.41	-23.96	14.99	measure 2	88.30	-3.36	20.91
measure 3	75.24	-23.92	14.62	measure 3	88.14	-3.43	21.40
avg	75.38	-23.57	14.76	avg	88.26	-3.47	21.29
ref	78	-25	12	ref	90	-6	22
ΔE_{00}	2.58	ΔE_{ab}	3.15	ΔE_{00}	2.73	ΔE_{ab}	3.11

.

Table 5: A representation of the measured mean colorimetric values in CIELab-CIELCh of the reference colour centres

Colour centre	***L****	***a****	***b****	***C**** $_{ab}$	***h*** $_{ab}$
NHS Blue	51.07	-3.50	-40.14	40.29	265.02
Brown	51.19	9.12	15.80	18.25	60.01
NHS Light Yellow	88.26	-3.47	21.29	21.57	99.25
NHS Light Green	75.38	-23.57	-14.76	27.81	212.06

Colour differences between reference and samples ranged between 0.14 ΔE^*_{ab} – 57.46ΔE^*_{ab}, incorporating tint options present in the NHS brand colour palette (**http://www.nhsidentity.nhs.uk**). With increased lightness, the colour tints exhibited larger colour difference shifts for which measurements were more influenced by the substrate. The NHS colour palette includes 9 tints for each primary colour. Large colour differences exceeding 20 ΔE^*_{ab} was encountered mainly between reference and in samples with changing lightness values for the light colours. Such colours represent tints that are representative of the colours used within the NHS brand for hardcopy prints. They are considered as supplementary colours that can be used as background colours for hardcopy content. Such hardcopy prints vary in substrate types and would include wayfinding signage. In Figure 28 below a distribution of the reference and their samples are shown on an a*b* plane with square markers indicating the position of references.

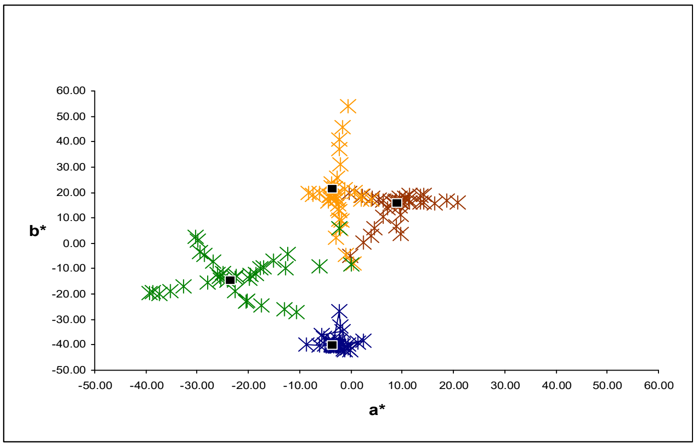


Figure 28: Distribution of samples on a* b* projection. Reference colours are indicated with square markers.

4.2.2 Viewing conditions

A VeriVide DAC viewing booth with D50 simulating fluorescent lamps (CCT 4962K and CRI 97) in a psychophysical lab at the London College of Communication, University of the Arts London, was used in all phases of the experiment. The lab was completely dark with the only illumination being that of the viewing booth. Using a 25-point mesh, of the viewing booth observer facing plane, a series of illumination measurements were made. Samples were mounted centrally within the viewing booth at a height that enabled on a fixed platform the achievement of an illumination consistency across samples. Illumination levels for each observation task were varied over a range of 25-3000 lux by means of a dimmer control. Once the dimmer is set a lux meter, Reed Model ST-1301 Light Meter, was used to take a reading of the area where reference and sample targets are placed. Viewing booth dimmer settings, set as percentage values, were noted and checked before commencing each test. Table 6 shows the correlation between each illumination level and which area of an NHS hospital it typifies.

Table 6: The table shows the correlation between each illumination level and what each represents. It was also decided to include the maximum level of illumination achievable at the point of sample positioning.

Illumination levels and their corresponding associations	
25 lux (±5 lux)	NHS hospital stairwell night illumination
50 lux (±10 lux)	NHS hospital corridor night illumination
250 lux (±25 lux)	NHS hospital reception minimum illumination
500 lux (±30 lux)	ISO 3664:2009 practical appraisal illumination
1000 lux (±50 lux)	NHS hospital critical examination illumination
2000 lux (±60 lux)	ISO 3664:2009 critical appraisal illumination
3000 lux (±75 lux)	Max illumination at test and ref stimulus location

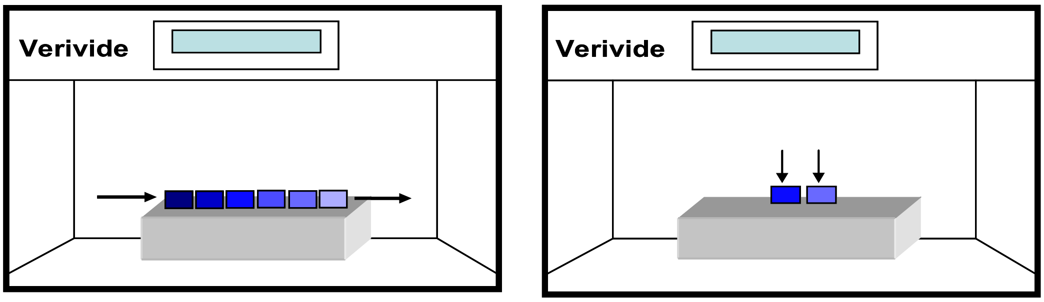
The chromaticity of the fluorescent lamps is known to vary over the range of illuminances used, but this was not measured because the experiment was only interested in the effect of a change in illuminance.

4.2.3 Observers

Twenty-four observers (12 male, 12 female), from a group of colour science students, graphic designers, web developers and NHS brand managers. The age range of the observers were from 16-60 years old for with an overall observer mean age was 34 years old and a standard deviation of 11.21 years. Female observers mean age was 29 years old with a standard deviation of 7.24 years and male observers mean age was 38 years old with a standard deviation of 12.4 years. NHS brand managers and web developers tested for normal colour vision using the Ishihara test and the City University Color Vision Tests (http://www.colblindor.com/2007/05/21/city-university-online-color-vision-test/), whilst the other participants only had to pass an Ishihara test before they participated in the experiment. The reason for the split in colour vision tests was purely due logistics of availability. The NHS brand managers selected to be observers were all directly responsible for wayfinding deployment and the NHS identity branding for their respective trusts. Observers completed two types of tasks, during which each observer completed 980 observations of 140 samples at seven different illumination levels between 25-3000 lux. For each session, a participant would typically carry out 80 assessments and 1960 to complete both stages. Each session of observer judgment took 45-60 minutes including a period of 3-5 minutes for adaptation to illumination. No observer undertook more than two sessions of testing because of fatigue so sessions were grouped into morning and afternoon sessions. The presentation of stimulus for experimentation was made in a completely random order.

4.2.4 Observer assessments

Experimentation tasks were split into two stages of psychophysical assessments. The first the task required observers to perform a sorting of samples by arranging them in a continuum of increasing or decreasing value for each group of samples. The samples were prepared in lightness, chroma and hue groups and kept in separate boxes in order of increasing or decreasing value. The reference is placed at a raised point in the viewing booth and samples are placed at the base to be ordered along with the reference as depicted in task 1 of Figure 29. The sequence of illumination levels was selected randomly for each observer. The efficiency with which observers sorted the samples on the measured dimensions of lightness, chroma and hue was taken as a measure of their ability to discriminate small colours differences to detect differences in a similar manner to the Ishihara test. The Ishihara test however, elicits the detection of a number whereas in this instance observers are detecting differences and ordering based on the small differences. The Ishihara test is used to determine observer colour visual deficiency. It consists of several coloured plates with each plate containing a circle of dots randomised in lightness and contrasting hue pattern. The dots are also varied in colour and size. To screen observers, the plates are presented to them under controlled illumination and they are asked to report the number they can see within the pattern. Using the Spearman rank test, it was possible to establish the degree of agreement between the expected, measured and individually ordered samples to that of the mean observer. The closeness of the correlation coefficient to a value of unity was indicative of a more efficient ranking. It was additionally possible to estimate a relationship between observer visual scaling and theoretical rank order mean observer representation (**Engledrum 2000**).



Task 1 Task 2

Figure 29: Ordinal ranking and category judgment psychophysical tasks 1 and 2 configurations.

In the second stage of the experiment, (Task 2) observers judged each sample to a reference colour stimulus and judged both the degree of perceived change and its acceptability, under the different illumination levels of 25-3000 lux. A 6-point category scale scoring was used for this task:

0 = Not perceptible;

1 = Barely perceptible;

2 = Perceptible but acceptable;

3 = Barely acceptable;

4 = Just unacceptable;

5 = Unacceptable.

Observers were required to determine whether a given sample passed or failed the criterion of acceptability with some degree of tolerance. The additional verbal label for each score provided observers with a descriptive anchor that was intended to make decisions more efficient. Judgment variability between observers in such scaling is assumed to follow a standard normal distribution that can be used to construct an interval scale (**Kuehni 2003**). Observer scores were converted to an interval scale where the analysis of judgment responses at corresponding parameters were determined. Derived analysis was based on the dose-quantal response experiments developed by D.J. Finney (**1952**), known as probit analysis. Quantal, pass/fail, experiments result in outcomes that are dependent on the strength of the stimulus being judged by an observer. The observer’s choice is therefore an indication of their tolerance level. Using probit analysis the relationship between stimulus colour difference and the resulting observer response was established for the median threshold of 50% acceptance. A 50% threshold is considered as being an indication of perceptual threshold where half of all observers can perceive a stimulus change. Probits are derived from the unit normal cumulative distribution function where obtaining tolerance results are derived from an equation that considers the rejection frequency to express tolerances by regression analysis (**Finney 1952**). In this paper, the probit value (*P*) is expressed as;

$$P = \alpha + \beta\left[\log_{10}\left(\Delta E_{00}\right)\right] \qquad (1)$$

for which the inverse normal transform of the response rate is added to five to result in the probit (*P*), thereby reducing the possibility of negative probits. The assumption is that the percentage response relates to the log colour difference in the cumulative normal distribution for which the $\log_{10} \Delta E_{00}$ represents variables that are interpreted as the percent threshold from the cumulative normal. The weighting of total observations and decisions is denoted by $\alpha + \beta$ where β is the parameter of regressional estimate of maximum likelihood. Observer decision of acceptance or rejection is expressed as either 1 or 0 at a specific illuminance level for a given sample which in turn is defined by the colour-difference representation within the cumulative distribution function.

4.3 Results

As described earlier, colour differences were calculated using three colour-difference formulas namely ΔE_{ab}, CIEDE2000 and CIECAM02_UCS. The CIEDE2000 model was proved to be marginally the better performing model for colour difference when tested for goodness to fit using the standardized residual sum of squares (STRESS) test. The formula used to obtain the STRESS values is defined as follows (**Garcia et al. 2007**):

$$\mathrm{STRESS} = \left(\frac{\sum (\Delta E_i - F\Delta V_i)^2}{\sum F^2 \Delta V_i^{\ 2}} \right)^{1/2} \quad \text{where} \quad F = \frac{\sum \Delta E_i^{\ 2}}{\sum \Delta E_i \Delta V_i} \qquad (2)$$

In STRESS ΔV_i and ΔE_i represent the visual and computed color differences for the pairs of colours denoted by $i = 1, \ldots, n$. The F is a factor that adjusts the scales of ΔV_i and ΔE_i. In STRESS the results are reported as being between 0-100 with greater values showing as worse agreement between visual and computed color differences. A perfect agreement of would score 0 thus indicating that the colour difference formula was ideal. In Table 7 the STRESS scores do not show any of the colour difference as standing out. The CIEDE2000 colour difference formula performed better than CIELAB and CAM02 however, there is no great significance between the three formulas. The mean category ΔV was used to calculate the STRESS values for the comparison data.

Table 7: Results derived from the testing of colour-difference model's goodness of fit for CIELAB, CIEDE2000 and CIECAM02. Results showed no significant differences between them.

	Mean ΔV						
ΔE^*_{ab}	25 lux	50 lux	250 lux	500 lux	1000 lux	2000 lux	3000 lux
3.07	2.13	1.65	1.80	2.08	2.22	2.55	2.07
6.44	3.26	2.47	3.19	3.11	2.63	3.15	3.32
8.16	3.93	3.13	3.92	3.83	3.42	3.79	4.13
11.23	4.32	3.75	4.42	4.20	4.00	4.37	4.27
15.24	4.68	4.25	4.48	4.57	4.34	4.78	4.60
18.67	4.73	4.50	4.60	4.49	4.33	4.38	4.68
11.13	3.44	2.93	3.23	3.18	3.79	3.67	3.35
13.34	4.01	3.26	3.90	3.86	3.96	4.08	3.81
14.22	4.07	3.83	4.29	4.29	4.23	4.27	4.19
15.46	4.57	4.05	4.73	4.45	4.50	4.59	4.27
17.16	4.29	4.18	4.41	4.42	4.30	4.75	4.30
18.11	4.51	4.10	4.53	4.48	4.44	4.41	4.32
STRESS values	20.91	27.46	20.09	20.24	18.91	21.95	22.34
	Mean ΔV						
ΔE_{00}	25 lux	50 lux	250 lux	500 lux	1000 lux	2000 lux	3000 lux
3.57	2.13	1.65	1.80	2.08	2.22	2.55	2.07
6.22	3.26	2.47	3.19	3.11	2.63	3.15	3.32
7.60	3.93	3.13	3.92	3.83	3.42	3.79	4.13
8.79	4.32	3.75	4.42	4.20	4.00	4.37	4.27
8.49	4.68	4.25	4.48	4.57	4.34	4.78	4.60
11.12	4.73	4.50	4.60	4.49	4.33	4.38	4.68

12.73	3.44	2.93	3.23	3.18	3.79	3.67	3.35
12.27	4.01	3.26	3.90	3.86	3.96	4.08	3.81
10.82	4.07	3.83	4.29	4.29	4.23	4.27	4.19
11.08	4.57	4.05	4.73	4.45	4.50	4.59	4.27
10.01	4.29	4.18	4.41	4.42	4.30	4.75	4.30
10.99	4.51	4.10	4.53	4.48	4.44	4.41	4.32
STRESS values	20.07	20.92	20.42	20.77	15.79	19.93	21.36
			Mean ΔV				
ΔE_{CAM02}	25 lux	50 lux	250 lux	500 lux	1000 lux	2000 lux	3000 lux
2.71	2.13	1.65	1.80	2.08	2.22	2.55	2.07
7.98	3.26	2.47	3.19	3.11	2.63	3.15	3.32
9.99	3.93	3.13	3.92	3.83	3.42	3.79	4.13
11.40	4.32	3.75	4.42	4.20	4.00	4.37	4.27
13.49	4.68	4.25	4.48	4.57	4.34	4.78	4.60
15.61	4.73	4.50	4.60	4.49	4.33	4.38	4.68
18.85	3.44	2.93	3.23	3.18	3.79	3.67	3.35
17.96	4.01	3.26	3.90	3.86	3.96	4.08	3.81
17.00	4.07	3.83	4.29	4.29	4.23	4.27	4.19
15.91	4.57	4.05	4.73	4.45	4.50	4.59	4.27
16.80	4.29	4.18	4.41	4.42	4.30	4.75	4.30
15.96	4.51	4.10	4.53	4.48	4.44	4.41	4.32
STRESS values	24.03	23.09	23.72	24.01	19.52	23.42	25.06

Combined STRESS data	ΔE^*_{ab}	**21.70**	ΔE_{00}	**19.89**	ΔE_{CAM02}	**23.26**

STRESS testing is used to determine the statistical significance of the difference between performances of two colour-difference formulas for the same visual data (**Melgosa et al. 2011**).

4.4 Task 1

Since the sorting of results are scaled in an ordinal sequence, Spearman rank correlation was employed to assess the link between the illumination level and visual tasks carried out by observers. The results can be considered as the Pearson correlation coefficient between the ranked variables (**Gibbons 2003**) in terms of the proportion of variability. For this the observer scores were converted to ranks and their coefficients and computed as:

$$r_s = 1 - \frac{6\sum D_i^{\ 2}}{n\left(n^{2-1}\right)} \qquad (3)$$

In the formula $D_i^{\ 2}$ was the difference between the expected and observer ranks and the number of pairs with $D_i = x_i - y_i$. The number of values in each data set is *n*. The Spearman rank correlation analysis of the visual ranking test resulted in observer responses shown in Table 8b. The categories of assessments were grouped into combined mean results and correlates of lightness, chroma and hue sample categories for each specified level of illuminance. The combined mean results did not show a significant difference in the outcome of observer ability to accurately rank samples at the different illumination levels. Individual lightness, chroma and hue sample categories however, exhibited varying degrees of correlation, with lightness and hue indicating better correlation in comparison to chroma. Observer uncertainty in this experiment was determined to be ±1.38ΔE_{00}. It was noted that observer judgment of the blue samples had the largest observer uncertainty at ±1.96ΔE_{00}.

Table 8: Correlation coefficients for observer perceived colour discrimination at different levels of illumination and Spearman correlation coefficients for observer ΔV data.

7a: Correlation coefficients of perceptibility							
Illumination	25 lux	50 lux	250 lux	500 lux	1000 lux	2000 lux	3000 lux
ΔE_{00}	3.56	2.67	3.18	3.77	3.78	2.67	2.35
Logit	0.8438	0.8715	0.8125	0.8229	0.8438	0.8160	0.8160
Linear	0.9180	0.8810	0.8800	0.8700	0.8760	0.8930	0.9060

7b: Spearman correlation coefficients							
Illumination	25 lux	50 lux	250 lux	500 lux	1000 lux	2000 lux	3000 lux
CIELAB	0.9180	0.8810	0.8800	0.8700	0.8760	0.8930	0.9060
L*	0.9930	0.9890	0.9770	0.9640	0.9680	0.9750	0.9840
C^*_{ab}	0.8570	0.7740	0.7870	0.7760	0.7710	0.8080	0.8120
h^*_{ab}	0.9040	0.8740	0.8690	0.8630	0.8790	0.8910	0.9160

The relationship between measured colour-difference and observer visual positioning of the samples provided data, shown in Table 7a, from which a threshold of perceptible colour difference per observer was established. The maximum variation between the perceptible colour differences was 1.73 ΔE_{00}. In the first row, the values represent the different levels of illuminance at which observations were carried out. The next row shows the computed threshold of perceived colour difference for all the samples under the different illumination conditions. The next two rows show the results of calculating the logit (**Green and Johnson 2001**) and linear visual threshold coefficients for all observations. The logit denotes the log-odds of the probability of an observer correctly ranking samples for a session and the use of linear regression facilitates the modelling of the relationship between expected and actual positioning of samples by fitting a linear equation to the results data. The logit models estimate the probability of a dependent variable being equal to 1, where there is a probability that an event happens. The logit is calculated as:

$$log(p) = log\left(\frac{p}{1-p}\right)$$

The symbol p is a probability where p /(1 − p) is the corresponding odds therefore the logit of the probability is the logarithm of the odds.

To visualize the distribution of observers' efficiency in positioning of samples relative to reference targets, at different illumination levels, **Figure 30** below shows that samples judged under lower illuminance levels resulted in colour-difference errors that peaked in the region of 3.77ΔE_{00}. As illumination level increased the threshold of perceptibility reduced in colour difference to about 2ΔE_{00}.

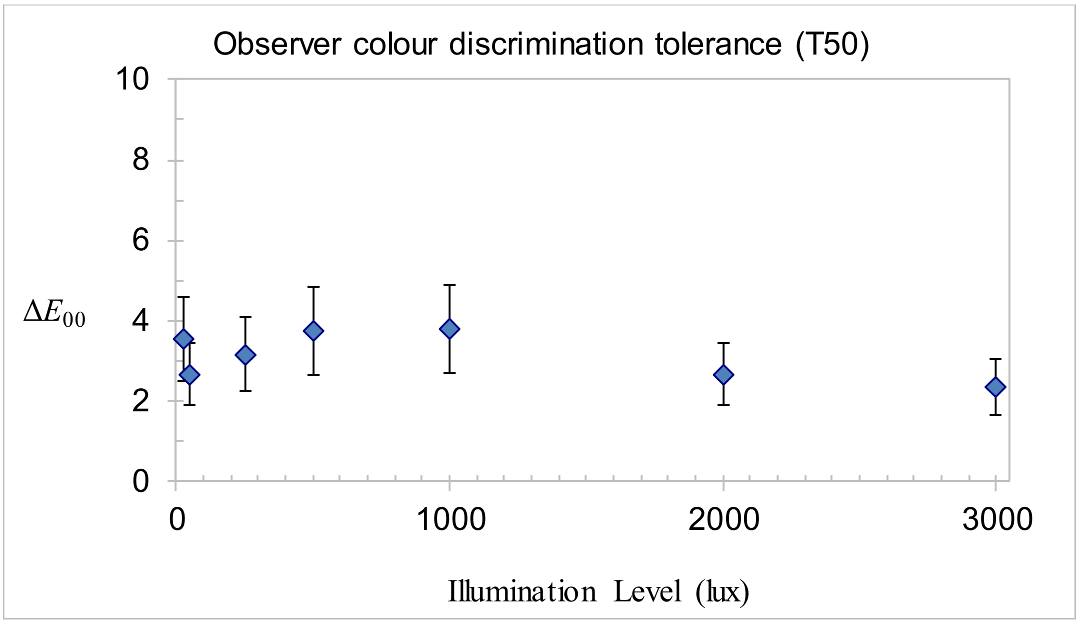


Figure 30: The graph shows colour discrimination thresholds at different illumination levels for a probit analysis tolerance of 50%. Between 25-50 lux there is an indication of noise in the results where observer judgments showed a low discrimination threshold at 50 lux which accounts for a colour difference of less than 1ΔE_{00}.

4.5 Task 2

The second stage was designed to determine the threshold of colour acceptability at the different levels of illuminance between 25-3000 lux. The threshold estimation of colour difference acceptability is based the computation of the CIEDE2000 value at which 50% of observers consider a sample an acceptable match to its reference. Observers assign their acceptability judgments to a 6-point category scale scoring of:

0 = Not perceptible; 1 = Barely perceptible; 2 = Perceptible but acceptable;

3 = Barely acceptable; 4 = Just unacceptable; 5 = Unacceptable.

Judgments assigned scores of 4 or 5 are considered as rejections. Probit analysis was used in this analysis, where the frequency of rejection data is assumed to follow a cumulative normal distribution and hence that the median colour difference corresponds to a 50% tolerance level (T50). Figure 31 shows the probit fit for lightness at 25 lux, 50 lux, 2000 lux and 3000 lux for blue samples, with the T50 model projection. Figure 32 is the distribution of the T50 acceptable colour difference threshold for all the data derived from observer judgment at each illuminance. The visualization of the distribution of threshold for ΔL*, ΔC* and ΔH* in relation to ΔE^*_{00} is shown in Figure 33.

Figure 31: Blue samples probit ΔE_{00} prediction for lightness at illumination levels of 25, 50, 2000 and 3000 lux. Acceptable colour difference for lightness observer responses at 50 Lux was about $2\Delta E_{00}$ larger than at 25 Lux which indicated a reduced detection at the lower level of illumination. Probit analysis of combined observer responses at various levels of illumination and for CIELCH correlates with a 95% Confidence level indicated is at Appendix A.

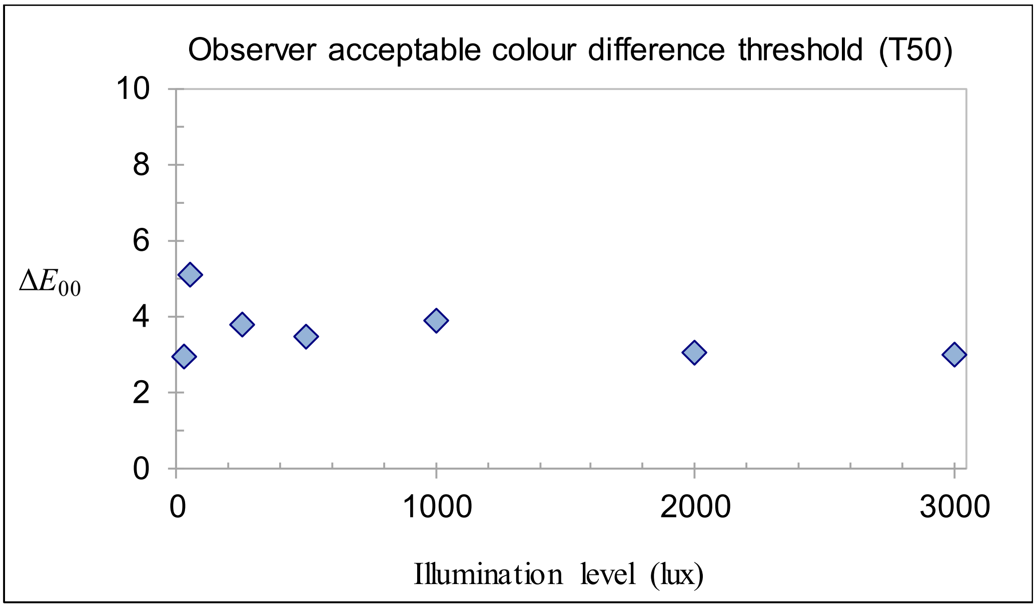


Figure 32: CIEDE2000 colour differences for acceptability with 50% probability of rejection calculated using probit analysis. The acceptance thresholds, which fall between $3\text{-}5\Delta E_{00}$, are in good agreement with the acceptable tolerances determined by Sharma (2004) and Stokes et al (1992).

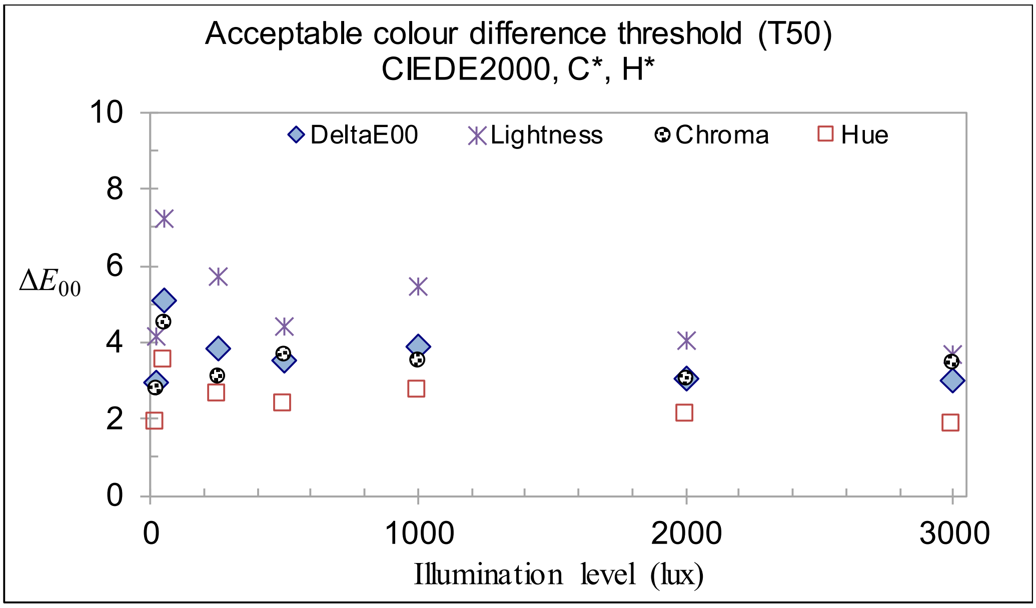


Figure 33: T50 (acceptable colour difference tolerance with 50% probability) projected for ΔE_{00}, L*, C* and H*. Observer acceptable colour differences in chroma and hue alter by no more than $2\Delta E_{00}$ an approximating a maximum of $4\Delta E_{00}$.

4.6 Conclusion

The objective of this experiment was to establish the degree to which changes in illumination levels affect the perceptibility and acceptability thresholds for a brand identity colour palette used in coding. It was established that end-use illuminance clearly has an influence on colour discrimination. This in turn can have significant impact on colour coded wayfinding if there are large variations in illumination levels and colour differences in individual coding. Having comparison points with studies done using other datasets including graphic arts was useful in testing for this. The observers' ability to perform a visual sorting of samples indicated a minimum perceptibility of about $2\Delta E_{00}$ as illuminance levels change between 25lux to 3000lux. The mean observer detection of colour difference was 2.35 – $3.77\Delta E_{00}$ with a maximum difference in perceptibility between observers was $1.43\Delta E_{00}$. The mean colour difference acceptability value was $3.6\Delta E_{00}$ with a resulting range of 3-$5\Delta E_{00}$. Inter-observer colour differences, across the illuminance range considered, accounted for an approximate change of $1\Delta E_{00}$.

The results indicate that colour discrimination of lightness and chroma vary more with illuminance changes than hue. The results also indicate that perceptions of hue differences are fairly stable in comparison to lightness and chroma. Acceptability tolerances of colour variation could therefore be significantly affected for colours close to the acceptability threshold, especially if lightness and chroma are the differentiating components. For an individual wayfinding colour code a colour-difference threshold would be expected to not exceed $4\Delta E_{00}$ from point to point in providing visual consistency, based on the NHS specifications tested in this work.

It would have been useful to also simulate a typical wayfinding journey for observers to judge and compare with lab results. In the live simulation, the reference point would be the initial location of the wayfinding code, which could be either a directional signage or colour coded inscription. This would evoke memory judgment as the observer navigated along the wayfinding pathway so there is an expectation that there may be differences in perceptibility and acceptability. This was however not possible to carry out because of the scope of the research and its constraints. Further work is additionally needed in this area of research to establish the relationship between viewing conditions and thresholds in different colour reproduction workflows for acceptability and perceptibility.

Chapter 5 - Perceived acceptability of colour matching for changing substrate white point

5.1 Introduction

Production and proofing substrates often differ in their white points, for example between proof and print, or between a target paper colour and an actual production paper. Production substrates are often whiter than that of proofing because of the presence of optical brighteners (OBA) that make such papers look brighter. Generally, most papers contain whitening agents that are used to bleach the natural yellow colour of paper pulp (**Tian and Chung 2010**). ISO 12647-2 print standards specify a series of substrate white points that are a maximum of 5ΔDE^*_{ab}, which may result from the presence of OBAs or a more natural state of colour. It is possible to generate characterization data for the printing process on the production side, shown in Figure 34, to achieve an accurate colorimetric match but in many cases, it is not practical to generate this data empirically by printing samples and measuring them (**Sharma 2003**). This approach however, does not account for any degree of adaptation between the differing substrate white points whereas its acceptability may depend on accounting for the change in paper colour such that appearance preservation of the original when printed on the production substrate is achieved.

Figure 34: Proof image simulations in the centre with print reproductions, using characterization data that does not account for changes in substrate white point, on either side showing different simulations of substrate white points that are yellowish and bluish. (*Original image is Copyright, ISO, 1995. All rights reserved.)*

A feasible approach would be to achieve an acceptable visual match between colours specified for the reference substrate, when printed on a different material, by adjusting printed colours to compensate for observer adaptation to the production substrate white point. A widely-used method of adjustment is to convert all measurement data to media-relative measurements, thus scaling the tristimulus values by the ratio of reference to sample white point (**ISO 15076-1:2010**) as in Figure 35. In doing so, the reproduction goal is considered as a *corresponding colour reproduction*, where the luminances and chromaticities of the original are matched in a relative rather than absolute sense.

Figure 35: Proof simulation image in the centre with print reproductions simulations corrected using media relative transformation, scaling colours relative to the substrate white point.

When the visual match of the reproduction is considered critically important, such as in the case of the proof-to-print match, optimized colour re-rendering between different media in color reproduction is often suited to media colorimetric transform. The outcome of re-targeting is designed to achieve comparable reference and sample characteristics. This method of transformation also presents the possibility of inverting reproduction data to the original media with only minor colour information loss (**ISO 15076-1:2010**). On the other hand, an absolute conversion would result in either clipping of the source white lightness or introduction of a background tint, depending on whether the source medium lightness is higher or lower than that of the original reproduction (**Green 2010**).

Typically, substrate spectral reflection data are transformed to colorimetric values as a product of a source spectral power distribution (SPD) and this is intended to correspond to the SPD of the viewing illumination. The ensuing measurements represent an adapted white point which has the characteristics of perfect diffuse reflectance. In proofing situations, the substrate is often the lightest neutral within the field of view for reference and sample judgment in viewing booths. This assumption also lends itself to the finding that observers are approximately 60% adapted to the display peak white when viewing colours on a display (**Katoh and Nakabayashi 2001**) and consequently it is considered that the observer is partially adapted to the substrate white. Prior to this Katoh (**1998**) found that when softcopy images on a CRT were compared with a hardcopy version, under an F6 illuminant (CCT of 4150 K), it was found that the observers were 60% adapted to the white point of the monitor. There was a 40% adaptation shift to the ambient light, when seeing softcopy images on the monitor. When observers are fixated on the display the effect of ambient light, Brainard and Ishigami (**1995**) and Choh et al. (**1996**), indicated that adaptation shifted between 10-20%. The state of adaptation between hardcopy and softcopy images when viewed under mixed illuminations, CIE Illuminant D50 simulator (CCT=4964K), an Illuminant A (CCT=2478K) and a typical office lighting (Cool-white Fluorescence with a CCT of 3867K), also produced the same results (Sueeprasan and Luo 2001). Furthermore, under a single illumination source it has been shown that there is similarity between the process of adaptation to different substrate colours and adaptation to different illumination sources on a single substrate (**Green and Oicherman** 2004). Green and Oicherman suggested that there was approximately 70% adaptation to substrate colour by observers for chromatic substrates. Of the various adaptation factors and models, it was found that an adaptation of 0.66 performed best.

ICC Media-relative Colorimetric rendering intent (MRC), **ISO 15076-1:2010**, provides a pathway, used in ICC profiles as a colour management parameter, to facilitate the assumption of the media white as the adapted white point. ISO 15076-1:2010 is an image technology colour management standard which deals with architecture, profile format and data structure. It is technically the same as ICC.1:2010 and provides procedure for colour matching that is transferred between applications and operating systems from creation to final output for either display or print. Von Kries chromatic adaptation itself, as previously discussed in Chapter 2.1.4, describes the relationship between an illuminant and visual sensitivity represented by a diagonal adaptation matrix. The ‘wrong Von Kries’ model is a scaling of XYZ tristimulus values.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} {}^{X_w}\!/_{X'_w} & 0 & 0 \\ 0 & {}^{Y_w}\!/_{Y'_w} & 0 \\ 0 & 0 & {}^{Z_w}\!/_{Z'_w} \end{bmatrix} \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} \qquad (1)$$

Media relative colorimetry uses a form of ‘wrong Von Kries’ conversion, based on tristimulus ratios instead of cone response ratios, in matching the source white point to the destination white point regardless of differences in luminance or chromaticity.

$$X_r = \left[\frac{X_i}{X_{mw}}\right] * X_a \qquad (2)$$

$$Y_r = \left[\frac{Y_i}{Y_{mw}}\right] * Y_a \qquad (3)$$

$$Z_r = \left[\frac{Z_i}{Z_{mw}}\right] * Z_a \qquad (4)$$

The MRC transform is achieved through linearly scaling the source colorimetry to the reproduction medium to produce 'media-relative' colorimetry $X_r Y_r Z_r$ as denoted in the equations 1-3 above. The values of X_a, Y_a, Z_a are the XYZ tristimulus values relative a perfect diffuser, $X_i Y_i Z_i$ are the XYZ of the D50 illuminant, and X_{mw}, Y_{mw}, Z_{mw} the XYZ of the reproduction medium white point. These media-relative values can be converted back to 'absolute' values by rearranging equations above. The Von Kries model suggests that colour responses of corresponding colours under two illuminants are linearly scaled apart (**Strassunk and Finlayson 2005**). Complete or incomplete chromatic adaptation transform is another technique that can be employed to adjust differences in substrate media white points. In chromatic adaptation transformation of colour is based on individual cone responses. In their experiment, which investigated mixed adaptation in cross-media color reproduction, Henley and Fairchild (**2000**) found that iterations of using such a von Kries transform in gave very good results to compensate for mixed chromatic adaptation. The experiment tested efficiency of appearance models in predicting observed matches for cross-media color reproduction. Of the single adaptation models used to transform the viewing booth target white point and that measured display a simple von Kries adaptation transform performed best.

Using media relative colorimetric rendering adjustment techniques this research targets two main goals:

- to determine the acceptability of colour matches made on different substrates;
- to determine the range of acceptable colour differences between reference and re-targeted media.

Earlier in this thesis it was established that ISO DIS 12647-2 (**2012**) specifies the colorimetry of a number of reference papers, which form a range separated by a maximum of 5 CIELAB ΔE*ab. It is therefore assumed that if a colour difference of 2.5 ΔE*ab between target and reproduction were found to be acceptable, when using a media relative colour adjustment technique, the approach would be considered valid for most commercial papers by selecting the closest reference characterization data set and adjusting it accordingly (**ISO DIS 12647-2: 2012**). In this experiment, a psychophysical experiment was carried out to find out the impact of media white points, including the presence of OBAs, on acceptability and perceptibility. The experiment determines the acceptable range for media-relative colour matching, in terms of their colour difference between the media white points. Additionally, the determining of the conditions of adaptation for hard copy viewing when substrate influences adapted white point was researched.

5.2 Experiment

The experiment was configured into three groups of assessment use cases to reflect simultaneous, sequential and soft proof viewing, as shown in Figure 36:

- The observer judges a print against a proof on a different paper
- The observer judges a print having previously viewed a proof on a different paper
- The observer judges a print against a soft copy proof on screen.

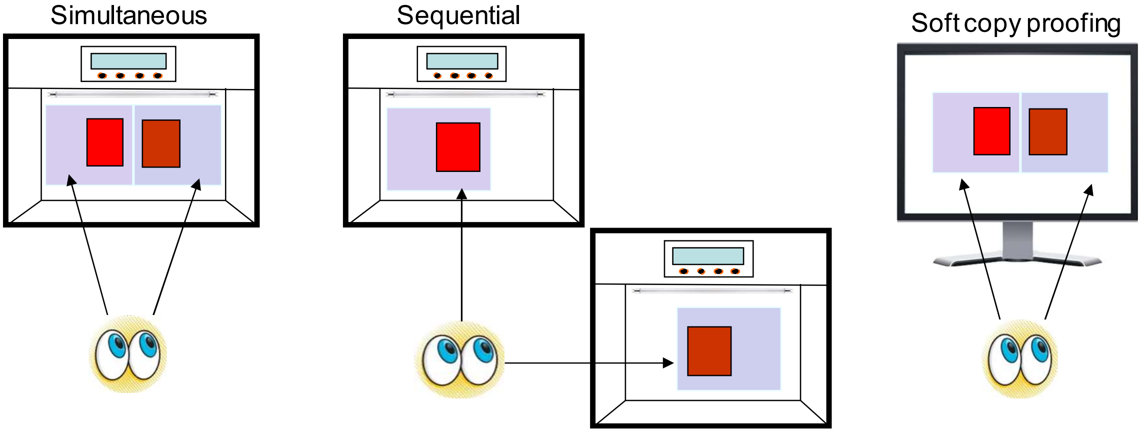


Figure 36: Experimental viewing configurations.

5.3 Samples

CIELAB coordinates of a reference paper was selected from the ISO 12647 paper types, and 14 variants were generated which differ from the reference by 1-10 CIELAB ΔE^*_{ab}. The reference paper white point and the variants were simulated by printing on a non-optically brightened proofing paper. Five colour centres in red, green, blue, orange and purple were selected, together with a light tint of each colour centre, and printed as a

25x25 mm uniform patch with the simulated reference paper as a background. A solid colour, referred to in this experiment, is a colour that does not have any gradations in printed terms. A tint on the other hand is a colour that has been changed by adding whiteness to result in a lighter appearance. The colour patches were positioned offset to the short edge border of 5mm and displayed on the monitor with a separation of 5mm as depicted in Figure 36. All colour centres were within the gamut of the printer used to prepare the samples, and the gamut of sRGB. A transform was applied to the 10 colour centres which shifted their colour coordinates in a similar direction to the difference between reference paper and variant. Figure 38 is a visualization of the 10 colour centres and their reference values are detailed in Table 9. The colour centres were chosen from the NHS brand palette to represent colour coded navigation and health clinician uniforms. Substrate variants were designed to show increasing blueness that papers with optical brighteners (OBAs) exhibit and yellowness seen in papers with no OBAs. This shift approximated the media-relative correction for substrate, but in order to test the general approach rather than a specific adjustment technique the shift was larger and with some randomness based on perceptual adjustments, as in Figure 37. This resulted in a total of 10x14 samples in each experimental phase, varying by up to 10 ΔE^*_{ab} from the reference colour centre, detailed in Table 10 as CIELAB values of varying yellowness and blueness. The samples were printed using an HP Officejet 8600 printer and measured with a GretagMacbeth Spectrolino spectrophotometer.

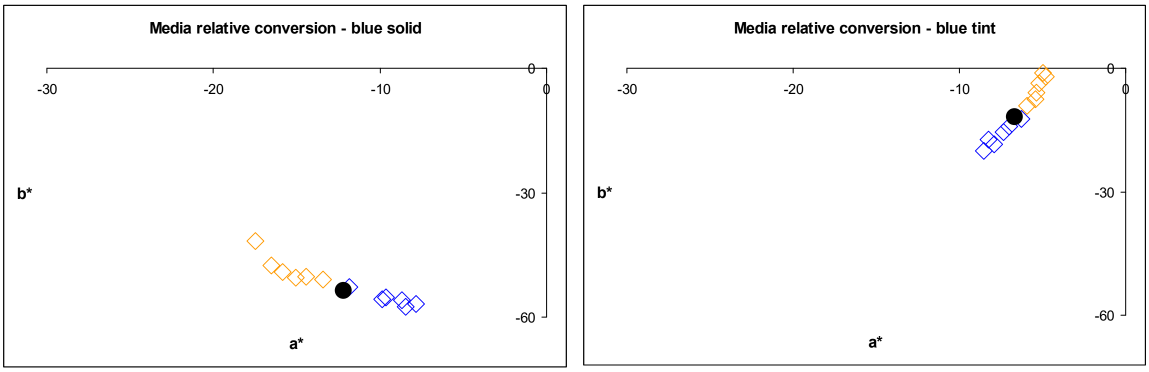


Figure 37: Media relative conversion of blue solid and tint colours respectively on a CIELAB a*b* coordinate plane, showing the influence of substrate white point with changing blueness/yellowness. The a* axis is approximately twice as long as the b* axis, but represents half the value.

For the soft proof phase, the reference papers and colour centres were simulated on an Eizo colour monitor with a 120cd/m^2 peak white luminance. All colours on the display were measured using a Minolta CS-1000A telespectrophotometer, located at the observer position relative to the screen. The spectral radiance data were converted to tristimulus values normalized to the display peak white as L*=100.

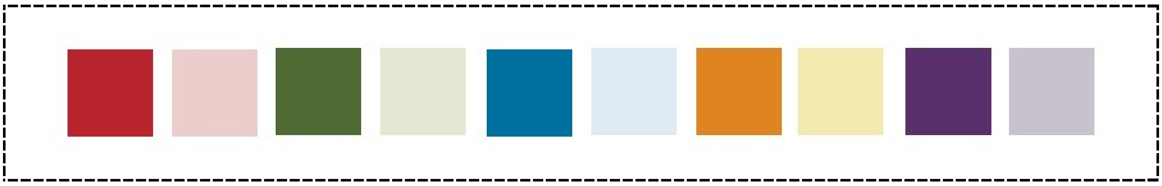


Figure 38: Colour centres used in the experiment to test MRC (media relative colorimetry).

Table 9: Reference colour centres CIELAB values.

	Red	**Green**	**Blue**	**Yellow**	**Purple**
L*	39.77	38.99	40.61	61.45	29.15
a*	59.07	-22.21	-15.02	32.27	26.73
b*	31.47	25.76	-50.72	55.62	-28.03
	L. Red	**L. Green**	**L. Blue**	**L. Yellow**	**L. Purple**
L*	84.83	88.61	89.26	88.73	80.47
a*	7.77	-4.70	-2.85	-2.98	2.50
b*	1.74	7.27	-7.94	23.86	-5.35

Table 10: Reference white point and varied white points with blueness and yellowness.

	REF	Sample white points with increasing and decreasing b* values						
L*	**92.46**	90.87	91.49	90.37	92.44	92.08	89.52	91.55
a*	**-0.74**	0.17	0.09	0.03	-0.69	-0.91	0.14	-1.00
b*	**-4.47**	-5.00	-5.20	-3.57	-5.59	-6.35	-7.99	-6.87
		89.97	91.98	89.19	88.80	90.69	88.57	91.42
		0.29	-0.67	0.57	0.23	-0.39	-0.16	-0.16
		-1.40	-0.50	-2.36	-0.67	0.72	4.83	-4.39

5.4 Psychophysical

Eight females and 13 males with good colour vision participated as observers in the psychophysical experiments. All observers participated in each of the experiment phases. The observers were asked to rate the size of colour difference between reference and sample using a six-point category (**Johnson and Green 2001**) scale where:

0 = Not perceptible;

1 = Barely perceptible;

2 = Perceptible but acceptable;

3 = Barely acceptable;

4 = Just unacceptable;

5 = Unacceptable.

Hard copy samples were presented in a Verivide proof viewing cabinet with D50 simulating illumination at 500 lux (±25 lux) against a surround with 20% reflectance. In the simultaneous viewing experiment, the simulated papers were presented adjacent to each other with 10mm margins separating the colour patches. In the sequential viewing experiment, reference and sample were presented with a 10-second interval. Finally, in the soft proof experiment, samples were presented simultaneously as in the hard copy experiment. The same 21 observers completed both simultaneous and soft proof experiments, and 16 of the observers had completed the sequential viewing experiment.

5.5 Results

The threshold at which 75% of the observers judged the samples to be acceptable was determined using the method described in Johnson and Green (**2001**), for which ‘instrumental wrong decisions’ are minimised. This is the threshold which minimizes the number of times samples were judged to be acceptable (or unacceptable) when the metric difference is greater (or less) than the threshold. The threshold at which 50% of the observers judged the samples to be perceptibly different from the reference was determined by the same method, and the results for acceptability and perceptibility are shown in Table 2.

Table 11: Perceptibility and acceptability thresholds determined with probit analysis for simultaneous and sequential hardcopy assessments as well as softcopy. The difference between solid and tint thresholds are considerably different because observers are also judging the visible substrate where there are minimal dots in tints.

	Acceptability		**Perceptibility**	
	Solids (ΔE*ab)	Tints (ΔE*ab)	Solids (ΔE*ab)	Tints (ΔE*ab)
Simultaneous	9.52	2.27	1.24	0.56
Sequential	9.52	1.67	1.73	0.56
Soft proof	11.67	5.70	5.18	1.75

From the results in Table 11 it can be seen that the acceptability thresholds for solid colours are considerably greater than the 2.5 ΔE^*_{ab} representing the maximum of substrate differences in standard characterization data sets. As the lighter tints are printed with a minimal dot and are close to paper white, the smaller acceptability thresholds strongly suggest that observers are considering the paper colour itself when determining acceptability. Figure 39 represents a visual relationship for the results in Table 9. Soft proofing is shown to be significantly different in perceptibility in comparison to sequential and simultaneous configurations. This could in some way be attributed to the combination of varying judgement skills of observers resulting in approximately $2\Delta E^*_{ab}$ difference. When judging softcopy targets observers are able to assess only changes in the target colour without consideration for the substrate, so texture representation for tints on display and hardcopy are likely to be different.

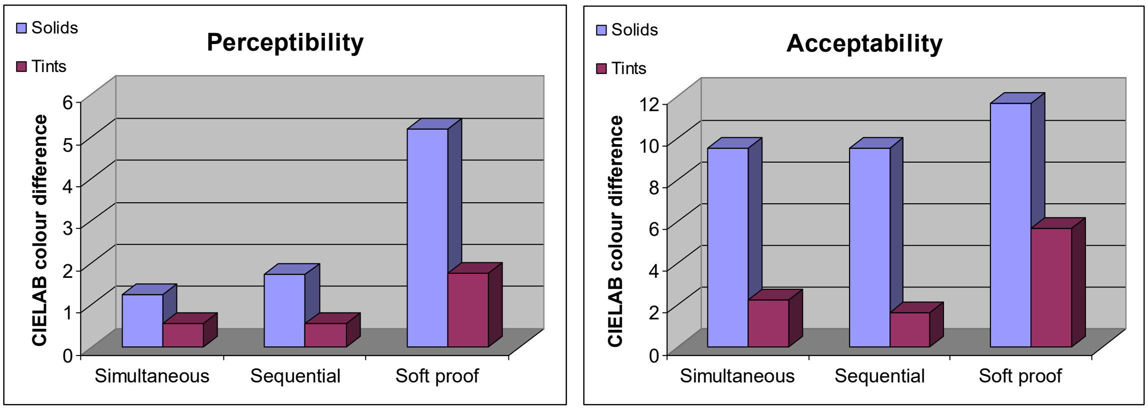


Figure 39: 50% perceptibility thresholds (CIELAB ΔE*ab) and 75% acceptability thresholds.

response representing acceptable threshold of 75% probit analysis was employed and it was established that for simultaneous and sequential configurations predicted acceptability for solid colours was $8.52\Delta E^*_{ab}$ and $1.31\Delta E^*_{ab}$ for tints.

A stimulus judged 50% of the time as being acceptable is considered as the point of subjective equality (PSE). In a graph projection, the usual measure of slope is half the stimulus distance between the 25th and 75th percentiles; termed as the just-noticeable difference (Luce and Galanter 1963). An acceptable judgment of 50% is however considered to be influence by a chance of guessing by observers at some point (Macmillan and Creelman 2005). To make sure that the response bias is significantly diminished a threshold of 75% is considered as most efficient by Macmillan and Creelman 2005. The target of 75% is reached by setting the increasing step to be three times the magnitude of a decreasing one (Kaernbach 1991). Furthermore, it is recommended in ISO ISO 20462-1 (2005).

5.6 Degree of adaptation

The degree of adaptation represented by the judgements of observer was investigated using the following method. First, the geometric mean of the observer scale values was calculated for each sample (interpreting the scale categories as psychophysical magnitudes) to give a vector of visual differences ΔV. Next, the reference colours were transformed using the Bradford (**Lam 1985 and Kuo 1995**) chromatic adaptation transform (CAT), using the XYZ tristimulus values of the reference paper as source adapted white and tristimulus values of each variant as destination adapted white. The difference ΔS was calculated between the coordinates predicted by the CAT and the measured samples used in the experiment. Here ΔS represents the colour difference between the source and destination substrates adapted white points. The effect of varying the degree of adaptation, D, in the transform was then investigated by comparing the ΔV and ΔE^*_{ab} values, assuming that where the CAT accurately predicts the visual match both ΔV and ΔE^*_{ab} will be small. It was noted that this correlation was slightly improved when D=1 (i.e. under conditions of full adaptation) but the result was not significant. A different design of experiment will be required to investigate this further.

5.7 Conclusion

The acceptability thresholds for solid colours on a reference paper modified by a media-relative type of adjustment were found to exceed the colour difference which would arise from retargeting to a similar paper type, and confirms that some form of adaptation to paper white point does indeed take place. For the tints, the acceptability threshold is slightly smaller than the $2.5\Delta E_{ab}$ difference which could arise from re-targeting, and this result suggests that the paper colour itself is the determining factor in the acceptability judgement for these lighter colours. Presenting proof and print simultaneously or sequentially made little difference to the acceptability thresholds, while the thresholds resulting from the soft proof experiment were somewhat higher.

5.8 Future work

Further work is needed to evaluate specific models of incomplete visual adaptation to paper colour, using complex images as well as uniform colours.

Chapter 6 - Psychophysical evaluation of grey scale functions performance

6.1 Introduction

The use of displays for branded content and the complementing of film-based medical imaging with displays is becoming more commonplace across the NHS estate. This is because displays have the ability to support dynamic multimedia content that can be seamlessly deployed at a low cost at multiple locations. In branded content, specific colours might be associated with the brand, whereas in medical imaging the discrimination or detection of colour is often more important than colour identification. For each non-medical display, the luminances may differ and result in perceived differences between any pair of displays for the same content. For both categories of displays, non-medical and medical, luminance related functions are designed to suit purpose. Medical imaging requires significantly higher intensity to accommodate grey levels that far exceed the 256 shades used in displaying non-medical information. The intention here is to evaluate the performance of greyscale functions, relative to their corresponding luminances, that are reproduced by different methods.

Hunt (**1996**) summarised that in the human visual system there is retina-to-brain communication facilitated by an achromatic (greyscale) signal and two color-difference signals; a red-green and a yellow-blue. The presence of achromatic signals has important implications in imaging. Detection of small colour changes is facilitated by a neutral reference. These defects are usually very noticeable as a result of the achromatic perceptions corresponding to the color-difference signals being balanced at their null levels. The achromatic signal can be a determinant of contrasts within scenes and corresponding images would look correct if their greyscales are adjusted based on the effect of the surround of the black-white signal.

Greyscale is a component of colour represented by a luminance dimension and is subject to a nonlinear transfer function that mimics the lightness perception of human vision (**Poynton 2012**). In colour science it is perceived that the grey components of a colour image holds key information about each colour channel that relates to pixel luminance (**Carter 2005**). Carter (**2013**) considers that the increasing penetration of computation and information display in society makes it a high priority for self-luminous greyscale calculation to be realised, on account that CIE L* is best suited for surface reflection and not displays. Greyscale self-luminous neutral calculations can estimate equal-appearing steps of greyscale, matching appearance of greys, the modelling of grey target discriminability with an illuminated background and similar grey distracters. "The applications can be extended to achromatic scale as a component of more general color space and color difference" (**Carter and Brill 2014**). Calculations designed to produce high contrast for grey scale imaging differ from that designed to increase detection at a lower contrast (**Barten 1999 and Whittle 1992**). In either case it results in visually perceptual linear image transitions that are functions of luminance intensity but because the human perception of brightness is not a linear response the calculations are nonlinear.

The electro-optical transfer function used in displays approximates the non-linear way in which the human visual system perceives brightness when there is an increase in luminance. Consequently, the judgment of a linear increase in grey scale would require a nonlinear increase in the luminance (**Barten 1999**). Commonly used consumer displays that previously had a recommended luminance setting of between 80-120cd/m^2 with an optimal gamma correction of 1.8 or 2.2, now average 160-1500cd/m^2 depending on purpose. The same gamma corrections, may have limitations in producing good quality images that would be considered pleasing for an observer using a display with higher dynamic luminance range (**Kykta 2008**). Kykta (**2008**) compared the DICOM Greyscale Standard Display Function to three electro-optical transfer functions of 0.5, 1.0, 2.0, and 3.0, for 1023 distinct greyscale levels luminances between 0.5 and 3993 cd/m^2. The results revealed that none of the functions were able to match the DICOM standard which models the human contrast sensitivity which is a measure of discriminability between luminances of different levels of intensity in medical imaging. The three electro-optical transfer functions are only able to approximate the DICOM function, but for a limited luminance range. It was also determined a constant Weber fraction matches DICOM only in middle and high luminance levels but not at low luminance levels (**Scherr 1993**) for which the Weber's fraction is defined as:

$$\left(\frac{\Delta L}{L}\right) = \left(\frac{L_{i+1} - L_i}{L_i}\right) \qquad (1)$$

In equation 1 *L* is the luminance and L_i is the change in luminance similar to Δ*L*. However, a modified Steven's law was shown to be consistent with the DICOM standard up to 5000 cd/m^2:

$$\left(\frac{\Delta L}{L}\right) = (KL^n + C) \qquad (2)$$

In this modified brightness perception model presented by Kykta (**2008**) *ΔL* represents a JND in luminance, *L* is the measured luminance, *K* (=0.017738) and *C* (=0.0058472) are constants that depend on the units used (cd/m2), and *n* is an exponent (=0.49985). To generate the standard DICOM curve a proposed adaptation of the formula is:

$$(L_i) = L_{i+1} - L_{i+1}(KL_{i+1}{}^n + C) \qquad (3)$$

An additional test using CIE L* showed that there was incompatibility with DICOM due to the scaling nature of CIE L* to fit luminance ranges.

The IEC 61966-2-5:2007 Colorimetric RGB color space display reference specifies a reference extended colour gamut with an encoding range of linear RGB: 0.0 - 1.0 for which the bit depth is 8 bit or as required for an output-referred image state.

Colorimetric RGB color space

- RGB primaries:

	x	y	z
R	0.64	0.33	0.03
G	0.21	0.71	0.08
B	0.15	0.06	0.79

- Color component transfer function using 2.2 gamma
- White point luminance: 160 cd/m2
- White point chromaticity: x = 0.3127, y = 0.3290 (D65)

Reference viewing environment

- Image background (proximal field): 32 cd/m2
- Viewing surround: 4.07 cd/m2
- Ambient illuminance: 64 lux
- Ambient white point chromaticity: x = 0.3457, y = 0.3585 (D50)

The adapted white point luminance and chromaticity are assumed to be equal to reference medium white point luminance as they are unspecified.

Reference medium

- White point luminance: 160 cd/m2 as referred to earlier regarding new standards minimum;
- White point chromaticity: x = 0.3127, y = 0.3290 (D65)
- Black point luminance: 0.4 cd/m2
- Black point chromaticity: x = 0.3127, y = 0.3290 (D65)

The IEC 61966-2-5:2007 specification suggests that a viewer-observed reference black would have a luminance of 0.5557 cd/m2 and as such the veiling glare would be

0.1557 cd/m2.

Colour component transfer function:

If R_L, G_L, B_L are less than or equal to 0.0031308

$$R = 12.92\ R_L$$

$$G = 12.92\ G_L$$

$$B = 12.92\ B_L$$

If R_L, G_L, B_L are greater than 0.0031308

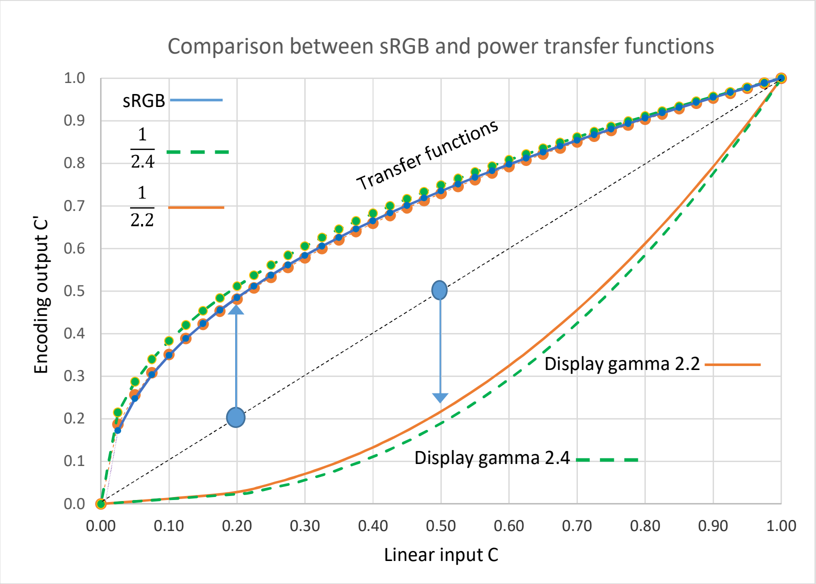
$$R = 1.055\ R_L^{(1/2.4)} – 0.055$$

$$G = 1.055\ G_L^{(1/2.4)} – 0.055$$

$$B = 1.055\ B_L^{(1/2.4)} – 0.055$$

It is important to note that the above produces sRGB digital values with a range 0 to 1, which must then be multiplied by 2bit depth – 1 and quantized. A comparison between sRGB and transfer functions commonly used in displays is shown in Figure 40a and Figure 40b shows changes in input values as the RGB luminance change relative to scaled luminance intensity. Further to this Figure 41 shows how different luminance ranges produce different RGB values and the data representation of variations for the same colour transfer function with different max luminance distributions is detailed in Table 12.

(a)



(b)

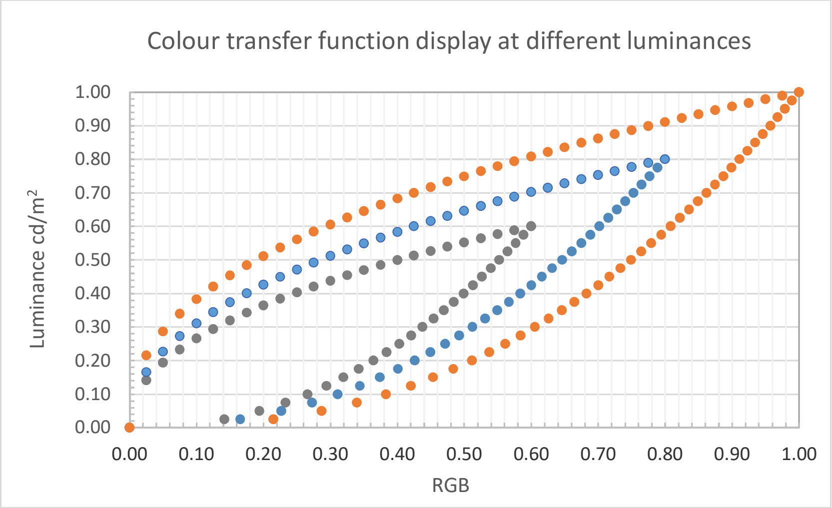


Figure 40: (a) Colour transfer functions for sRGB, 2.2 and 2.4 with indicative display gamma for 2.2 and 2.4. It can be seen that the sRGB transfer function is close to gamma 2.2. In the chart (b) below changes in input values as RGB luminance change is shown relative to scaled luminance intensity. The luminance ratio between the white and black points, defined by their max luminances, result in RGB differences.

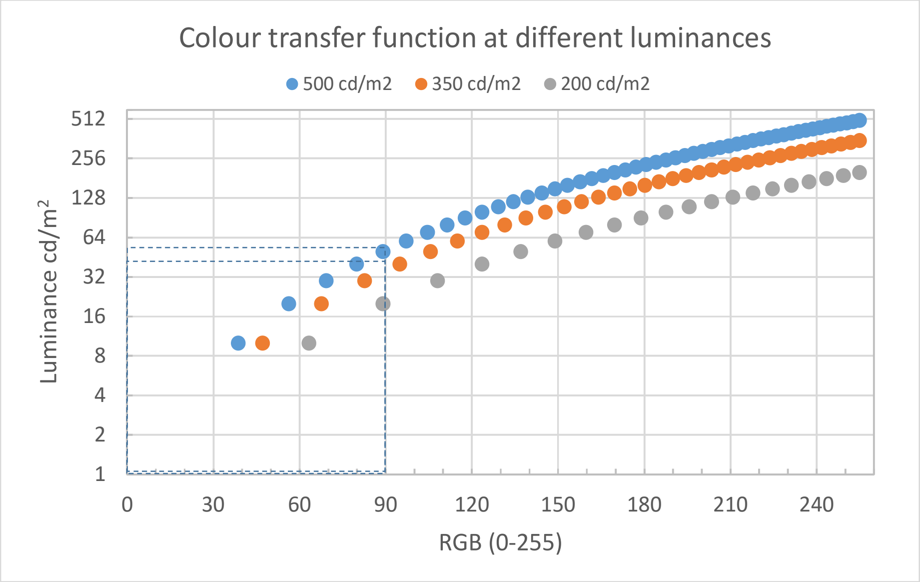


Figure 41: The chart shows how different luminance ranges produce different RGB values. In the chart an RGB channel value of 90 is produced at 50cd/m^2 for a maximum luminance of 500 cd/m^2, 35cd/m^2 and 20cd/m^2 for maximum luminances of 350 cd/m^2 and 200 cd/m^2 respectively.

Table 12: The table shows how varying luminance ranges produce different RGB values in Figure 41. The data represents variations for the same colour transfer function with different max luminance distributions.

Max luminance	200 cd/m^2	90 cd/m^2	40 cd/m^2	10 cd/m^2
	RGB values			
500 cd/m^2	170	118	80	39
350 cd/m^2	199	139	95	47
200 cd/m^2	255	179	124	63

As mentioned earlier the NHS in embracing a ‘digital first’ policy now that complements film imaging with displays as a transition to becoming a digital focused environment (**GDS 2012 and NHS Constitution 2013**). The ability to present shared digital radiographic images across their estate is intended to aid increased patient care with such digitisation. Medical imaging approaches these limitations differently by using a standard calibration methodology for displays that tend to have a much higher dynamic range, with an approximate maximum luminance of 500cd/m^2 (**Kykta 2008**) for processing highly detailed image scans that facilitate diagnosis. Medical imaging uses the Digital Imaging and Communication in Medicine (DICOM) standard which proposes JNDs as perceived digital data units that are a mapping between luminance and JNDs defined by a mathematical interpolation of the 1023 Luminance levels (**Mena.org 2014**). The relationship between image values and display luminance models measurements of the human contrast sensitivity proposed by Peter G.J. Barten (**1999**) and is known as the GSDF (Greyscale Standard Display Function).

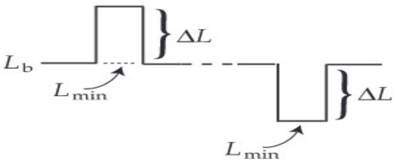
$$Log_{10}L(j) = \frac{a + c * Ln(j) + e * (Ln(j))^2 + g * (Ln(j))^3 + m * (Ln(j))^4}{1 + b * Ln\,(j) + d * (Ln(j))^2 + f * (Ln(j))^3 + h * (Ln(j))^4 + k * (Ln(j))^5} \tag{1}$$

Ln referring to the natural logarithm, j the index (1 to 1023) of the Luminance levels L_j of the JNDs, and a = -1.3011877, b = -2.5840191E-2, c = 8.0242636E-2, d = -1.0320229E-1, e = 1.3646699E-1, f = 2.8745620E-2, g = -2.5468404E-2, h = -3.1978977E-3, k = 1.2992634E-4, m = 1.3635334E-3.

Barten's model represents an experimental measure of visual sensitivity to a low contrast sinusoidal luminance signal presented on uniform luminance backgrounds conducted over a large luminance range of about 10^{5}cd/m^2. The luminance difference of the target from the background was varied to identify the changes needed to render the target just barely visible and result in a just noticeable difference (JND) which, defined luminance change in the target necessary for the target to be perceived (**Fetterly et al. 2008**).

There is a recent school of thought that an alternate approach could feasibly complement CIE L* and facilitate the increase of JNDs relevant to maximum luminance, that could rival the DICOM GSDF established discrimination levels (**Carter**

and Brill 2014). This greyscale function which facilitates rescaling of display luminance that befits high luminance displays is Paul Whittle's logarithmic computation. Whittle (**1992**) offered a computational logarithmic calculation approach designed to quantify JNDs amongst visual targets for luminance within a scene. The calculation accounts for luminance changes in ΔY in cd/m^2 that would result in a just noticeable difference, JND, which Carter and Brill (**2005**) consider as suited to representing a change in ΔL. As such the difference would be denoted as $JNDs\ between\ x\ and\ Y_t = a\ Log_{10}(1 + bW)$ with *x* and Y_t being the background and target luminances. The mathematical model describes brightness as a scale of equal interval lightness values relative to the background similar to CIE L*(**Cater 2010 and Nema.org 2014**).



$$W = \Delta L / (L_{min} + k) \qquad (2)$$

$LogW$, $W = \Delta L / (L_{min} + k)$, where ΔL is the difference in luminance between target and background, L_{min} is the smaller of the target and background luminance, and k is a constant that prevents W approaching infinity when L_{min} approaches zero. k can be regarded as a measure of the internal noise level when luminance is zero. However, if L_{min} is not close to zero the constant can be omitted (**Kingdom 2010**). Carter and Silverstein (**2012**) present Whittle's gray scale as:

$$W^* = aLog[1 + b(1 - (k_p \text{ or } k_n)\ \Delta Y / (k_n \Delta Y + Y_d + Y_{min})]$$

$$= W^*(Y_{target}, Y_{background}) \text{ where } \Delta Y = Y_{target} - Y_{background} \qquad (3)$$

$$\text{and } Y_{min} = \text{ the lesser of } Y_{target} \text{ and } Y_{background}$$

In formula 3 k_p is employed to account for a positive contrast and a negative contrast k_n, where they are treated separately apply to alternate situations. Appropriate parameters for positive contrasts = 8.22 and for negative contrasts - 7.07. In this version of the formula, W*, Carter and Silverstein successfully incorporated a model of intraocular scattering. The term Y represents the luminance and the subscript d denotes the background.

Recently Carter and Brill (**2014**) simplified Whittle's function to account for intraocular scattering and near zero Y_{min}. As such for a positive contrast, where Y_d is approximately 0.39cd/m^2, and negative contrasts the adjusted respective functions are as follows:

$$W = (1-k)\Delta Y/(Y_d + Y_{min}) \tag{4}$$

$$W = (1-k)\Delta Y/(k\Delta Y + Y_d + Y_{min}) \tag{5}$$

The term k is a constant of value 0 or 1 that increases with a reduction in the target subtense. Additional factors used in the calculation of equations 4 and 5 are b=6.58 and a=-7.07 for negative contrasts and b=0.26 + 0.3095 x with a=8.22 for positive contrasts. Carter provides an Excel spreadsheet that models Whittle's JND function that is used in this research to compare with GSDF through a series of psychophysical greyscale evaluations. Carter (**2014**) suggests that using Whittle's logarithmic formula it possible to produce data that can model GSDF thresholds intervals.

It has been shown that different greyscale functions result in variations of perceived brightness relative to increases in luminance. As such where a pair of displays have varying dynamic ranges in luminance an equal unit of change in luminance will result in different perceived changes. It can therefore be assumed that the display of branded content on multiple displays, with similar viewing conditions, will look broadly the same if all of the displays use the same greyscale function and luminance range. Where the displays, including non-medical, are being used for a workflow that originates from a medical imaging source the greyscale function should mimic the original source. To test these hypotheses a psychophysical experiment was conducted to evaluate the performance of both brand content and medical imaging grey scale functions as metrics of observer perceived difference detection for a set of near neutral samples at different luminance levels. The medical imaging DICOM standard function GSDF is mimicked by Whittle’s brightness function and used to evaluate observer magnitude estimation. There is no assumption of a fixed range of grey scale discrimination levels as this can alter with changes in the background (**Nema.org 2014**). In all cases the upper limits of JNDs are determined by the dynamic range of the display’s luminance setting. Psychometric assessments by observers are based on judgment of the just-noticeable-differences between reference targets and their corresponding samples.

6.2 Methods and materials

The display used was a calibrated EIZO ColorEdge CG246 monitor for which approximate peak white point luminance levels of 282cd/m^2, 229cd/m^2 and 166cd/m^2 were set for three phases of experimentation. The black point of the display was measured with a Minolta telespectroradiometer and determined as having a luminance of 0.22cd/m^2 located at the observation position relative to the screen. The measurement environment was dark with the display providing the only light source therefore a zero-veiling glare was assumed. Black point differences relative to this experiment’s luminance changes were 1.17cd/m^2, 0.92cd/m^2 and 0.69cd/m^2 respectively.

There were 23 observers who participated in the experiment from the following disciplines:

- 9 Brand Managers
- 7 Web & Graphic Designers
- 7 Colour Science Students

Observers initially participated in a series of practice sessions to acquaint themselves with the experiment design. Their responses to perturbations were required within a maximum duration of 5 seconds and progression to the next observation was generated remotely on their command in order to facilitate a quicker throughput.

For the 3 near neutral reference stimulus set a total of 24 sample perturbations were generated respectively at CIELAB L*22, L*52 and L*88 to result in 72 observations at each at approximate peak white luminances of 282 cd/m^2, 229 cd/m^2 and 165 cd/m^2. The peak white luminance corresponds to minimum and maximum luminances of the display such as 0.92 - 229 cd/m2. Three near neutral reference stimuli, from which a total of 24 sample perturbations were generated, were judged at each peak white point luminance.

6.3 Viewing conditions

The standard ISO3664:2009 display viewing condition with dark surround was used and samples were centrally positioned on the screen with observers at approximately 80cm away in distance relative to target size. Observers were provided with dark coloured overalls because during the training phase it was noted that white clothing affected results due to secondary reflection.

6.4 Psychophysical

10 female observers and 13 male observers with good colour vision participated as observers in the psychophysical experiments. A total of 23 observers participated in this the psychophysical experiment. Observers were required to estimate the magnitude of difference between each reference and 24 near neutral sample perturbations from the reference. The reference and sample configuration used for the psychophysical experiment is shown in Figure 42, where the background represents the minimum display luminance. They were initially presented with a colour pair that had a nominal magnitude difference of 1, as a judgment guide. Afterwards, judgements at each of the display white point luminances mentioned earlier commenced. The resulting mean data of observer estimations were then used to calculate JNDs (just noticeable difference) functions for predicting GSDF and Whittle's greyscale differences.

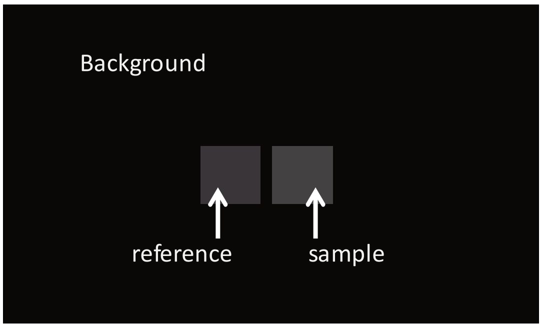


Figure 42: This is a simulated configuration of the reference and sample stimulus presented to the observer. The two-degree-square stimuli are centrally positioned on the display monitor.

For logistical purposes, each observer carried observations for one luminance level across all samples at each sitting. An adaptation period of 2 minutes was allowed to occur prior to commencing observations and during this period the session procedure was explained.

6.5 Results and Discussion

Non-medical displays showed significant differences in greyscale dependent on luminance contrast. It was found that for the luminances tested, 200-500 cd/m^2, a different grey value was produced at a specific luminance. A luminance value of 200 cd/m^2 produced RGB 170 for a maximum luminance of 500 cd/m2 and was equal to the RGB 255 peak white for a maximum luminance of 200 cd/m^2. As such, having displays with varying luminances, under the same viewing condition showing the same brand content would result in visual differences between their greyscale content on the displays. In Figure 43, showing 6 charts, the error bars show that as luminance increases observers' confidence in judgment increases and is most confident for light grey samples than dark or mid greys. As luminance increases observer estimated magnitude threshold reduces when judging dark grey samples. Mid and light grey samples are adjudged to have larger estimated differences closer to their maximum set luminances of 229 and cd/m^2 282.3 cd/m^2 respectively

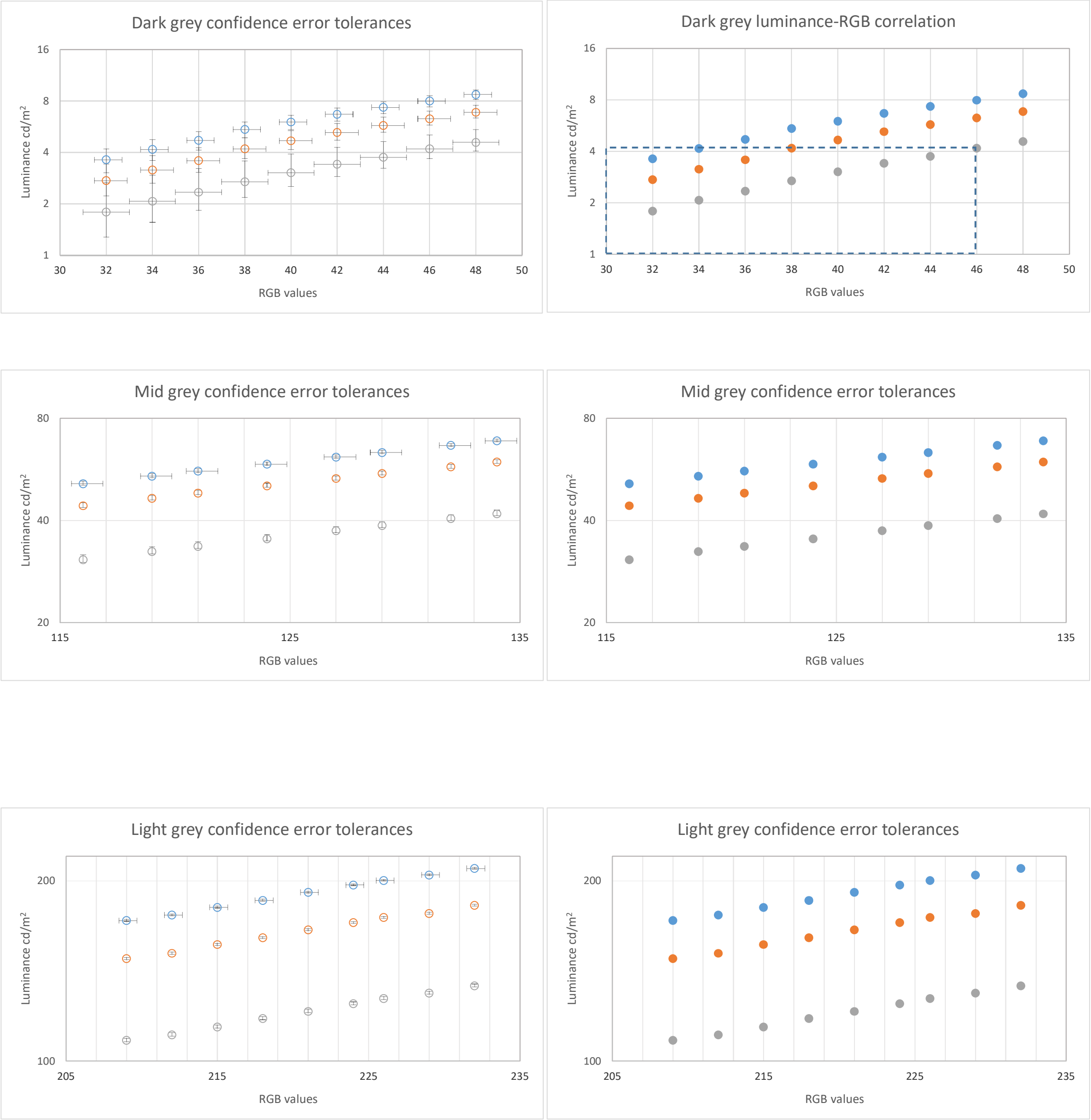


Figure 43: Observer confidence mapped responses to dark, mid and light grey display samples for magnitude judgements

In considering the possible complementing of the CIE L* DICOM GSDF greyscale was compared to an implementation of Whittle's logarithmic function. The GSDF luminance data was recalculated with Whittle's formula (**Carter 2014**) with the background set to produce positive values. A third-order polynomial function was applied generate a smooth function from the individual data points. The outcome results in a very close correlation to the GSDF dataset of JNDs however, in the middle of the curve there is a slight departure. The threshold correlation between the JNDs are r^2 0.9998.

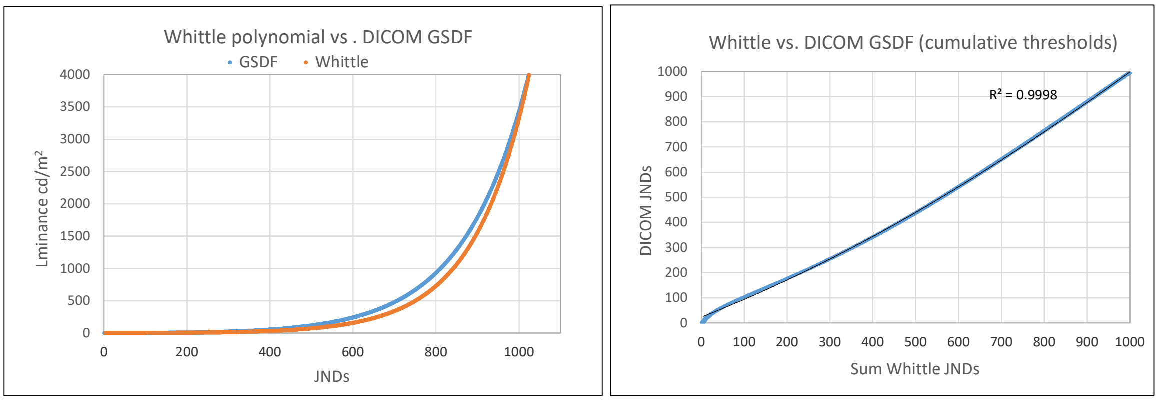


Figure 44: DICOM GSDF greyscales compared to Whittle's log function. The chart on the right is a cumulative threshold correlation comparison between GSDF and Whittle.

Using the DICOM GSDF equivalent range for the observers' experimental data a chart was plotted to compare the distribution of JNDs with output from Whittle's function where each JND represents a unique grey scale level. The data range includes values between samples and references as a first step comparison between charted data in Figure 44.

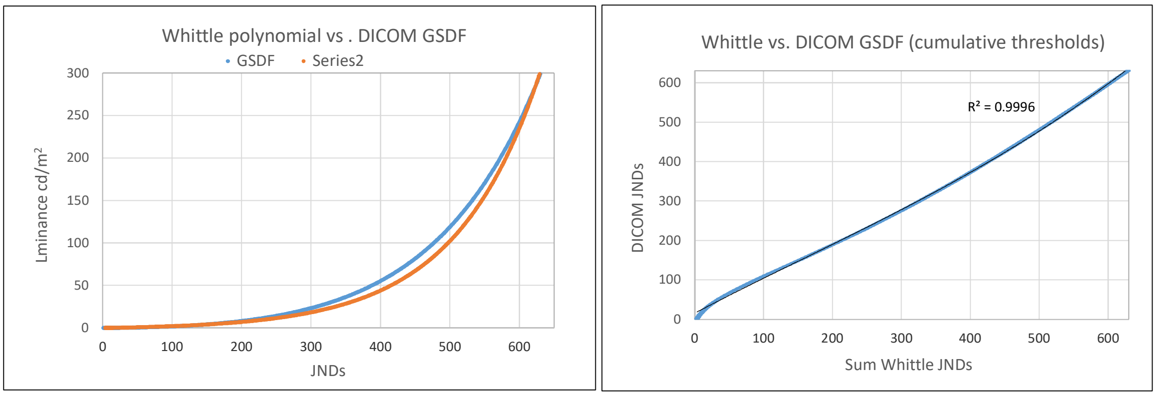


Figure 45: JND distributions for the grey scale functions for a dynamic luminance range between 0.05-300cd/m^2 representing non-medical displays. On the left Whittle's logarithmic function has been scaled to mimic DICOM GSDF greyscale using 3rd order polynomial correction. This is representative of using a non-medical display as part of an imaging workflow.

The scaling of this GSDF-Whittle comparison is aligned to non-medical display, which is to show a simulated distribution of greyscale JNDs on such displays, within a medical imaging workflow. The correlation for GSDF-Whittle is r^2 0.9996 for 635 JNDs as shown in Figure 45.

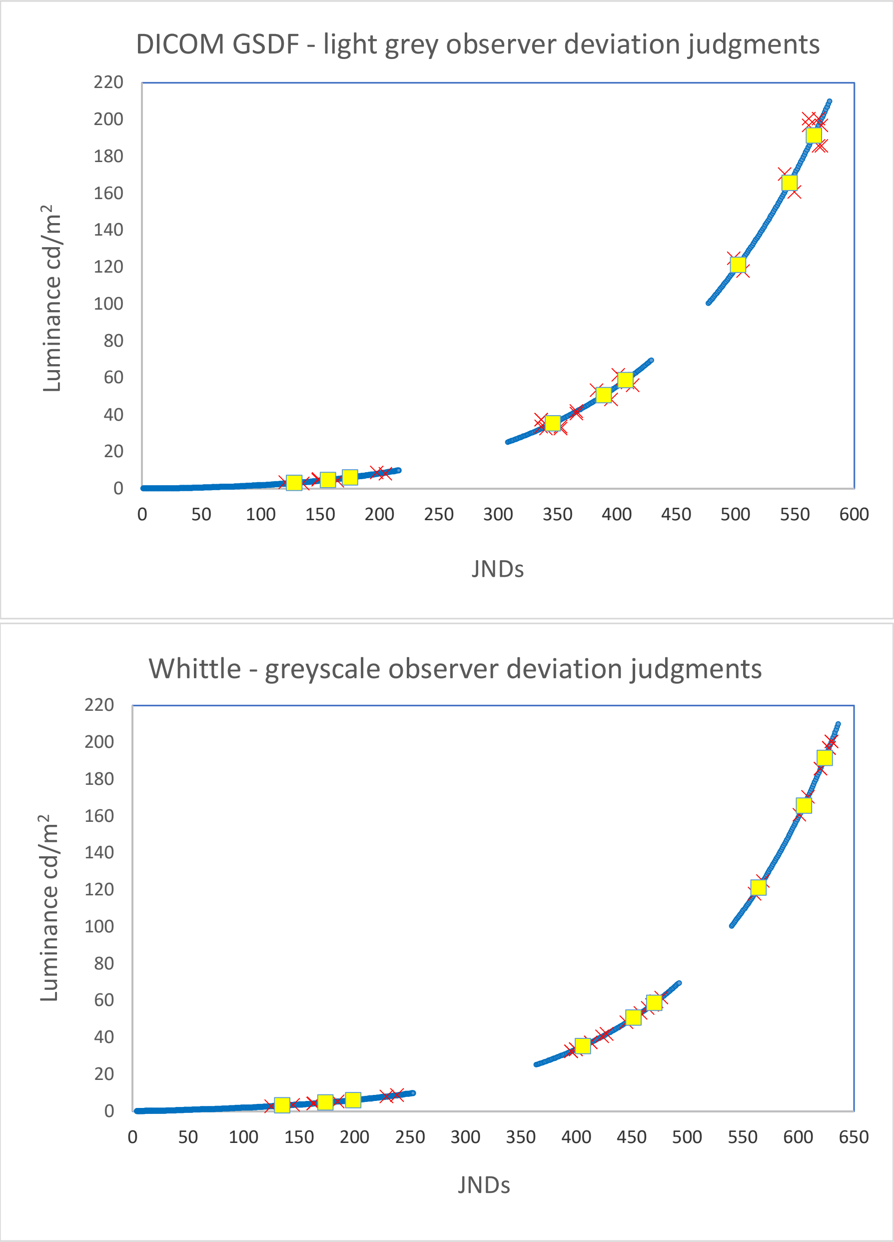


Figure 46: Observer judgment plotted onto GSDF and Whittle greyscale JND distribution. The yellow points represent reference luminance values and the red symbols the estimations for sample judgments.

In Figure 46 are charts that represent a simulation of experiment reference points and observer judgment estimations. A deviation is considered as a judgment of magnitude for a sample close to a reference considered as having a larger difference than a sample much further away from the reference. On the GSDF projection observations tend to have much larger estimations in comparison to when projected on the Whittle scale. Differences between the two functions and how observer deviations are handled may relate to how each function determines a unit of threshold. In DICOM GSDF JND thresholds are based on re-centered differences from a unit of noticeable difference proceeding to another (**NEMA 2011 and Carter 2014**). This results in a form of stacking of thresholds with set values, so a deviation shifts the centered threshold. Whittle threshold calculations on the other hand are continuous differences between targets and backgrounds that result in a continuous threshold contrast scaling. deviations for the Whittle chart are repositioned in relation to the defined background which keeps them synchronised to the curve.

To calculate the goodness-of-fit between the Grey Scale Display Function and observer estimated differences the (STRESS) test was calculated. It is a multidimensional scaling index (Melgosa et al. 2011, Kruskal 1964 and Coxon 1982), that allows a statistical judgment in determining whether the predictions of two visual difference formulas differ significantly with respect to a given set of visual data in this instance (Garcia et al. 2007). In this instance, the computed differences are represented by the resulting JNDs that are calculated with GSDF and Whittle's log brightness function. The perceived difference is the observer estimates of the magnitude of difference between reference and sample. The agreement of the Greyscale Standard Display Function (GSDF) with an empirical grey scale is compared to that of Whittle's brightness log function using the Standardized Residual Sum of Squares (STRESS) measure. The GSDF is defined by a mathematical interpolation of the 1023 Luminance levels derived from Barten's (1999) model. The GSDF allows us to calculate displayed luminance, *L*, in candelas per square meter, as a function of the Just-Noticeable Difference (JND) Index, j (NEMA PS 3.14-2011).

STRESS values for observer-estimated magnitude of differences for near neutral grey samples are calculated, where difference magnitudes between reference and samples are denoted as ΔV (cd/m^2). The resulting difference is then converted to JNDs using the greyscale functions. The reference luminances corresponding to white points (165– 282 cd/m^2) are shown in the Table 13 below, and are grouped into three categories of greyness:

Table 13: The different display white point luminances that were used in the psychophysical experiment are represented in the first column. Each white point luminance value is an average where the maximum difference of ±5 cd/m^2, covering the area of a sample and reference. There are three near neutral reference colours namely, dark, mid and light greys. Each reference colour value has been measured, using a Minolta spectroradiometer, at each of the white points and the results per reference is shown in columns 2-4.

White point luminance	**Dark grey reference** (cd/m^2)	**Mid grey reference** (cd/m^2)	**Light grey reference** (cd/m^2)
165 cd/m^2	3.04	35.33	121.10
229 cd/m^2	4.68	50.61	165.70
282 cd/m^2	6.02	58.63	191.40

The following results, in Table 14, are STRESS goodness of fit between near neutral sample luminance values and corresponding observer estimated magnitude differences. Further statistics provided in rows 2 and 3 are Pearson's coefficient correlation and a series of polynomial orders. The visualisation of the correlation is in Figures 47,48 and 49. Details for Whittle's formula is shown in Table 15 and their correlation fit visualisation is in Figures 50, 51 and 52.

Table 14: The table above shows the STRESS results for GSDF data acquired from the psychophysical experiment described in this paper. The most efficient fit for detection of differences is in the light grey samples. It was found that there was no advantage was achieved in going beyond 2nd order polynomial fitting.

GSDF	Dark grey	Mid grey	Light grey
STRESS	20.47	15.28	14.05
Linear R^2	0.9550	0.9745	0.9867
Polynomial 2nd	0.9764	0.9847	0.9928

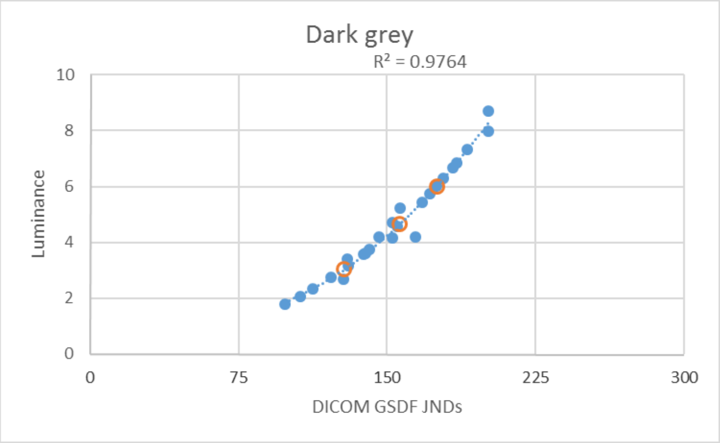


Figure 47: This chart shows a distribution of observers estimated differences for dark grey references and samples. The red circles represent three reference points for each of the display luminance white points. The blue dots are the mean values for observer estimated differences between reference and sample pairs. The data is projected using DICOM Greyscale Standard Display Function JND scale which is outperformed by Whittle's log function cumulative JNDs.

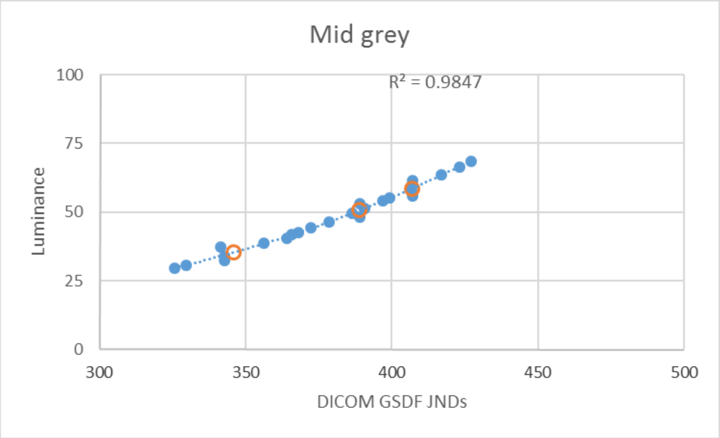


Figure 48: This chart shows a distribution of observers estimated differences for mid grey references and samples. The red circles represent three reference points for each of the display luminance white points. The blue dots are the mean values for observer estimated differences between reference and sample pairs. The data is projected using DICOM Greyscale Standard Display Function JND scale and was found to provide a marginally better linear correlation than using Whittle's log function cumulative JNDs. Whittle's function however performed better with a 2nd polynomial fitting.

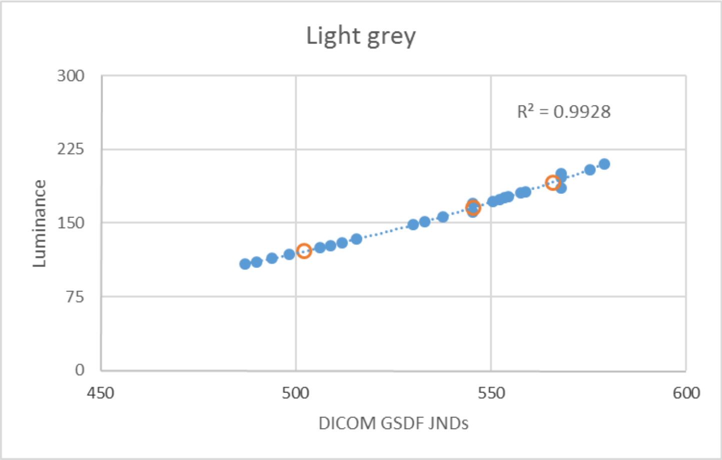


Figure 49: This chart shows a distribution of observers' estimated differences for light grey references and samples. The red circles represent three reference points for each of the three display luminance white points. The blue dots are the mean values for observer estimated differences between reference and sample pairs. The data is projected using DICOM Greyscale Standard Display Function JND scale and was found to provide a marginally better linear correlation than using Whittle's log function cumulative JNDs. When a polynomial 2nd order fitting was applied the performance between GSDF and Whittle was the same.

Table 15: The table above shows the STRESS results for Whittle's brightness log function data acquired from the psychophysical experiment described in this paper. Overall there is not any significant difference in the STRESS values or other statistical fitting method results. There is an indication that Whittle's function performs better than GSDF in its correlation to observer estimation of near neutral sample differences.

Whittle	Dark grey	Mid grey	Light grey
STRESS	16.20	15.96	14.85
R^2	0.9692	0.9744	0.9857
Polynomial 2nd	0.9873	0.9868	0.9928

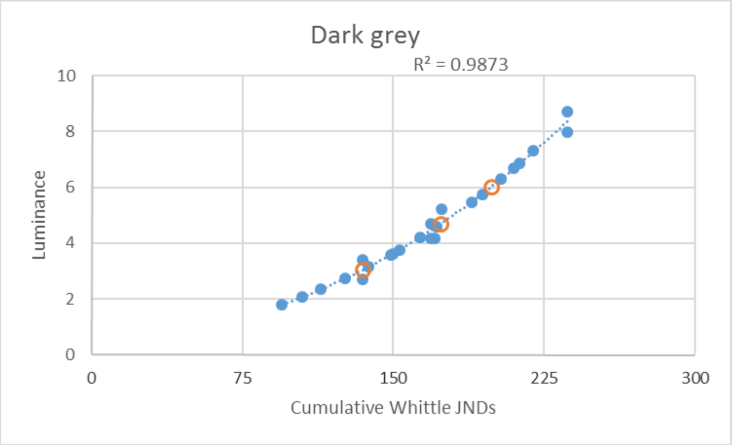


Figure 50: This chart shows a distribution of observers' estimated differences for dark grey references and samples. The red circles represent three reference points for each of the three display luminance white points. The blue dots are the mean values for observer estimated differences between reference and sample pairs. The data is projected using Whittle's brightness log function cumulative JNDs (**Carter and Brill 2014**). Whittle's function was found to result in a better correlation to observer estimation.

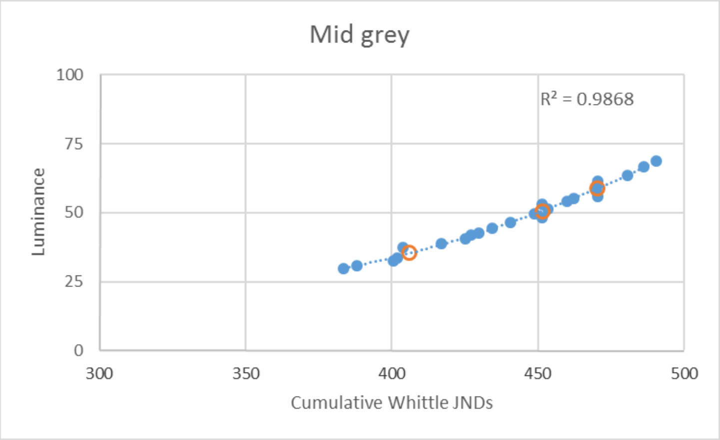


Figure 51: This chart shows a distribution of observers' estimated differences for mid grey references and samples. The red circles represent three reference points for each of the three display luminance white points. The blue dots are the mean values for observer estimated differences between reference and sample pairs. The data is projected using Whittle's brightness log function that mimics DICOM GSDF (**Carter and Brill 2014**). No significant difference was found in linear correlation but Whittle's function mimicking GSDF performed better in all polynomial fitting orders than GSDF.

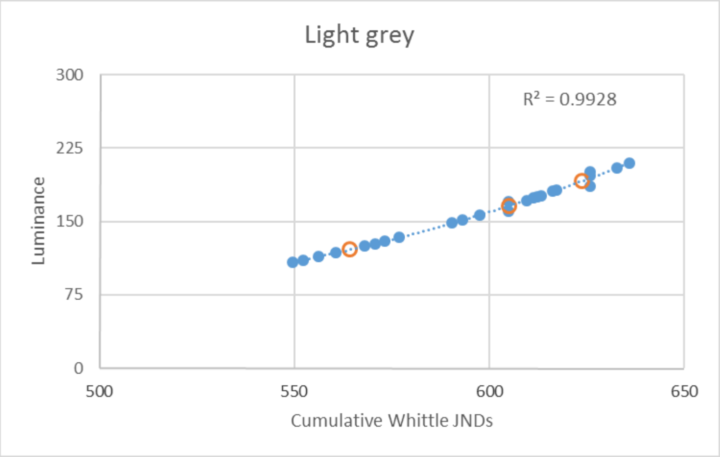


Figure 52: This chart shows a distribution of observers' estimated differences for light grey references and samples. The red circles represent three reference points for each of the three display luminance white points. The blue dots are the mean values for observer estimated differences between reference and sample pairs. The data is projected using Whittle's brightness log function that mimics DICOM GSDF (**Carter and Brill 2014**). There was a better performance in linear correlation in using a GSDF projection but a 2nd order polynomial fit showed no difference between either function.

6.6 Conclusion

When non-medical displays are used to display branded content presenting an acceptable appearance will depend on luminance and greyscale matching between them, assuming that they are displayed in the same viewing conditions. If such displays are then deployed to be used as part of a medical imaging workflow their ability to switch to a greyscale function that accommodates medical imaging requirements will suffice. On the other hand if a Whittle function can be adapted to complement CIE L* and mimic GSDF it would be a more efficient solution for non-medical displays.

It has been shown that Whittle logarithmic function can be used to mimic GSDF with good correlation. Here a simple modelling, using Carter's (2014) multiplier of 10.36 and a polynomial correction, gave good results however further work is required to improve the middle part of the curve. Applying data from the greyscale experiment showed that the function also scaled deviations along the curve whilst GSDF was more sensitive to such errors in judgment. The judgments in themselves represent an observer not being able to detect changes in luminance of 1 cd/m^2 in the dark region, 5.65 cd/m^2 in mid greys, and 7.10 cd/m^2 in light greys close to max luminance. The high contrast of Whittle’s logarithmic function conceptually makes it well suited to colour displays if a suitable characterisation were implemented to account for the colour components. An efficient comparison with GSDF would require implementation of rendering a DICOM image or relevant JND distribution for observer judgment, where health practitioners were observers. Whilst the data in this paper is not sufficient to represent the high detailed scans of medical imaging it does provide an understanding of similarity in detection differences for changing luminance levels. To account for typically high detailed medical imaging scans set of sample data points from actual scans could be used to develop realistic targets. It would also be necessary to use medical grade displays to carry out experimentation and also have a larger number of clinicians to participate in the test.

The STRESS data showed that Whittle’s function performed better than GSDF for observer estimated differences in the dark grey region. GDSF performed marginally better than Whittle in the mid and light grey regions. If the mean of the STRESS data is considered however, it could be seen that Whittle performs marginally better across the entire dataset. The mean STRESS value for Whittle’s function was 15.67 and GSDF 16.60. When a linear correlation was considered the results show the same trend however if a polynomial curve fitting is applied to the data Whittle performs better in both dark and mid grey samples. In the light samples the polynomial curve fitting shows the same value for both functions.

Some future work considered for this subject would be to show how one could define a transform, and a profile, that would convert between GSDF or Whittle to ICC PCS for a given display peak luminance. Additionally, the series of experiments could be carried out on an extended colour version of GSDF and also implemented for Whittle’s log function.

Chapter 7 - Near neutral colour parametric weighting for CIEDE2000

7.1 Introduction

Recently Cui, Luo et al. (**Cui G. et al 2013**) tested the performance of colour difference formulae for assessing colour differences near the neutral axis. The dataset used was of neutral colours extracted from the existing BFD colour-difference model experiment. It was determined that CIELAB and CIEDE2000 colour difference model prediction of hue, near the neutral axis, was better than its prediction of lightness, chroma and the chroma-hue interaction. The assessment of the two parametric factors k_L and k_C, showed that the lightness parameter k_L had a greater influence on the balance of an overall colour difference than the k_C factor. The BFD data that was used by Cui, Luo et al. in their experiment was extracted from a larger set that had been accumulated by Luo and Rigg (**Luo and Rigg 1986**), mostly relating to small to medium colour differences of surface colours. A psychophysical experiment was conducted by Luo and Rigg, using the grey-scale method, for over 600 pairs of wool samples close to the colour centres of the accumulated. The results were used to generate a pattern of ellipses for the neutral scale that was relative to the BFD set of ellipses shown in Figure 53 and the data for the neutral samples in Table17.

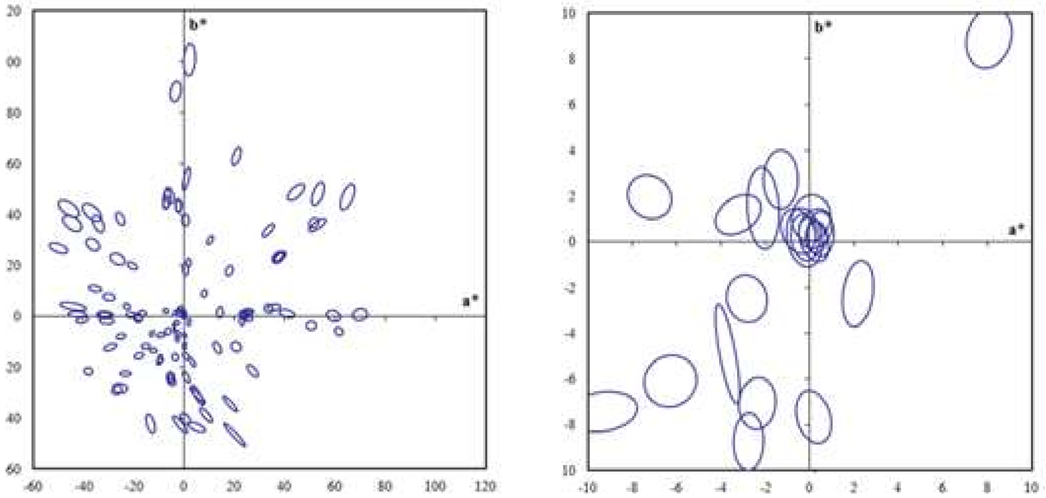


Figure 53: BFD experimental colour discrimination ellipses plotted in a* b* diagrams. BFD ellipses on the right and BFD neutral ellipses mapped by Luo and Rigg using CIELAB. The lack of uniformity in the CIELAB colour space is evident in both figures and even more so near the neutral axis. As chroma increases it can also be seen that the ellipses are larger and longer (**Luo and Rigg 1986**).

Table 16: BFD data neutral samples (C*ab ≤ 10) (Luo and Rigg 1986).

Sub-data	**Conditions**	**Pairs**	**Mean ΔE**	**Max ΔE**
All Neutral	C*ab≤10	423	1.7	8.3
ΔL only	|ΔL/ΔE|≥ 90%	88	2.30	6.20
ΔL + ΔC + ΔH	|ΔL/ΔE|, |ΔC/ΔE|, and |ΔH/ΔE|are< 90%	64	1.70	8.30
$(\Delta C^2 + \Delta H^2)^{0.5}$	$(\Delta C^2 + \Delta H^2)^{0.5}/\Delta E \geq 90\%$	271	1.50	5.10
ΔC	|ΔC/ΔE|≥90%	88	1.40	4.30
ΔH	|ΔH/ΔE|≥90%	70	1.50	5.10
ΔC + ΔH	|ΔC/ΔE|<90% and |ΔH/ΔE|< 90%	113	1.30	4.30

In this chapter, the same assessment was carried out, using near neutral data depicted in Figure 53 from the NHS identity branding palette, as detailed in Table 18, and the results agree with those of Cui, Luo et al. However, in the same experiment conducted on a display, using the same data, slight variations were found. The results showed that the CIELAB and CIEDE2000 colour difference model predictions of lightness, near the neutral axis, was marginally better than their prediction of chroma, hue and chroma-hue interaction. Display light grey near neutral samples however did perform in the same manner as the Cui, Luo et al. results, and the lightness parameter k_L had a greater influence on the balance of an overall colour difference for all samples.

Table 17: NHS identity branding near neutral data with maximum colour difference of 6.50ΔE* for hardcopy and softcopy samples.

Data type	Pairs	Mean ΔE^*_{ab}	Min ΔE^*_{ab}	Max ΔE^*_{ab}
Hardcopy				
ΔL	24	2.20	0.37	5.14
ΔL + ΔC + ΔH	168	2.54	0.55	5.69
ΔH	48	3.02	1.09	5.44
$(\Delta C^2 + \Delta H^2)^{0.5}$	128	2.71	0.19	6.50
ΔC + ΔH	144	2.71	0.64	5.97
ΔC	96	2.39	0.19	6.50
Data type	Pairs	Mean ΔE^*_{ab}	Min ΔE^*_{ab}	Max ΔE^*_{ab}
Softcopy				
ΔL	24	2.50	1.00	4.00
ΔL + ΔC + ΔH	168	3.13	1.72	4.73
ΔH	48	3.87	3.40	4.37
$(\Delta C^2 + \Delta H^2)^{0.5}$	128	3.17	0.75	5.84
ΔC + ΔH	144	3.17	1.72	4.74
ΔC	96	3.02	0.75	5.84

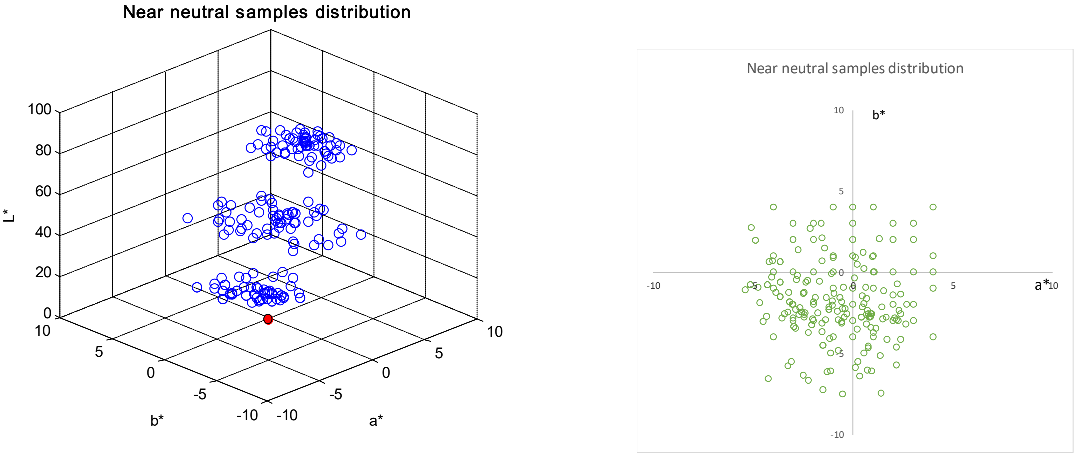


Figure 54: CIELAB distributions of near neutral samples on an L*a*b* plane three dimensional and a*, b* Cartesian coordinates showing a visual relationship

In the printing industry, grey or near neutral colour scale is used to calibrate consistency of colour balance through close control of the relative response of its characteristics (**Lo 2006**). The method uses near neutral as the criterion to define substrate-corrected grey reproduction aim points to attain consistent visual grey scale, which can be applied to diverse substrates as well as different printing methods.

. Using this method to generate press calibration depends on successfully mapping near-neutral colours of a substrate white point to its black point, for full tone black ink or three-color overprint ink.

With increased adoption of grey calibration process worldwide the ISO TC-130, have sought to find out the best way to define visual differences between two grey stimuli that may differ in chroma and hue. The CIE was introduced in chapter and CIE TC-130 is concerned with colour differences and colour tolerances in graphic technology. Additionally, there is a requirement to obtain a clearer definition of the perception of grey that is linked to a CIE colour metric (**Cui G. et al 2013**). Colour difference formulas are designed to establish a quantitative correlation between computational (ΔE) and observer perceived differences (DV) for a colour pair under (**Melgosa et al. 2004**) that satisfies industry requirements. Modern colour difference formulas have varying agreements with perceptual data so performance testing between models using infrequently tested colours is crucial in improving their results (**Shamey et al. 2013**). Shamey et al also reported that colour differences for “black-appearing” objects, based on visual and measured differences, has significant importance for industrial applications. Haslup et al. (**2013**), in his paper that sought to determine the influence of hue on the perception of preferred blackness, found that there was a limited amount of literature of colour difference tests using near neutral blacks.

The three-dimensional colour space of CIEXYZ tristimulus values is known to be visually non-uniform since equal distances in the colour space does not represent equal steps of perceived differences. Subsequent spaces developed have still retained aspects of non-uniformity, namely CIELAB and CIELUV (**ISO 2008**). To address the correlation with the relative perceived size of differences with much more uniformity more sophisticated colour-difference formulae were developed, of which some are CMC (**Clarke et al. 1984**), CIE94 (**CIE 1995**), CIEDE2000 (**Luo et al. 2001**), and CAM02-UCS (**Luo et al. 2006**). The colour difference models of CIE and from the textile industry, CIEDE2000 and CMC, have been shown to have major flaws in assessing colours near the neutral axis (**Rich 2012**). However, CIEDE2000 formula, which is an extension of the CIELAB colour-difference formula, was developed to account for variations in colour-difference perception dependency on lightness, chroma, hue and chroma-hue interactions. In addition, a new redness-greenness scale (a’) was derived to improve its performance in predicting chromatic differences in the neutral region (**Luo et al. 2001**).

In the graphic arts industry and for industrial applications CIEDE2000 is increasingly becoming a preferred replacement for CIELAB colour difference formula because of its improved uniformity and statistical significance (**Johnson and Fairchild 2003**). CIEDE2000 colour difference formula is discussed in detail in chapter 1. Previous shortcomings in the practical uses of CIELAB highlighted the need for adopting weightings to improve the prediction of colour differences for a given industry (**Mangine 2006**). To this effect CIEDE2000 incorporates weighting functions S_L, S_C, S_H to correct for CIELAB non-uniformity and parametric factors k_L, k_C, k_H to account for viewing configurations. It is a known practice in the textile industry to set k_L to 2 whilst k_C and k_H are set to 1. In their paper (**Green and Johnson 2005**) Johnson and Green determined weightings of k_L-1.5, k_C-1: and k_H- 0.5 respectively for critical appraisal of graphic arts data set. There are adjustments to a* scale to reshape the tolerance ellipses to become more circular (**Luo et al. 2001**).

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{k_L S_L} \right)^2 + \left(\frac{\Delta C'}{k_C S_C} \right)^2 + \left(\frac{\Delta H'}{k_H S_H} \right)^2 + R_T \left(\frac{\Delta C'}{k_C S_C} \right) \left(\frac{\Delta H'}{k_H S_H} \right) \right]^{1/2} \quad (1)$$

Figure 55: CIEDE2000 weighting functions SL, SC, SH, RT and Neutral that correct the non-uniformity which exists in CIELAB. The parametric factors *kL, kC,* and *kH* are corrections that account for the viewing conditions.

These adjustments account for the presence of different viewing parameters such as textures, backgrounds, separations for the lightness, chroma and hue components. CIEDE2000 however, is considered to have some flaws in assessing colours near the neutral axis (**Luo et al. 2001**) which is inherited from its predecessor CIE94. Despite improvements the model is known to fail to generate reasonably accurate predictions in the near neutral regions of colour (**Shamey 2014**) and as such over predicts differences at times in this region.

In this experiment, the magnitude of observer visual perceptibility threshold judgments was made for near neutral colours and the derived data used to optimise the parametric factors in the CIEDE2000 colour difference equation. The CIEDE2000 model is mainly based on adjacent colour pairs with colour differences between 1 and 5 CIELAB units. Testing of CIEDE2000 using appropriate data near threshold, about $\Delta E^*ab=0.2$ in CIELAB, and is desired by CIE Division 1 – colour and vision.

7.2 Experiment and materials

This experiment was designed to generate weighting metrics for near-neutral CIEDE2000 colour differences and define the dark end of the display luminance function using a series of psychometric assessments. In this experiment, a total of 23 observers participated of which 10 were female and 13 males. Observers were asked to estimate the magnitude of difference between a reference and sample for 24 near neutral sample perturbations from the reference. A combined total of 532 observations were completed by each observer for hardcopy and display configurations.

Using the CIELAB colour space model a near neutral reference point with lightness variations of L* 22, 52 and 88 are chosen. Lightness, chroma and hue step intervals of $\pm 6\Delta E^*_{ab}$ from the references are assigned as samples. The chosen hardcopy reproduction media was a bright white proofing paper with minimal optical brighteners in it. The white point of this media was measured as CIELAB data using a white backing, L*93.86 a*0.58 b*-3.77. The samples were printed using an HP Officejet 8600 printer and measured with a GretagMacbeth Spectrolino spectrophotometer. For display judgments, the stimulus is presented using an Adobe Flash developed application.

The display used was a calibrated EIZO ColorEdge CG246 monitor for which approximate peak white point luminance levels of 282cd/m^2, 229cd/m^2 and 166cd/m^2 were set for three phases of experimentation. The black point of the display was measured with a Minolta telespectroradiometer and determined as having a luminance of 0.22cd/m^2 located at the observation position relative to the screen. The measurement environment was dark with the display providing the only light source therefore a zero-veiling glare was assumed. Black point differences relative to this experiment’s luminance changes were 1.17cd/m^2, 0.92cd/m^2 and 0.69cd/m^2 respectively. All stimuli on the display were measured using a Minolta CS-1000A telespectrophotometer, located at the observer position relative to the screen. The spectral radiance data was converted to tristimulus values normalized to the display peak white as L*=100, with a 99.08% reproducibility.

The reproduction of each stimulus on the chosen media is 3cm x 3cm and the background is 9cm x 8cm positioned so that they are .25cm to one edge and centred according to the viewing surface. Hardcopy samples were presented in a Verivide proof viewing cabinet with CIE D50 simulating illumination of CCT 4962K and CRI 97 at 2000lux (±250) against a surround with 20% reflectance.

7.3 Psychophysical assessments

In the first stage observers were asked to arrange each set of samples in a continuum of increasing or decreasing greyness shown in Figure 56, which included each corresponding reference for the hardcopy format in the booth. Inaccurate positioning of either a sample or reference was judged as a colour difference perception threshold.

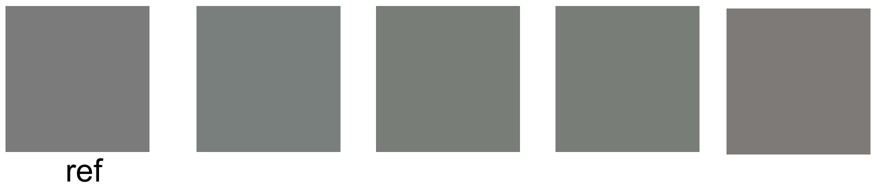


Figure 56: Reference and samples ordered according to increasing chroma as observers were expected to match for an error-free score. Such a score would be considered as having a score equal to the smallest colour difference between reference and sample.

In the second stage, each sample was then compared to its reference for which observers made a magnitude judgement of the perceptual differences. The same procedure was carried out for the corresponding display configuration shown in Figure 57.

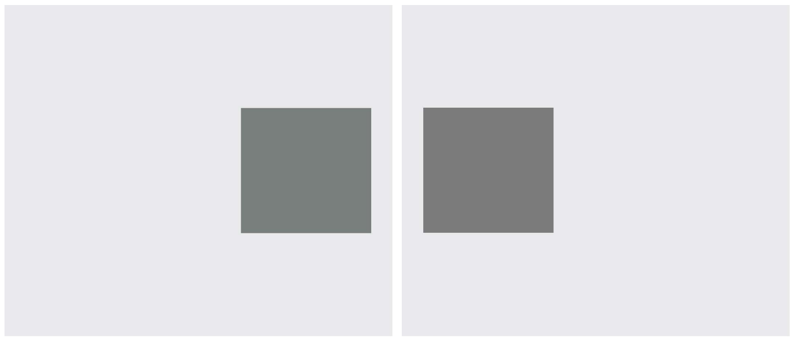


Figure 57: Reference and sample compared for magnitude of difference.

For each sample observation scores were then recorded, where scores were an indication of estimated magnitude in relation to its magnitude of measured colour difference.

7.4 Analysis

The linear least squares fitting model is a commonly applied form of regression which provides a solution to finding the best fitting straight line through a set of data points. In least squares the results of every single equation is minimised for the sum of the squares of the errors occurring (**Tibshirani 1996**). In achieving the best fit the function minimises the sum of squared residuals, where a residual is the difference between an observed value and fit the model provides. The criterion for the least squares produces a regression line that fits to the data points relative to the sum of the squared errors, Σe^2 (**Grimm 1993)**

The least squares regression line depicts the best representation of observations in the bivariate data set. The regression line is described as (**Berman 2015**):

$$Y = B_0 + B_1 X \qquad (2)$$

Where B_0 is a constant, B_1 is the coefficient of the regression, X is the independent variable, and Y is the dependent variable value. To solve for a random set of observations the regression line that describes the population is estimated by:

$\hat{y} = b_0 + b_1 x$ and to calculate b_0 and b_1 (3)

$$b_1 = \frac{\Sigma[(x_i - \bar{x})(y_i - \bar{y})]}{\Sigma\left[(x_i - x)^2\right]} \qquad (4)$$

$$b_1 = r * \left(s_y / s_x\right) \quad \text{and} \quad b_0 = \bar{y} - b_1 * \bar{x} \qquad (5)$$

- b_0 is the constant in the regression equation;
- b_1 is the regression coefficient;
- r is the correlation between x and y;
- x_i is the X value of observation i;
- y_i is the Y value of observation i;
- x bar is the mean of X;
- y bar is the mean of Y;
- s_x is the standard deviation of X;
- s_y is the standard deviation of Y.

In Excel, the LINEST function generates uncertainty estimates for the nominated values requiring a fit. Using a least squares criterion, the LINEST function finds the best fit for the given criterion, where the known *Y*'s represent data on the dependent variable, and known *X*'s represent data on one or more independent variables.

LINEST was applied as the regression method which provided a best fit for visual judgements to optimise for the parametric factors for CIEDE2000 and CIELAB. “The k_L, k_C and k_H values are the *parametric factors* to be adjusted according to different viewing parameters such as textures, backgrounds, separations *etc.* for the lightness, chroma and hue components respectively” (**Luo et al. 2001**). Observer’s visual judgments and the measured colour differences of samples for each viewing configuration were therefore assigned to the *X* and *Y* of the regression model.

7.5 Results

CIELAB and CIEDE2000 colour difference formulas were tested for their performance in predicting NHS identity branding near neutrals colours using STRESS. This method of colour difference model multidimensional scaling for goodness of fit, STRESS, is discussed in detail in section 2.2.3 of Chapter 1. The data in Table 19 shows a good correlation with test results of Cui, Luo et al for the pairs in Table 20.

Table 18: The data in this table are the results for STRESS tests for CIELAB and CIEDE2000 for NHS brand identity near neutral colours. It shows that there is a good correlation with test results of Cui, Luo et al. (2013).

Hardcopy formula performance (STRESS)		
Data type	CIELAB	CIEDE2000
ΔL	25.95	26.37
$\Delta L + \Delta C + \Delta H$	30.59	24.55
ΔH	28.30	23.83
$(\Delta C^2 + \Delta H^2)^{0.5}$	20.72	16.87
$\Delta C + \Delta H$	32.90	30.61
ΔC	37.51	37.39

Table 19: The table shows the numbers of pairs, mean, min and max colour differences for data tested.

Data type	Pairs	Mean ΔE^*_{ab}	Min ΔE^*_{ab}	Max ΔE^*_{ab}
Hardcopy				
ΔL	24	2.20	0.37	5.14
$\Delta L + \Delta C + \Delta H$	168	2.54	0.55	5.69
ΔH	48	3.02	1.09	5.44
$(\Delta C^2 + \Delta H^2)^{0.5}$	128	2.71	0.19	6.50
$\Delta C + \Delta H$	144	2.71	0.64	5.97
ΔC	96	2.39	0.19	6.50

The display assessments, shown in Table 22, exhibited inconsistencies when STRESS tests were carried out. Whilst the differences in stress values were not significantly different for DL and DC, CIEDE2000 performed better than CIELAB. Combined data however, shown in Table 21, indicates that CIEDE2000 performs best overall.

Table 201: Combined STRESS data for hardcopy and softcopy showing that when all of the observers' responses are assessed CIEDE2000 outperforms CIELAB.

STRESS for all data					
Hardcopy			Display		
	CIELAB	35.73		CIELAB	33.30
	CIEDE2000	35.12		CIEDE2000	31.12

Table 212: Results for the performance of CIELAB and CIEDE2000 models of display data using STRESS. Whilst the results indicate that CIEDE2000 performs better than CIELAB there are some inconsistencies in comparison to the hardcopy test results. Mid grey display data however performs similar to hardcopy data.

Softcopy formula performance (STRESS)			Samples	ΔL	ΔC	ΔH
Data type	**CIELAB**	**CIEDE2000**		**ΔE_{ab}**	**ΔE_{ab}**	**ΔE_{ab}**
			Dark-grey	12.85	22.88	23.29
ΔL	22.28	22.10	Mid-grey	**35.95**	**35.95**	**39.84**
ΔL + ΔC + ΔH	23.24	23.43	Light-grey	18.06	11.63	8.76
ΔH	23.96	24.94		**ΔE_{00}**	**ΔE_{00}**	**ΔE_{00}**
$(\Delta C^2 + \Delta H^2)^{0.5}$	33.55	34.10	Dark-grey	12.75	22.01	23.46
ΔC + ΔH	23.72	24.10	Mid-grey	**36.21**	**33.69**	**37.97**
ΔC	23.49	23.26	Light-grey	17.35	14.07	13.39

Table 22: This table shows the numbers of pairs, mean, min and max colour differences for data tested.

Data type	Pairs	Mean ΔE^*_{ab}	Min ΔE^*_{ab}	Max ΔE^*_{ab}
Softcopy				
ΔL	24	2.50	1.00	4.00
ΔL + ΔC + ΔH	168	3.13	1.72	4.73
ΔH	48	3.87	3.40	4.37
$(\Delta C^2 + \Delta H^2)^{0.5}$	128	3.17	0.75	5.84
ΔC + ΔH	144	3.17	1.72	4.74
ΔC	96	3.02	0.75	5.84

Stress values for mid-grey, whilst considerably higher than other samples in Table 22, show consistency with the trend seen in the results of Cui, Luo et al. (**2013**). In terms of correlation with observer judgments dark and light samples were better suited. Table 23 shows the numbers of pairs used in testing.

Table 24 shows that optimisation of the parametric factors improves the goodness of fit for each colour difference model in stress terms. Overall CIEDE2000 shows that it is better performing than CIELAB, except in ΔL* differences. Whilst the display data optimisation shows that CIEDE2000 still outperforms CIELAB in ΔL* the STRESS difference is much less than 1.

Table 234: STRESS results for optimised parametric factors for k_L and k_C are detailed for both hard copy and softcopy in this table.

Hardcopy formula performance (STRESS)		
Data type	CIELAB	CIEDE2000
optimised k_L parametric factor		
ΔL	22.62	22.83
ΔL + ΔC + ΔH	26.53	24.75
ΔH	23.52	18.77
$(\Delta C^2 + \Delta H^2)^{0.5}$	30.90	27.67
ΔC + ΔH	28.49	25.71
ΔC	33.46	32.66
	$k_L \approx 1.5$	$k_L \approx 1.14$

Hardcopy formula performance (STRESS)		
Data type	CIELAB	CIEDE2000
optimised k_L and k_C parametric factors		
ΔL	22.62	22.98
ΔL + ΔC + ΔH	26.53	24.36
ΔH	23.52	18.21
$(\Delta C^2 + \Delta H^2)^{0.5}$	30.90	26.73
ΔC + ΔH	28.49	25.05
ΔC	33.46	31.90
	$k_L \approx 1.56$	$k_L \approx 0.86$

Softcopy formula performance (STRESS)		
Data type	CIELAB	CIEDE2000
optimised k_L parametric factor		
ΔL	19.62	19.46
ΔL + ΔC + ΔH	23.37	23.24
ΔH	23.98	24.30
$(\Delta C^2 + \Delta H^2)^{0.5}$	35.75	35.56
ΔC + ΔH	25.25	25.13
ΔC	26.52	25.96
	$k_L \approx 1.56$	$k_L \approx 1.14$

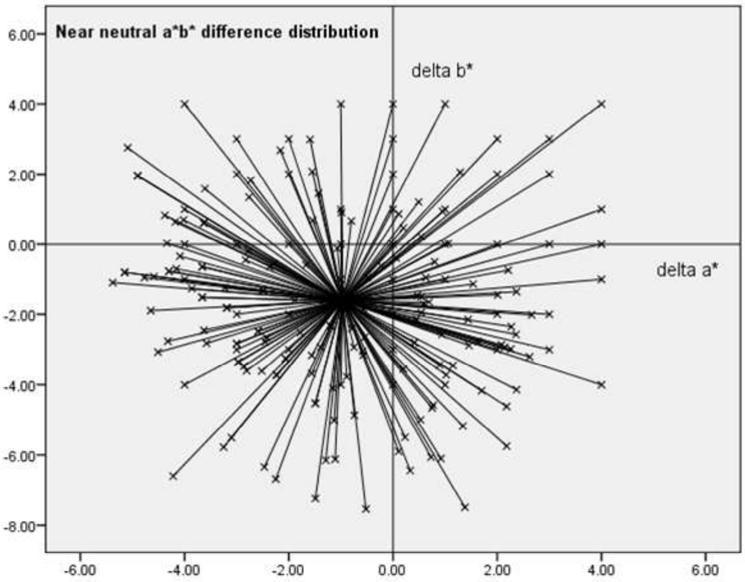


Figure 58: Distribution of colour differences for sample on a*b* plane anchored on the reference point. The shift off the centre indicates a reference neutral that is offset in relation to the NHS brand colours.

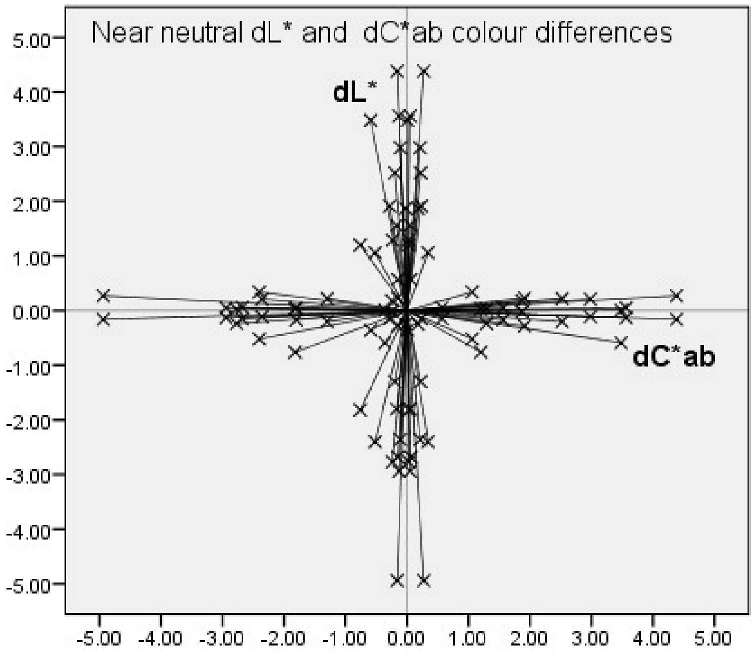


Figure 59: Lightness and chroma colour differences projected on an a*b* scale.

The distribution of the visualisation for the near neutral targets on and a*b* scale is shown in Figure 58 and as ΔC* vs ΔH* in Figure 59.

7.6 Conclusions

It can be concluded that for near neutral samples of small colour differences CIEDE2000 outperforms CIELAB except in lightness differences. The results also show that observer chroma estimation deviated from measured colour difference considerably. Additionally, it was found that prediction of lightness difference in the near neutral region was judged easier by observers. This however may be explained by observer experience in judging small colour differences. When optimised the parametric weighting for k_L is approximately 1.5 for CIELAB and 1.14 for CIEDE200. However, when both k_L and k_C are optimised weighting for CLELAB increases to 1.56 and CIEDE2000 reduces to 0.86. Softcopy data also shows that CIDE2000 outperforms CIELAB colour difference formula, including for lightness differences.

Chapter 8 - Results and discussion

Observer discrimination of NHS brand colours used for colour coded navigation resulted in a perceptibility range of 2.35ΔE_{00} - 3.77ΔE_{00} as the illuminance varied from 25lux up to 3000lux. The mean colour difference was about 3ΔE_{00}. The acceptable colour difference was determined by observers to reside between 3-5ΔE_{00} with a mean value approximately 4ΔE_{00}. This is well within typical tolerances used in graphic arts for colour reproduction. Where reproduction tolerances of such colour coded signage fall outside the graphic standards it could affect wayfinding negatively to some degree. Especially when an observer is entirely relying on the colour cues that such wayfinding provides under changing viewing conditions mentioned earlier.

The use of substrates with varying white points between print and proof was found to be an issue that could be resolved to a degree with ICC media relative correction. However, it was established that solid colours could be corrected for changes in the white point up to 9.5ΔE*ab. Substrate white point adjustments for tints were only suitable for up to 2.5ΔE*ab colour difference. Where displays were concerned such white point media relative corrections exceeded that of substrates with an approximation of 11ΔE*ab for solid colours. The correction value for different white points on displays for tints was twice as much as for substrates. In the experiment, all colours used were uniform and did not consider how to correct for complex brand images.

The white point of a display is dependent on the dynamic range of their luminance as such white point corrections can still fail to result in suitable outcomes. If equal luminance colour values cannot be reproduced on two displays for the same RGB signal they will visually look different. Carter and Brill (2014) proposal of using Whittle's log brightness function to complement CIE L* and replace DICOM GSDF across displays yielded feasible results. Observer estimation of magnitude differences projected onto DICOM GSDF showed point shifts that sat outside predefined values. This is bearing in mind that DICOM GSDF predict a fixed set of values for luminances that are averaged. Whittle’s function however showed estimated shifts as new value points as functions of difference between the background and luminance value. Testing observers’ data with STRESS indicated that Whittle’s function slightly outperformed that of DICOM GSDF. Whittle’s function notable resulted in larger JNDs, in comparison to DICOM GSDF, and this could be attributed to Whittle’s modelling of light scattering between a target and background. The STRESS test results have been contributed to the draft CIE document TC 1-93: Calculation of self-luminous neutral scale.

The communication of colour differences is now shifting to CIEDE2000 and the analysis carried out in Chapter 8 showed that it outperforms CIELAB for small differences of near neutral colours. It was also highlighted that whist this was the case for hardcopy judgments on displays inconsistent. For dark and mid grey near neutral samples on the display CIEDE2000 outperformed CIELAB but the opposite occurred for Light grey samples. There is also the likelihood of noise present in the results from non-expert observers who participated in the assessments. Renzo et al. (2010) showed that there were some differences between expert and naïve observer in the judgment of color difference using a gray scale comparison for colour change.

Chapter 9 - Conclusion

9.1 General conclusion

In conclusion, it was found that identity branding could conform with colour tolerances used in the graphic industry but only in the instances where a single target viewing condition was required. It has been shown that when colour coding is used for indoor navigation a colour tolerance threshold of $4\Delta E_{00}$ would be sufficient for varying illumination levels between 25-3000 lux. Crawford (**1973**) considered 30 lux as the lowest limit for colour discrimination, which is closely correlated to this research as it was determined that a lower limit resided somewhere between 25-50 lux. Between 20-50 lux observers results presented considerable noise and an averaging out of this would be 37.5 lux which is close to Crawford's finding. More recently Tidbury et al. (**2016**) determined that changes in illuminance have a statistically significant effect on visual acuity where increases in illuminance from 50 to 500 lx resulted in an improvement of visual acuity. Furthermore Ishida (**2002**) found that observers colour discrimination diminished as illuminance decreased from 1000 lux to 0.1 lux.

Where brands consider multiple targeted substrates or media white points for each media type would likely be larger in colour difference than suggested in ISO 12467-2. This can be typified in NHS stationery substrates which vary from recycled paper to ones that contain high levels of optical brighteners (OBAs). In such instances, commonly used identity branding solid colours could be corrected for white point differences up to $9\Delta E^*_{ab}$ using ICC media relative correction. If such colours were tints ISO recommendations would apply. Colour tolerances for identity branding should be aligned with targets and the information included in their brand visual identity documentation, which is not the case currently. When brands are using displays to present their branded content white point corrections in tints are twice as large in tolerance at $5\Delta E^*_{ab}$. The findings in this thesis show that like Tian and Chung (**2011**) less ink coverage results in larger differences between substrates of varying white points. Previous work by Shaw et al. (**2003**) had considered characterisation of the different substrates, which was labour intensive.

The use of two colour difference formulas in this paper was tested to determine the one that described observer perceived differences best. Using STRESS testing applied to observer estimated magnitude of colour differences CIEDE2000 was found to perform better that CIELAB for hardcopy targets. The same test found that CIELAB performed marginally better for display targets. Cui, Luo et al. (**2013**) tested the performance of CIELAB vs CIEDE2000 in an assessment of colour differences near the neutral axis. In their experiment, which considered hardcopy samples they found that CIEDE2000 gave a better prediction for observed colour differences. This is in line with the findings of this thesis for hardcopy and display data. Shamey et al. (**2014**) compared many CIELAB derived colour difference formulas and found that CIEDE2000 performed best in determining observer colour discrimination. In this thesis the tests were extended to display sample judgment which also found the same outcome of CIEDE2000 performing best overall.

A comparison between two greyscale functions DICOM GSDF and Whittle's log brightness, as detailed by Carter and Brill (**2014**) showed that the latter performed better. This outcome presents the possibility of complementing CIE L* with Whittle's log brightness to allow JND scaling as a function of the luminance of a display. This would improve non-medical displays used to present medical images and brand imagery across remote NHS networks. This type of network design where medical and non-medical displays are used in a workflow configuration is prevalent within the NHS. The comparison of the two greyscale functions relate to a CIE project TC 1-93 which is based on work by Carter (**2005**) and later developed in 2014. The differences extrapolated, using STRESS testing of observer data, rely on Carter's method for calculating a grey target as a function of its background. Key differences are presented in that GSDF scales are fixed and as such variable backgrounds will influence detection of greys closer to that area. Conducting a psychophysical test with a set of observers from varied disciplines, carried out in this thesis, is the first time this has been done. The resulting experiment data has been contributed to the TC 1-93 document. Theoretically, the complementing of CIE L* with Whittle's log luminance would facilitate a more relative display in network configurations that used both medical and non-medical grade displays.

This is perhaps the first instance of identity branding has been researched to this depth in establishing efficient correlations between branded images and their targets. Future psychophysical work using separate groups of brand managers and graphic artwork assessors in larger numbers would provide very useful data.

9.2 NHS Recommendations

Recommendations for the NHS identity branding it would be essential to categorise broad areas of branding by media type and define specifications within such grouping. Such groupings could be:

- outdoor wayfinding and signage;
- indoor wayfinding and signage;
- stationery, leaflets and posters;

To facilitate indoor wayfinding illumination levels for each health location variation in illumination should be no less than 30 lux at a minimum, ideally 50 lux would be at best the lowest illuminance prescribed, so that a minimum requirement of colour discrimination is met. This would improve wayfinding where colour coding is used to aid navigation.

Reference white point tolerances for each media should be specified with ICC media relative corrections nominated as the main method of correction. A tolerance of 9 ΔE*ab for correction of solid colours and 2.5*ab for correcting tints. Whilst it may not be possible to restrict the order of stationery by their compliant white points. It would go a long way to achieve appearance acceptability, in having their suppliers use the same method of colour correction for substrates that are outside the specified white point tolerance. An ideal would be to embrace the idea of only contracting suppliers of print who were ISO 12647 accredited.

References

Ailawadi, K.L. and Keller, K.L. (2004) Understanding retail branding: conceptual insights and research priorities, Journal of Retailing, Vol. 80, pp. 331-42.

Alba, W. Hutchinson, J. W and Lynch, J. G. Jr. (1991) Memory and decision making, In T. S. Robertson and H. H. Kassarjian (eds.), Handbook of Consumer Behavior, 1-49. Englewood Cliffs, N. J.: Prentice-Hall.

Albers, J. (1963) Interaction of color, Yale University Press, New York, USA.

Alder, C., Chaing, K. P., Chong, T. F., Coates, E., Khalili, A. A. and Rigg, B. (1982) Uniform chromaticity scales—new experimental data, J. Soc. Dyers Colour. 98, pages 14–20.

Alder, C., Chaing, K.P., Chong, T.F, Coates, E., Khalili, A.A., and Rigg, B., (1982) Uniform chromaticity scales – new experimental data, Journal of Society of Dyers Colour 98, pages 14-20.

Alesandrini, L. (1982) Strategies that influence memory for advertising communications, in Information Processing Research in Advertising, Harris, R.J. (ed) Lawrence Erlbaum Associates, Hillside NJ, pp. 65-81.

Alman D. H., Berns R. S., Snyder G. D., Larsen W. A., (1989) Performance Testing of Color-Difference Metrics Using a Color Tolerance Dataset. Col Res Application, 14:139-151.

Alman, D. H., Berns, R. S., Snyder, G. D. and Larsen, W. A (1989) Performance testing of color-difference metrics using a color tolerance dataset," Color Res. Appl. 14, pages 139–151.

Amano, K., Uchikawa, K. and Kuriki, I. (2002) Characteristics of color memory for natural scenes," J. Opt. Soc. Am. A **19**, pages 1501-1514.

Aubert, H. (1865) "Physiologie der Netzhaut". E. Morgenstern, Breslau pp. 394.

Baah, K. F., Green, P. J. and Pointer, M. R., (2012) Colour perception with changes in levels of illumination Proc. SPIE Vol. 8292.

Baker, M. and Balmer, J.M.T. (1997) Visual identity: trappings or substance?, European Journal of Marketing, Vol. 31 Nos 5/6, pp. 366-83.

Bala, R., DeQueiroz, R., Eschbach, R. and. Wu, W (2001) Gamut mapping to preserve spatial luminance variations, J. Imaging Science and Technology, 45(5): 436-443.

Balmer, J.M.T. (2001) Corporate identity, corporate branding and corporate marketing – seeing through the fog, European Journal of Marketing, Vol. 35 Nos 3/4, pp. 248.

Balmer, J.T. and He, H (2007) Identity studies: multiple perspectives and implications for corporate-level marketing, European Journal of Marketing, Vol. 41 No. 7/8, 2007, pp. 765-785.

Barten, P. G. J. (1999) Contrast Sensitivity of the Human Eye and Its Effects on Image Quality, 1-232 pages; ISBN: 9780819434968, Volume: PM72.

Bartleson CJ (1960) Memory colors of familiar objects, J Opt Soc Am., 50(): pp. 73-7.

Bartleson, C. J. and Breneman, E. J. (1967) Brightness Perception in Complex Fields, J. Opt. Soc. Am. 57, pp. 953-956.

Bartleson, C.J. (1960) Memory colors of familiar objects. J. Opt. Soc. Am. 50, pages 73-77.

Baudrillard, J. (1981) For a Critique of the Political Economy of the Sign, Telos Press, St Louis, MO.

Berkson, J., (1944) Reviewed work(s), Journal of the American Statistical Association, Vol. 39, No. 227, pages 357-365, September.

Berman, H. (2015) Least squares regression, http://www.stattrek.com/regression/linear-regression.aspx, Georgia Institute of Technology, Georgia-USA.

Berns R. S., Alman D. H., Reniff L, Snyder G. D., and Balonon-Rosen M. R., (1991) Visual Determination of Suprathreshold Color-Difference Tolerances Using Probit Analysis. Col Res Application, 16:297-316.

Berns, R. S. (1991) Visual determination of color-difference vectors using probit analysis: phase II, *Proc. of the 22nd Session of the CIE*, part I, pages 35-38.

Berns, R. S. (2000) Measuring color quality: perceptibility and acceptability visual judgments, in Billmeyer and Saltzman’s Principles of Color Technology, 3rd ed. John Wiley & Sons, NY, USA.

Berns, R. S., Alman, D. H., *Reniff, L., Snyder, G. D.* and *Balonon-Rosen*, *M.R.* (1991) Visual determination of supra-threshold color-difference tolerances using probit analysis, *Color Res. Appl*. **16**, pages 297-316.

Billmeyer, F.W. (1988) Quantifying color appearance visually and instrumentally, Color Research & Application, Volume 13, Issue 3, pp. 140–145.

Boiko E V, Chernush V F, Rogovanov D I, and Koskin S A, (2006) Optimisation of dark adaptation for specialists who work in different light conditions Perception 35 ECVP.
Boring E. G. (1939) The Psychophysics of color tolerance, The American Journal of Psychology, Vol. 52, No. 3, pages 384-394.

Brainard, D. H. and Ishigami, K. (1995) Factors Influencing the Appearance of CRT Colors, Proc. IS&T/SID Color Imaging Conf. 3, 62-66.

Brown SM and Bradley JC. (2011) Comparison of 2 monocular pupillometers and an autorefractor for measurement of the dark-adapted pupil diameter, Journal of Cataract Refract Surg. 37(4):660-4.

Bunkall, P. R. and Quinn, M. (1969) Instrumental colour measurement and control, J. Soc. Cosmetic Chemists 20, pages 265-281, Society of Cosmetic Chemists of Great Britain.

Burke, R.R. and Srull, T.K. (1988) Competitive interference and consumer memory for advertising, Journal of Consumer Research, Vol. 15 pp. 55-68.

Cao, D. and Shevell, (2005) S.K., Chromatic assimilation: Spread light or neural mechanism? Vision Research, 45, pp. 1031–1045.

Carter, R. C. and Brill (2014) Calculation of self –luminous neutral scale: how many steps can you see on that display? Journal of the Society for Information Display, pages 177-186.

Carter, RC (2005) Biological Gray Scale for Digital Imagery, Journal of Electronic Imaging, 14(2), 023004-1 – 023004-10.

Carter, RC and Silverstein, LD (2010). Size Matters: Improved Color-Difference Estimation for Small Visual Targets, Journal of the Society for Information Display, 18(1), 17-28. http://medical.nema.org/standard.html (accessed 17 March 2014).

Carter, RC and Silverstein, LD (2012). Perceiving Color Across Scale: Great and Small, Discrete and Continuous, JOSA A, 29, 1346-1355.

Cheney, G. and Christensen, L.T. (1999) Identity at issue: linkages between `internal' and `external' organisational communication, forthcoming in Jablin, F.M. and Putnam, L.L. (Eds), New Handbook of Organisational Communication, Sage Publications, Newbury Park, CA.

Cheney, G. and Christensen, L.T. (1999) Identity at issue: linkages between `internal' and `external' organisational communication, forthcoming in Jablin, F.M. and Putnam, L.L. (Eds), New Handbook of Organisational Comm., Sage Publications, Newbury Park, CA.

Cheung, V. et. al. (2005) A comparative study of the characterisation of colour cameras by means of neural networks and polynomial transforms, Coloration Technology, Volume 120, Issue 1, pp. 19–25.

Choh, K. H. et al. (1996) Effects of Ambient Illumination on the Appearance of CRT Colors," Proc. IS&T/SID Color Imaging Conf. 4, 224-226.

Choi, I., Shim, H. and Chang, N. (2002) ISLPED'02, August 12-14, 2002, Monterey, California, USA.

Choi, S.Y., Luo, M.R., Pointer, M.R. Li, C. and Rhodes, P.A., (2010) Changes in colour appearance of a large display in various surround ambient conditions, Color Research & Application, Volume 35, Issue 3, pages 200–212.

Christensen L.T. and Askegaard S (2001) Corporate identity and corporate image revisited European Journal of Marketing; Volume: 35 Issue: ¾.

Christensen, L.T. (2001) Corporate identity and corporate image revisited: a semiotic perspective, European Journal of Marketing, Vol. 35 Nos 3/4, pp. 292.

Christensen, L.T. and Cheney, G. (1994) Articulating identity in an organisational age, in Deetz, S.A. (Ed.), Communication Yearbook, Vol. 17, Sage Publications, Thousand Oaks, CA, pp. 222-35.

CIBSE - Chartered Institution of Building Services Engineers (1989) Lighting Guide: Hospitals and Healthcare Buildings, London.

CIBSE (2008) Lighting Guide 02: (SLL LG2) Hospitals and Healthcare Buildings, London, ISBN 9781903287996.

CIE (2007) Colorimetry - Part 4: CIE 1976 L*a*b* Colour space, pp 4.

CIE Publication No. 116 (1995) Industrial colour-difference evaluation, CIE Central Bureau, Vienna.

CIE, (1986) Colorimetry, CIE Publication No. 15.2, Vienna.

CIE, (1987) International lighting vocabulary, Number 17.4 CIE, 4th edition, Vienna.

CIE, Technical report (1993) Parametric effects in colour-difference evaluation. CIE Pub. No.101, Vienna, Austria: Central Bureau of the CIE.

Clarke F. J. J., McDonald R., and Rigg B., (1984) Modification to the JPC79 colour-difference formula, J Soc Dyers Col, 100, pp. 128-132 and pp. 281-282.

Clifford, C.W.G. (2007) Visual adaptation: Neural, psychological and computational aspects, Vision Research, Volume 47, Issue 25, November, pp. 3125–3131.

Coxon, A. P. M. (1982) The User's Guide to Multidimensional Scaling, Heinemann.

Crowley, A. E. (1993) The two-dimensional impact of color on shopping, Marketing Letters, 4 (1), pp. 59-69.

Cui G. et al (2013) Assessing Colour Differences near the Neutral Axis, Workshop on colorimetry: graphic arts and colour management - University of Leeds, UK.

Cui, G., Luo, M. R., et al (2013) Assessing Colour Differences near the Neutral Axis, AIC Colour - 12th Congress, Newcastle, UK.

Dalke, H., Littlefair, P. J. and Loe, D. L. (2005) Lighting and colour for hospital design, BRE, London South Bank University, London, ISBN 978-0113224913.

de Fez, M. D., Luque, M. J., Capilla, P., P´erez-Carpinell J. and D´ıez, M. A. (1998) Colour memory matching analysed using different representation spaces, J. Opt., Institute of Physics, 29, pages 287–297.

Engeldrum, P.G., (2000) Psychometric scaling: a toolkit for imaging systems development, Imcotek Press, Winchester, Mass.

Enterprise IG (2005) Wayfinding, Effective wayfinding and signage systems: Guidance for healthcare facilities, The Information Design Unit of Enterprise IG, TSO, Norwich.

Ewen, S. (1988) All Consuming Images: The Politics of Style in Contempory Culture, Basic Books, New York, NY.

Fairchild, M. and Reniff, L. (1995) Time course of chromatic adaptation for color-appearance judgments, J. Opt. Soc. Am. A/Vol. 12, No. 5/May.

Favre, J.P. and November, A., (1979) Color and Communication, Zurich, ABC Zurich.

Ferwerda, J. A. et. al. (1996) A model of visual adaptation for realistic image synthesis, ACM Computer Graphics, (Proc. of SIGGRAPH)'96, pp. 249--258.

Fetterly, KA et al. (2008) Introduction to Grayscale Calibration and Related Aspects of Medical Imaging Grade Liquid Crystal Displays, J Digit Imaging. Jun 2008; 21(2): 193–207.

Finney, D. J., Ed. (1952) Probit Analysis. Cambridge, England, Cambridge University Press.

Fleming, R. W., Dror, R. O. and Adelson, E. H. (2003) Real-world illumination and the perception of surface reflectance properties, Journal of Vision 3, 347-368.

Fleming, R. W., Dror, R. O. and Adelson, E. H. (2003) Real-world illumination and the perception of surface reflectance properties, Journal of Vision (2003) 3, 347-368, ISSN 1534-7362 © 2003 ARVO.

Foxman, E.R., Muehling, D.D. and Berger, P.W. (1990) An investigation of factors contributing to consumer brand confusion, Journal of Consumer Affairs, Vol. 24 No.1, pp.170-89.

Fraser, B. et. al. (2005) Real World Color Management, 2nd edition, Peachpit Press, Berkeley.

Garber, L. L., Jr., Hyatt, E. M., and Starr, R. G., Jr. (2000) The effects of food color on perceived flavor, Journal of Marketing Theory and Practice, 8, pp. 59–72.

García, P. A., Huertas, R., Melgosa, M., and Cui, G., (2007) Measurement of the relationship between perceived and computed color differences, JOSA A, Vol. 24 Issue 7, pages 1823-1829.

Garner. W. R. (1953) An informational analysis of absolute judgments of loudness, Journal of Experimental Psychology, 46, pp. 373-380.

Gatignon, H. and Robertson, T.S. (1991) Innovative decision processes, in Robertson, T.S., Kassarjian, H.H. (Eds), Handbook of Consumer Behavior, Prentice-Hall, Englewood Cliffs, NJ, pp.316-48.

Gibbons J.D., (2003) Nonparametric statistical inference, 4th edition Marcel Dekker, New York.

Government Digital service (2012) Research and analysis - Digital Efficiency Report, published 6 November, Cabinet Office.

Green, P and Johnson, A.J. (2001) Issues of measurement and assessment in hard copy colour reproduction Proc.

Green, P. (2010) Color management: Understanding and using ICC profiles, John Wiley & Sons Ltd., Chichester, UK.

Green, P. and Johnson, T. (2005) The Colour Difference Formula CIEDE2000 and its Performance with a Graphic Arts Data Set. TAGA Journal Technical Association of the Graphic Arts, volume 2 (edition 2). pp. 59-71.

Green, P. and Johnson, T. (2005) The Colour Difference Formula CIEDE2000 and its Performance with a Graphic Arts Data Set. TAGA Journal, vol2 (ed 2) pages 59-71.

Green, P., (2010) Color Management: Understanding and Using ICC Profiles, Wiley-IS&T Series in Imaging Science and Technology, UK.

Green, P.J. and Oicherman, B., (2004) Reproduction of colored images on substrates with varying chromaticity, Proc. SPIE Vol. 5293.

Griffin, L. D. and Sepehri, A. (2002) Performance of CIE94 for non-reference conditions, Color Res. Appl.27, 2, pp. 108–115.

Grimm, L. G. (1993) Statistical Applications for the Behavioral Sciences, John Wiley & Sons, Canada, ISBN-10: 0471509825.

Grossman R.P. and Wisenbilt J.Z (1999) What we know about consumers' color choices, Journal of Marketing Practice: Applied Marketing Science, Vol 5 Issue 3, pp 78-88.

Guan S. S., and Luo, M. R., (1999) Investigation of parametric effects using small colour differences, Color Res. Appl. 24, pages 331–343.

Guan, S.S. and Luo, L.R., (1999) Investigation of parametric effects using small colour differences, Color Research & Application, Volume 24, Issue 5, pages 331–343.

Hamwi, V. and Landis, C. (1955) Memory for color. J. Psychol. 39, pages 183-194.

Hanawalt, N.G. and Post, B.E. (1942) Memory trace for color. J. Exp. Psychol. 30, pages 216-227.

Hansen, T. et al. (2006) Memory modulates color appearance, Nature Neuroscience, 9(11): pp. 1367-8.

Haslup, J. R. C., Shamey, R. and Hinks, D. (2013) The effect of hue on the perception of blackness using munsell samples, Color Research & Application, Volume 38, Issue 6, pages 423–428.

Hect, S. et. al. (1937) The influence of light adaptation on subsequent dark adaptation of the eye, The Journal of General Physiology, pp. 831-849.

Helson, H. and Grove, J. (1947) Changes in Hue, Lightness, and Saturation of Surface Colors in Passing from Daylight to Incandescent-Lamp Light, J. Opt. Soc. Am. 37, pp. 387.

Helson, H., Judd, D.B. and Warren, M.H. (1952) Object color changes from daylight to incandescent filament illumination, Illum. Eng. 47, pp. 221-233.

Henley, S. and Fairchild, M.D. (2000) Quantifying Mixed Adaptation in Cross-Media Color Reproduction, IS&T/SID 8th Color Imaging Conference, Scottsdale, 305-310.

Hidayetoglu M. L., Yildirimb, K., and Akalinc, A. (2012) The effects of color and light on indoor wayfinding and the evaluation of the perceived environment, Journal of Environmental Psychology, Volume 32, Issue 1, pages 50–58.

Hine, T. (1996) The total package, New York: Little.

Hollingworth, H. L. (1910) The central tendency of judgment, Journal of Philosophy & Psychology, 7, pp. 461-469.

Holm, J. et.al. (2002) Color processing for digital photography in Colour engineering. eds. Green, P. J. and MacDonald, L. W. 2002 Wiley pp. 220.

Houston, M.J., Childers, T.L. and Heckler, S.E. (1987) Picture-word consistency and the elaborative processing of advertisements, Journal of Marketing research Vol 24, November, pp. 35-69.

Hoyer, W.D. and Brown, S.P (1990) Effects of Brand Awareness on Choice for a Common, Repeat-Purchase Product, Journal of Consumer Research, 17-2, pp 141-48.

http://www.colblindor.com/2007/05/21/city-university-online-color-vision-test/
http://www.nhsidentity.nhs.uk

Huang, M., et al. (2015) Power functions improving the performance of color-difference formulas, Optics Express, Vol. 23, No. 1, pp. 597-610.

Hunt, R. (1996) Why is Black-and-White so Important in Color?, 4th Color and Imaging Conference, Final Program and Proceedings, pp. 54-57, Society for Imaging Science and Technology.

Hunt, R. W. G. (1952) Light and Dark Adaptation and the Perception of Color, J. Opt. Soc. Am. 42, pp. 190.

Hunt, R. W. G. (1952) Light and Dark Adaptation and the Perception of Color, Journal of the Optical Society of America, Vol. 42, Issue 3, pages 190-199.

Hunt, R.W.G. , (2004) The Reproduction of Colour, John Wiley & Sons Ltd, Chichester, England.

Hunter, R.S. and Harold, R.W. (1987) The measurement of appearance, page 54, John Wiley and Sons.

Hurvich, L. M. & Jameson, D. (1957). An opponent process theory of color vision. Psychological Reviews, 64, pp. 384-404.

International Journal of Retail & Distribution Management; Volume: 35 Issue: 7. pp.531-543.

International Standard IEC 61966-2-1(1999), Default RGB Colour Space – sRGB.

Ishida, T., (2002) Color identification data obtained from photopic to mesopic illuminance levels," Color Research & Application, Volume 27, Issue 4, pages 252–259.

ISO 15076-1:2010 Image technology colour management — Architecture, profile format, and data structure.

ISO 20462-1: (2005) Photography -- Psychophysical experimental methods for estimating image quality -- Part 1: Overview of psychophysical elements.

ISO DIS 12647-2: 2012 Graphic technology — Process control for the production of half-tone colour separations, proof and production prints — Part 2: Offset lithographic processes.

Johnson G. M. and Fairchild M. D. (2003) A top down description of S-CIELAB and CIEDE2000, Color Res. Appl. 28, 425–435.

Johnson, A. J. 1996. Colour management in graphic arts and publishing, Pira International.

Johnson, A. J. and Green, P. J., (2001), The CIEDE2000 colour difference formula and its performance with a graphic arts data set Proc. IARIGAI.

Johnson, A., and Green, P. J, (2001) The CIE2000 colour difference formula and its performance with a graphic arts data set Colour Imaging Group, London College of Printing.

Johnson, A.J. and Green, P. (1999) Issues of colour measurement and assessment Proceedings TAGA Conference.

Kaernbach, C. (1991). Simple adaptive testing with the weighted up-down method. Perception & Psychophysics, 49, 227-229. 77.

Kaiser P K and Boynton R M. (1996) Human Color Vision. Optical Society of America, Washington D. C.

Kapferer, J.N. (1994) Strategic Brand Management: New Approaches to Creating and Evaluating Brand Equity, Simon & Schuster publishing, New York, ISBN 9780029170458.

Kathman, J (2002) Brand Identity Development in the New Economy, Design Issues, Vol. 18, No. 1, pp. 24-35 The MIT Press.

Katoh, N. and Nakabayashi, K., (2001) Applying Mixed Adaptation to Various Chromatic Adaptation Transformation (CAT) Models, Proc IS&T PICS.

Katz, D. (1999) The world of colour, Cognitive psychology volume 6, Psychology Press, pages 160-166.

Keller, K.L. (1998) Strategic Brand Management: Building, Measuring and Managing a Brand Equity, Prentice-Hall, Englewood Cliffs, NJ.

Keller, K.L. (2003), Strategic Brand Management: Building, Measuring and Managing Brand Equity, Pearson, Upper Saddle River, NJ.

Kennedy, S.H. (1977) Nurturing corporate images. Total communication or ego trip?, European Journal of Marketing, Vol. 11 No. 1, pp. 120-64.

Kent, T and Stone, D (2007) The Body Shop and the role of design in retail branding,

Kim, A., Kim, H. and Park S. (2011) Measuring of the Perceptibility and Acceptability in Various Color Quality Measures, J. of the Opt. Soc. of Korea, Vol.15, No.3, pages 310-317.

Kimpe, T. and Tuytschaever, T. (2007) Increasing the Number of Gray Shades in Medical Display Systems—How Much is Enough?, J Digit Imaging, issue 20(4), PMC3043920.

Kingdom, F.A. A. (2010) Lightness, brightness and transparency: A quarter century of new ideas, captivating demonstrations and unrelenting controversy, Vision Research.

Kinney, J. A. S (1962) Factors affecting induced color, Vision Research, Volume 2, Issue 12, pp. 503–525.

Kirchner, E. and Dekker, N. (2011) Performance measures of color-difference equations: correlation coefficient versus standardized residual sum of squares, J. Opt. Soc. Am. A, Vol. 28, No.9.

Krauskopf, J., Zaidi, Q., and Mandler, M. B. (1086) Mechanisms of simultaneous color induction, J. Opt. Soc. Am. A 3, No. 10, pp. 1752–1757.

Kruskal, J. B. (1964) Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis, Pychometrika 29, pages 1–27.

Kuehni RG, (2003) Psychophysical Scaling of Color Attributes Stimulus and Perception, in Color Space and Its Divisions: Color Order from Antiquity to the Present, John Wiley & Sons inc, Hoboken, New Jersey.

Kuehni RG, and Marcus R.T., (1979) An experiment in visual scaling of small color differences." Color Research Application, issue 4, pages 83–91.

Kuehni, R. G (2003) Color Space and Its Division: Color Order from Antiquity to the Present, John Wiley & Sons. INC: New York, NY, pp 204-270.

Kuo, W., (1995) Quantification of Metmarism and Colour Constancy, PhD thesis, Loughborough University of Technology.

Kykta, M., (2008) SID Symposium Digest of Technical Papers, Volume 39, Issue 1, pages 1336–1338.

Laborie, B., Vi´enot, F. and Langlois, S. (2010) Methodology for constructing a colour difference acceptability scale. Journal of Ophthalmic and Physiological Optics, 30 (5), pages 568-577.

Lam, K. L., (1985) Metamerism and Colour Constancy, PhD thesis, University of Bradford.

Lambin, J.J. (2002), Market-Driven Management: Strategic and Operational Marketing, Macmillan Business, London.

Lennie, P. (1993) Luminance, J. Opt. Soc. Am. A, Vol. 10, No. 6.

Lightfoot, C. and Gerstman, R. (1998) 'Brand Packaging', in S. Hart and J. Murphy (eds) Brands: the New Wealth Creators, pp. 46–55. Basingstoke: Macmillan.

Lindsay, P.H. and Norman, D.A. (1977) Human information processing, 2nd ed. New York: Academic Press.

Lo, M. C et al. (2006) The characterisation of colour printing devices via physical, numerical and LUT models, CGIV 2006, IS&T's Third European Conference on Color in Graphics, Imaging, and Vision, University of Leeds, UK, 95-99.

Loftus, G. R., (1972) Eye Fixations and Recognition Memory, Cognitive Psychology, 3, pp. 525-551.

Loken, B., Ross, I. and Hinkle, R.L. (1986) Consumer confusion of origin and brand similarity perception, Journal of Public Policy and Marketing, Vol. 5 pp 195-211.

Luce, R. D., & Galanter, E. (1963). Psychophysical scaling. In R. D. Luce, R. R. Bush, & E. Galanter (Eds.), Handbook of mathematical psychology (Vol. 1, pp. 245-307). New York: Wiley

Ludovic, Q., Mohamed-Chaker, L. and Christine F. (2008) Quality assessment of color reproduction devices: Cross-media vs. single media, Proc. SPIE. 6807, Color Imaging XIII: Processing, Hardcopy, and Applications.

Luo M. R., and Rigg B., (1987) BFD(l:c) colour-difference formula. Part I- Development of the formula. J Soc Dyers Col 1987, 103, pp. 86-94.

Luo M. R., and Rigg, B., (1987) BFD (l:c) colour-difference formula; Part 1—Development of the formula, J. Soc. Dyers Colour, 103, pages 86–94.

Luo, M. R. (2002) Development of colour-difference formulae. Rev. Prog. Coloration., 32, 28.

Luo, M. R. (2002) The CIE 1997 colour appearance model: CIECAM97s in Colour Engineering. eds. Green, P. J. and MacDonald, L. W. 2002 Wiley pp. 19.

Luo, M. R. Cui, G. and Li, C. (2006) Uniform colour spaces based on CIECAM02 colour appearance model, Color Res. Appl. 31, pages 320–330.

Luo, M. R., Cui G. and Rigg B., (2001) The development of the CIE 2000 colour difference formula, Color Res. Appl. 26, 5, pp. 340–350 .

Luo, M. R., Cui, G. and Rigg, B. (2001), The development of the CIE 2000 colour-difference formula: **CIEDE2000**. Color Res. Appl., 26: 340–350.

Luo, M. R., G. Cui, and B. Rigg. (2001) The development of the CIE 2000 colour-difference formula: CIEDE2000. Color Research and Application 26: 340-350.

Luo, M.R. and B. Rigg. 1986. Chromaticity-discrimination ellipses for surface colours. Color Research & Application 11: 25-42.

Luo, M.R., et. al. (2006) Uniform colour spaces based on CIECAM02 colour appearance model. Color Res. Appl., 31, pp. 320-330.

Lury, C. (2004) Brands: The logos of the global economy, Routledge, New York.

M. Stokes, M. Fairchild, and R. Berns, (1992) Colorimetrically quantified visual tolerances for pictorial images, in Proc. TAGA - Technical Association of the Graphic Arts, Proceedings of the 44th Annual Meeting, Williamsburg, VA, USA, pp. 757-777.

MacAdam, D. L. (1939) Representation of color tolerance on the chromaticity diagram, The American Journal of Psychology, pp. 412-418.

Macmillan, N. A. and Creelman, C. D. (2005) Detection Theory: A User's Guide, 2nd edition, Lawrence Erlbaum Associates, Inc, USA, pp

Mahy, M., Van Eycken, L. & Oosterlinck, A., (1994) Evaluation of uniform color spaces developed after the adoption of CIELAB and CIELUV. Color Res. App. 19(2), 105-121.

Mangine, H., Jakes, K. and Noel C. (2006) A preliminary comparison of CIE color differences to textile color acceptability using average observers, Color Research Application 30:288-294.

Martenson, R. (2007) Corporate brand image, satisfaction and store loyalty: A study of the store as a brand, store brands and manufacturer brands, International Journal of Retail & Distribution Management; Volume: 35 Issue: 7.

Martenson, R., (2007) Corporate brand image, satisfaction and store loyalty: IJRDM, vol. 35 issue7, pp. 544-554.

Aslam, M. M., (2006) Are you selling the right colors? A cross-cultural review of colors as a marketing cue, Journal of Marketing Communications, Vol. 12, No. 1, pp. 15-30.

Singh, S. P., (2012) Analyzing color on printed packaging to evaluate brand logo integrity and impact on marketing Universal Journal of Marketing and Business Research (ISSN: 2315-5000) Vol. 1(3) pp. 079-088.

Green, P and Johnson, A.J. (1999) Issues of measurement and assessment in hard copy colour reproduction, Proceedings of the SPIE, Volume 3963, pp. 281-292.

CIBSE (2008) Lighting Guide 02: Hospitals and Health Care Buildings (SLL LG2), ISBN 9781903287996, 96 pages.

McClintock, Anne (1995), Imperial Leather: Race, Gender, and Sexuality in the Colonial Contest. New York: Routledge.

Melewar, T.C. and Saunders, J. (1999) `International global visual identity: standardisation or localisation? Journal of International Business Studies, Vol. 31 No. 3, pp. 583-98.

Melgosa M., et al. (2011) Notes on the application of the standardized residual sum of squares index for the assessment of intra- and inter-observer variability in color-difference experiments, J. Opt. Soc. Am. A, Vol. 28, No. 5, pages 949-963.

Melgosa M., Hita E., Poza A. J., Alman D. H., Berns R. S. (1997) Suprathreshold Color-Difference Ellipsoids for Surface Colors. Col Res Application, 22:148-155.

Melgosa, M. et al. (2004) Relative significance of the terms in the CIEDE2000 and CIE94 color-difference formulas, Vol. 21, No. 12/December 2004/J. Opt. Soc. Am. A.

Melgosa, M. et al. (2011) Notes on the application of the standardized residual sum of squares index for the assessment of intra- and inter-observer variability in color-difference experiments, J. Opt. Soc. Am. A, Vol.28, No.5.

Melgosa, M., et al. (1997) Suprathreshold Color-Difference Ellipsoids for Surface Colors Color Research and Application, Volume 22, Number 3, pages 148-155.

Melgosa, M., Huertas, R. and Berns, R. S. (2008) Performance of recent advanced color-difference formulas using the standardized residual sum of squares index, J. Opt. Soc. Am. A/ Vol. 25, No.7.

Metha, A. B., Vingrys, A. J. & Badcock, D. R., (1994) Detection and discrimination of moving stimuli: the effects of color, luminance and eccentricity. Journal of the Optical Society of America A, 11, pp. 1697- 1709.

Morovic, J. and Pei-Li Sun, (2002) Visual Differences In Colour Reproduction and Their Colorimetric Correlates, 10th IS&T/SID Color Imaging Conference, Proceedings 12-15 November 2002, Scottsdale, Arizona, USA.

Morovic, J. and Wang, Y. (2003) A Multi–Resolution, Full–Colour Spatial Gamut Mapping Algorithm, 11th Color and Imaging Conference Proceedings, 282-287 (6).

N. Katoh, et al., (1998) Effect of ambient light on color appearance of softcopy images: mixed chromatic adaptation for self-luminous displays, J. Elec. Imaging 7, 794-806.

Nayatani, Y. and Sakai, H., (2007) Complexity of the color appearance of objects with nonuniform illumination, Color Research & Application, Volume 32, Issue 5, pages 372–377.

NEMA (2011) Digital Imaging and Communications in Medicine (DICOM), Part 14 - Grayscale Standard Display Function, Virginia, USA.

NHS Constitution (2013) National Pathology Programme, Digital First: Clinical transformation through pathology innovation, NHS Digital Technology England.

NHS Identity (2008) http://www.nhsidentity.nhs.uk/all-guidelines/guidelines/primary-care-trusts-new-guidance/signage/internal-and-wayfinding-signage
NHS Identity, (2003) http://www.nhsidentity.nhs.uk/all-guidelines/guidelines/acute-trusts/websites/nhs-identity.

Norberg O. and Andersson M., (2003) The influence of paper properties on color reproduction and color management, Proceedings of the IS&T NIP19: International Conference on Digital Printing Technologies, New Orleans, pp. 836-840.

Nundy, S. and Purves, D. (2002) A probabilistic explanation of brightness scaling, Proceedings of the National Academy of Sciences of the USA, vol. 99 no. 22, 14482–14487.

Ohno, Y. (2010) Radiometry and photometry review for vision optics in Handbook of Optics, Third Edition Volume III: Vision and Vision Optics edited by Bass M., McGRAW-HILL, London, pp. 381-384.

Olins, W (2008) The brand handbook, Thames & Hudson, London.

Olkkonen, M., Hansen, T. and Gegenfurtner, K.R. (2008) Color appearance of familiar objects: effects of object shape, texture, and illumination changes, Journal of Vision, 8(5):13. pp. 1-16.

Pérez-Carpinell, J., de Fez, M.D., Baldoví, R.and Soriano, J.C. (1998) Familiar objects and memory color. *Color Res. Appl*. **23**, pages 416-427.

Peterson, A.R., Smith, H.K and Zerrillo, C.P. (1999) Trademark dilution and the practice of marketing, Journal of the Academy of Marketing Science, Vol. 27, No. 2.

Petty, R.E. and Cacioppo, J.T. (1986), The elaboration likelihood model of persuasion, in Berkowitz, L. (ed.), Advances in Experimental Social Psychology, Vol. 19, Academic Press, San Diego, CA, pp. 123-205.

Pickton, D., Broderick, A. (2001), Integrated Marketing Communications, Pearson Education, London.

Poynton, C. (2012) http://www.poynton.com/notes/colour_and_gamma/GammaFAQ.html#brightness, accessed 12/08/2015.

Pridmore, R. W. and Melgosa, M. (2005) Effect of luminance of samples on color discrimination ellipses, Analysis and prediction of data, Color Res Appl. 30; pp. 186-197.

Puhalla, D.M., (2008) Perceiving hierarchy through intrinsic color structure, Visual Communication May 2008 vol. 7 no.2, pages 199-228.

R. G. Kuehni, (2008) Color difference formulas: An unsatisfactory state of affairs, Color Res. Appl. 33, pp. 324–326.

R., Shamey (2014) Performance of select color-difference formulas in the blue region, J. Opt. Soc. Am. A / Vol. 31, No. 6, 1328-1336.

Radonjić, A., Pearce, B., Aston, S., Krieger, A., Dubin, H., Cottaris, N. P., … Hurlbert, A. C. (2016) Illumination discrimination in real and simulated scenes, Journal of Vision, 16(11), 2. http://doi.org/10.1167/16.11.2.

Rafiq, M.and Collins, R. (1996) Lookalikes and customer confusion, International Review of Retail Distribution and Consumer Research, Vol. 6 pp. 328-50.

Rich D., (2012) L1-06 ISO/TC130: Graphic Technology, Division 1, Vision and colour minutes of the 5th Meeting of the Luo Term September, Taipei, Taiwan.

Rich, D., (2002) Instruments and methods for colour measurement in Colour Engineering. eds. Green, P. J. and MacDonald, L. W. 2002 Wiley pp. 19.

Robertson, A. R. (1970) A new determination of lines of constant hue, AIC Color 69, Stockholm, pp. 395-402.

Rotfeld, H.J. (2008) Brand image of company names matters in ways that can't be ignored, Journal of Product & Brand Management, Volume: 17, Issue: 2, pp. 121 – 122.

Schanda J. ed. (2007) Colorimetry – Understanding the CIE system, John Wiley & Sons.

Schechte L., (2010) Visual and taste rank-ordered probit analysis with correlated errors, Food Quality and Preference," Volume 21, Issue 1, January, pages 112-120.

Scherr, S. (1993) Electronic Displays 2nd. Ed. John Wiley & Sons, New York, p.29.

Schmitt, B H. and Simonson, A. (1997) Marketing Aesthetics: The Strategic Management of Brands, Identity and Image, Free Press, New York, ISBN

9780684867502.

Schultze, W. (1972) The usefulness of colour-difference formulae for fixing colour tolerances,” in Proceedings AIC/Holland, Soesterberg, pages 254–265.

Semmelroth C.C. 1970. Prediction of lightness and brightness on different backgrounds, J. Opt. Soc. Am. 60: pp. 1685-1689.

Shamey, R. et al. (2014) Evaluation of performance of various color-difference formulae using an experimental black dataset, Color Research & Application, Volume 39, Issue 6, pages 589–598.

Sharma, (2004) Understanding Color Management. Thompson Delmar Learning: New York.

Sharma, A. (2004) Understanding color management, Delmar Learning, NY, USA.

Sharma, G., (2003) Digital Color Imaging: Handbook, CRC Press Boca Raton, Florida.

Shaw, M., Sharma, G., Bala, R., and Dalal, E. N., (2003) Color Printer Characterization Adjustment for Different Substrates, Color Research and Application, 28, Part 6, 454-467.

Shepard R. N., (1966) Metric structures in ordinal data, Journal of Mathematical Psychology, Volume 3, Issue 2, July 1966, pages 287-315.

Shepard R.N. (1966) Metric structures in ordinal data J. Mathematical Psychology 3, pages 287-315.

Shepard R.N. (1980) Multidimensional scaling, tree-fitting and clustering, Science, New Series, vol. 210, issue 4468, pages 390-398.

Shevell, S. K. (1987) Processes mediating color contrast, Farbe 34, pp. 261–268.

Shevell, S. K. and Wei, J. (1998) Chromatic induction: border contrast or adaptation to surrounding light? Vision Res. 38, pp. 1561–1566.

Shimp, T.A. (1991), Neo-Pavlovian conditioning and its implications for consumer theory and research", in Robertson, T.S. and Kassarjian, H.H. (Eds), Handbook of Consumer Behavior, Prentice-Hall, New York, NY.

Shultze, W., (1972) The usefulness of colour-difference formulae for fixing colour tolerances, in Proceedings AIC Holland (Soesterberg), pages 254-265.

Slater, D. (2002), Capturing markets from the economists, in du Gay, P. and Pryke, M. (eds) Cultural Economics: Cultural Analysis and Commercial Life, Sage: London.

Stevens, J. C. and Stevens, S. S. (1963) Brightness Function: Effects of Adaptation, Journal of the Optical Society of America, Vol. 53, Issue 3, pages 375-385.

Stevens, J. C., and Stevens, S. S. (1963). Brightness function: Effects of adaptation. Journal of the Optical Society of America, 53, pp. 375-385.

Stewart, N., Brown, G.D.A. and Chater, N. (2005) Absolute identification by relative judgment. Psychological Review, 112(4), pages 881–911.

Stiles, W. S., & Burch, J. M. (1959). NPL colour-matching investigation: Final report. Optica Acta, 6, pp. 1-26.

Strassunk S., and Finlayson, G.D., (2005) Evaluating Chromatic Adaptation Transform Performance, Proc. IS&T/SID 13th Col Imaging Conference, pp 75-78.

Sueeprasan S, and Luo MR, (2001) Incomplete chromatic adaptation under mixed illuminations. Proceedings: The Ninth Colour Imaging Conference, IS&T and SID, Scottsdale, Arizona The Ninth Colour Imaging Conference, IS&T and SID, Scottsdale, Arizona.: 316-320.

Super marketing (1997), No confusion over own-label, Super marketing, pp. 14.

Süsstrunk S., Holm, J. and Finlayson, G. D. (2001) Chromatic adaptation performance of different RGB sensors, IS&T/SPIE Electronic Imaging, SPIE Vol. 4300.

Tarrant, A., (2002) Colorimetry and colour difference in Colour engineering, eds. Green, P. J. and MacDonald, L. W. 2002 Wiley pp. 7-8.

Theodoridis, S. and Chellappa, R. (2013) Academic Press Library in Signal Processing: Image, Video Processing and Analysis, Hardware, Audio, Acoustic and Speech Processing, Vol. 4 of Academic Press Library in Signal Processing, ISBN 0123972256.

Tian, Q. and Chung, R. (2011) A study of optical brightening agents (OBA) correction methods, Advanced Materials Research, vol. 174, pages 346-349.

Tibshirani, R., (1996) Regression shrinkage and selection via the lasso, Journal of the Royal Statistical Society, Series B, issue 58 volume 1, pages 267-288.

Tidbury, L. P., Czanner, G., & Newsham, D. (2016). Fiat Lux: the effect of illuminance on acuity testing. Graefe’s Archive for Clinical and Experimental Ophthalmology, 254, 1091–1097. http://doi.org/10.1007/s00417-016-3329-7

Tilley R., (2011) Colour and the optical properties of Materials, John Wiley & Sons, Ltd, Chichester.

Uchikawa, H., Uchikawa, K. and Boynton, R. M. (1989) Influence of achromatic surrounds on categorical perception of surface colors, Vision Res. 29, pp. 881–890.

Van Riel, C.B.M. & Van den Ban, A. (2001). The added value of corporate logos – An empirical study. European Journal 01 Marketing, 35 (¾), pp. 34-35.

van Riel, C.B.M. (2000). "Corporate communication orchestrated by a sustainable corporate story", in Schultz, M., Hatch, M.J., Larsen, M.H. (Eds), The Expressive Organization, Oxford University Press, Oxford, pp. 157-81.

Varey, R.J. (2002), Marketing Communication, Routledge, London.

Veglis A. (2007) Cross-media publishing by U.S. newspapers, Journal of Electronic Publishing, Volume 10, Issue 2, Spring.

Viggiano, J. A. S., and Moroney, N. M., (1995) Color reproduction algorithms and intent, Proc. IS&T/SID Color Imaging Conference.

Viggiano, J. A. S., and Wang, C. J. (1992) A Comparison of Algorithms for Mapping Color Between Media of Differing Luminance Ranges, TAGA/ISCC Proceedings, p 959 – 974.

Von Kries, J. (1902) Chromatic adaptation, Festschrift der Albrecht-Ludwig-Universität, (Fribourg) Translation in D.L. MacAdam, Sources of Color Science, MIT Press, Cambridge.

Ward, J., Loken, B., Ross, I.and Hasapopoulos, T. (1986) The influence of physical similarity on generalization of affect and attribute perceptions from national brands to private label brands, in Shimp, T.A. (Eds),AMA Educators' Proceedings, American Marketing Association, Chicago, IL, pp. 51-6.

Ware, C. and Cowan, W. B. (1982) Changes in perceived color due to chromatic interaction, Vision Res. 22, pp. 1353–1362.

Warlopa, L., Ratneshwarb, S., Stijn and M.J. van Osselaerc (2005) Distinctive brand cues and memory for product consumption experiences - International Journal of Research in Marketing Volume 22, Issue 1, pp. 27–44.

Wei, Shuo-Ting, Ou, Li-Chen, Luo, M. R. and Hutchings J. B. (2012) Optimisation of food expectations using product and colour appearance, Food Quality and Preference, Volume 23, Issue 1, pages 49–62.

Whittle, P (1992). Brightness, Discriminability and the 'Crispening Effect', Vision Research, 32, 1493-1507.

Wichmann F. A. and HILL N. J. (2001) The psychometric function: Fitting, sampling, and goodness of fit, Perception & Psychophysics, 63 (8), pages 1293-1313.

Wiley & Sons, New York, USA.

Worthey, J.A. (2004) Color rendering: A calculation that estimates colorimetric shifts, Color Research & Application, Volume 29, Issue 1, pages 43–56.

Zwick, R (1987) A note on random sets and the Thurstonian scaling methods, Fuzzy Sets and Systems 21, 351-356.

Figures – Appendix

Tables - Appendix