THE ROLE OF THE REFERENCE SOURCE IN IMPROVING THE CIE COLOUR-RENDERING INDEX FOR VISUAL PERCEPTION OPTIMISATION

by

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SUMMARY

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Keywords: Colour perception, CRI, Light-emitting Diode, Reference source, Wavelength, CCT, Human eye, Illuminant, Age

The technology for the measurement of colour-rendering and colour quality is not new, but many parameters related to this issue are currently changing. A number of standard methods have been developed and are used by different specialty areas of the lighting industry. CIE 13.3 has been the accepted standard implemented by many users and has been used for many years. Light-emitting diode (LED) technology moves at a rapid pace and as this lighting source finds wider acceptance, it appears that traditional colour-rendering measurement methods produce inconsistent results. Practical application of various types of LEDs yielded results that challenged conventional thinking regarding colour quality measurement of light sources.

This study investigates colour perception of human evaluators when applied to the traditional side-by-side booth method and also when applied to a unique double booth with rotating mirror. The reference source consists of an established incandescent lamp. The test source was assembled using four LEDs with wavelengths spanning the photometric spectrum fairly evenly.

Recent studies have shown that the anatomy and physiology of the human eye is more complex than formerly accepted. Therefore, the development of updated measurement methodology also forces a fresh look at functioning and colour perception of the human eye, especially with regard to LEDs. For this reason, colour perception was investigated, especially with regards to age.

As the most dominant and natural light source for human vision, sunlight and daylight were investigated as reference sources.

OPSOMMING

DIE ROL VAN DIE VERWYSINGSBRON IN DIE VERBETERING VAN DIE CIE-KLEURWEERGAWE-INDEKS VIR VISUELE PERSEPSIE-OPTIMERING

deur

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Sleutelwoorde:	Kleurpersepsie, kleurindeks, glimdiode, verwysingsbron, golflengte, kleurtemperatuur, menslike oog, ouderdom.

Die tegnologie vir die meting van kleurpersepsie en kleurkwaliteit is nie nuut nie, maar heelwat parameters wat verwant is aan hierdie vakgebied is besig om te verander. ’n Aantal standaardmetodes is ontwikkel en word gebruik en toegepas in verskeie spesialisareas in die verligtingsindustrie. CIE 13.3 is die aanvaarde standaard wat reeds vir baie jare deur navorsers en vervaardigers gebruik word. LED tegnologie vorder egter teen ’n snelle pas en soos wat hierdie tipe ligbronne al hoe wyer aanvaar word, word dit duidelik dat tradisionele metodes van kleurpersepsie metingresultate lewer wat nie konsekwent is nie. Praktiese toepassing van verskeie tipes glimdiodebronne lewer resultate wat tekortkominge in konvensionele meetmetodes beklemtoon.

Hierdie studie ondersoek kleurpersepsie van menslike beoordelaars nie alleen wanneer die tradisionele dubbelkastoetsmetode gebruik word nie, maar ook wanneer ’n unieke dubbelkastoetsmetode met roterende spieël gebruik word. Twee bronne word gebruik. Dit bestaan uit ’n verwysingsbron en ’n toetsbron. Die verwysingsbron is hoofsaaklik ’n konvensionele gloeilamp en die toetsbron is ’n versameling van vier LEDs waarvan die golflengtes so gekies is dat hulle eweredig oor die fotometriese spektrum versprei is.

Onlangse studies toon dat die anatomie en fisiologie van die menslike oog meer ingewikkeld is as wat oorspronklik vermoed is. Die ontwikkeling van ’n moderner meetmetode dwing die navorser dus ook om kleurpersepsie van die menslike oog met betrekking tot LEDs in ag te neem. Kleurpersepsie, veral met betrekking tot ouderdom, is dus om hierdie rede ingesluit in die studie.

Natuurlike lig in die vorm van sonlig en daglig is ook ondersoek as verwysingsbronne.

LIST OF ABBREVIATIONS

ANSI	American National Standards Institute
CCT	Correlated colour temperature
CDI	Colour discrimination index
CFL	Compact fluorescent lamp.
CIE	Commission Internationale de l’Éclairage
CPI	Colour preference index
CRI	Colour-rendering index
Duv	Distance from the Planckian locus
FL	Fluorescent light
FOV	Field of view
FWA	Fluorescent whitening agent
GAI	Gamut area index
H	High pressure mercury lamp
HCL	Human-centric lighting
HID	High intensity discharge
HPS	High-pressure sodium
HRR	Hardy-Rand-Rittler
JIS	Japanese Industrial Standard
LED	Light-emitting diode
MCC	Macbeth colour checker
MHL	Metal halide lamp
NH	High pressure sodium lamp
NX	Low pressure sodium lamp

pcPLED	Phosphor converted light-emitting diode
R_a	General colour rendering index
RGB	Red, green and blue
SPD	Spectral power distribution
SSL	Solid state lighting
UV	Ultraviolet

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

Is there really a need for research in lighting and visual perception? Indeed, this is the question asked by Boyce (2004). Humans are not really concerned about lighting, light perception and even colour perception except for some of the end results that these may yield. The lighting environment has an impact on some of the basic parameters concerned with life, such as safety, wealth and health. An additional reason why lighting and visual perception are researched is economic considerations. These include energy and cost optimisation. Two schools of thought exist. One group claims that research into lighting is superficial and that little is to be gained. Another group states that the living environment of humans can still be improved and research on lighting will contribute significantly to this goal (Boyce 2004).

1.1.1 Context of the problem

1.1.1.1 Investigating the role of the reference source

When colour perception tests are performed, established ideas are applied regarding reference light sources. The role of the reference source is thus very important, but is not particularly well understood. The International Commission on Illumination (CIE) developed a method of measurement of colour, called the "Method of Measuring and Specifying Colour Rendering Properties of Light Sources" (Method of Measuring and Specifying Colour Rendering Properties of Light Sources 1995).

For this procedure, eight colours are used, which have the same spectral reflectance as eight selected Munsell colours (Hunt 2004).

1.1.1.2 Investigating traditional test methods

Traditional colour perception tests are completed using established methods such as the side-by-side booth configuration. It is acknowledged that this method can be improved, as side-by-side bias may influence test outcomes. The traditional test method limits researchers' ability to perform visual perception tests away from established test centres, as a dark room is usually required.

1.1.1.3 Investigating the effect of age on colour perception

The effect of age on colour perception can be investigated by simulation and physical analysis of the ocular optical media. Measurements of spectral transmission can be performed on individual parts of the ocular system. The question is whether these results can be correlated to the visual perception of the user who uses the parts as a complete optical system, including visual interpretation performed by the human brain.

1.1.2 Research gap

Following the CIE colour-rendering index (CRI) test method, the correlated colour temperature (CCT) of the test source is expected to be close to the CCT of the reference illuminant. This requirement fails at extreme CCT. For example, consider a blackbody with a CCT of 2000 K. This CCT appears very reddish but will achieve a R_a of close to 100, which translates to a very good colour illuminator. In practice the colours of objects illuminated with this source will not be realistic (Davis 2010).

Another study confirmed that an increased level of blue is indeed needed to achieve a high R_a value when designing red, green and blue (RGB) light-emitting diodes (LEDs) as white light sources (Leuschner 2014). Narendran *et al*. (2002) claims that an LED light source with a low CRI value is preferred to a halogen or incandescent light source with a high CRI value. Bailey (Bailey 2013) states that an LED can produce good light quality and colour production with an R_a value of greater than 80 and a R_9 value above 0. These two studies show that measurement of R_a can be confusing and additional photometric parameters should be considered in context.

A number of researchers conducted a variety of visual perception tests. Many of these use side-by-side test configurations of different designs. It is evident however that researchers mainly use young students as observers (Narendran 2002; Fotios 2007; Schanda 2007; Wei 2012; Rea 2010; Dangol 2013; Islam 2013; Houser 2014). Other researchers use observers but do not supply age information. (Bartleson 1960; Yaguchi 2001; Moore 2002; Moore 2002; Thompson 2007; Taylor 2010; Spaulding 2011; Schanda 2015)

The question thus arises whether observer age is relevant or not when interpreting information on visual perception. Current published results do not seem to address the issue of whether all observers of all ages can be assumed to have the same visual perception regarding colour. Moreover, if it is found that the colour perception of observers varies with age, sex, nation, race and/or environment, what may be the influence of results already published in various journals?

1.2 RESEARCH OBJECTIVES AND QUESTIONS

The CIE defines colour-rendering as “The effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant” (International Lighting Vocabulary 1987). Objectives and questions are based on the science of colour rendering and are expanded in the following paragraphs.

1.3 HYPOTHESIS AND APPROACH

Reference sources and methods of measuring colour-rendering are investigated. As colour-rendering methods depend on human perception of colour, human vision qualities are studied, as well as differences in human perception across different age groups.

1.4 RESEARCH GOALS

The research goal is to contribute to the body of knowledge, specifying and defining the reference source used in similar colour-rendering studies. Improvement of the reference source will improve understanding of the composition of commercial light sources. Better designed light sources may be used to improve illuminated environments for work, play, education, sport and health. The goal is to be able to specify an alternative reference source, which can be used in a measurement system to improve the quality of any visual task.

1.5 RESEARCH CONTRIBUTION

This research contributes to improving the existing framework of human colour perception knowledge in terms of the following:

- The role of the reference source when considering colour perception of different age groups (excluding juveniles)
- An alternative test setup for side-by-side comparison in psychophysical colour perception evaluation, which may reduce side bias and enable researchers to use observers in remote study areas; and
- Psychophysical evaluation of human subjects one year apart to evaluate the repeatability of human colour perception.

1.6 OVERVIEW OF THIS STUDY

The engineer or researcher working in the field of illumination has a number of tools available that can be used for measurements, evaluation, implementation of new ideas and testing of established (and more recently applied) principles. The measurement of spectral power distribution (SPD) is certainly invaluable. The total luminous flux incident on a surface per unit area is important, as it is a measurement of how much the incident light illuminates a particular surface. This result can then be multiplied (wavelength adjusted) with the luminosity function to simulate human brightness perception.

A designer working in the field of lighting has the ability to influence the design of some parameters of the visual task (Fotios 2015; Houser 2015). These are:

- SPD;
- Quantity or intensity of light;
- Spatial distribution of light;
- Luminous efficacy of radiation;
- Luminous efficacy; and
- CCT.

Some factors are important in the design of an effective illumination system. These are the CRI and luminous efficacy, which is measured in lumens per watt (lm/W). Luminous efficacy differs from luminaire efficiency, which is defined as "the ratio of luminous flux emitted by a luminaire to that emitted by the lamp or lamps contained therein" (IESNA; 2005). Although CCT is not always presented in source specifications, it is still important and applicable. Architectural lighting designers use the CRI value as a means to determine the quality of white that a light source produces. (LRC October 2004)

The study field of human-centric lighting (HCL) is relatively new but is gaining importance. It is noteworthy that a joint study of Lighting Europe, the German Electrical and Electronic Manufacturers Association (ZVEI) and A.T Kearney shows that human-centric lighting (HCL) is due to cover about 7% of the general lighting market in Europe (AT Kearney, LightingEurope, German Electrical and Electronic Manufacturers Association (ZVEI); July 2013). Lighting and indeed the colour appearance of light sources are no longer perceived to fulfil the visual needs of people. The report shows that the correct level and spectrum of light sources are essential for the well-being of humans, while also saving energy. It has been shown that HCL systems can contribute biologically to improve cognitive performance and also emotionally to create stimulating environments and pleasant atmospheres. Halper reports on a case study completed at a Danish psychiatric hospital. Professional staff found that fewer drugs had to be administered to patients after the installation of HCL that followed a pattern simulating day and night illumination cycles (Halper 2017)

Another important aspect is the words that humans use to describe aspects of lighting. Schanda *et al*. (2015) alert the reader to the fact that both the terms “rendering” and “preferred” are used for the description of light quality, although the meanings of these words are quite different. Unfortunately, the problem is not solved easily, since different dictionaries present quite different meanings for the word “rendering”. For application in the study of photometry, Schanda suggests that the meaning as provided by the Concise Oxford Dictionary of Current English is the most appropriate. The word “reproduced” is also used in this context, which is applicable as colour-rendering really is about the reproduction of colours of objects. The researcher (as referred to in this context) is thus investigating the reproduction of colours and not preference for colours, as the word “prefer” suggests. It is recognised that this issue may not be resolved in such a trivial manner, but this study does not aim to research the hidden meaning of words and the term “rendering” will thus be applied for the sake of continuance and simplicity.

It is appropriate to consider the meanings of the words “perception” and “preference” as defined by Houser. (Houser 2015) “Perception” is described as follows: “It is helpful to distinguish between the color experience that occurs when a person looks directly at a light source, as opposed to the experience of viewing objects that reflect and scatter incident light. The perceived color of such objects is termed object color.” “Colour perception” is thus the way in which an observer experiences the colour of an object when the object is illuminated by a source that the observer cannot see directly. Colour perception therefore requires three components: a viewer, an object and a source of illumination. “Preference” is described as follows: “Preference refers to the aesthetic desirability of light sources, independent of a reference source.”

In this study, an adjustable reference source is used to illuminate a test object. The observer can only see the reflectance from the test object but has the ability to control the reference source. The observer evaluates the perceived colour as light is reflected from the test object and adjusts the reference source until the observer is satisfied that the reflected light from the test object is perceived to be the desired colour.

The CRI values consist of a set of values, R_i, which ranges from R_1 to R_{15}. The values can range from 0 to 100, although negative values are also possible. The value R_a refers to the R_i values that are averaged over the first eight colour samples. Although not technically correct, it has become the industry norm to use the terms “R_a” and “CRI” interchangeably. For the purpose of this study, the value CRI is defined in each context as it is used.

This study investigates the use and application of LED sources with regard to colour-rendering and human perception. It is important to note, however, that although the use of LED sources are advocated vigorously by many research and government institutions, it has been shown that many LED sources are not the most effective and appropriate in certain applications (Bedocs 2014).

The development of solid-state lighting (SSL) has escalated since 1990. Applications of SSL have also increased and include general lighting, architectural lighting, traffic lighting, stationary displays, mobile displays, computers, television sets, mobile devices, security and even automotive lighting. Indeed, a recent study has shown that the development of SSL is driven by many nations as a national priority. Many governments view the development of SSL as a major generator of wealth and also see it as an area of growth regarding employment (Simons 2011).

When a new technology is developed, such as LED technology in the field of lighting, end user requirements, preferences and expectations are important and should be investigated. User validation and evaluation are often required in order to know and assess the terms of end-user acceptance. This is why the design, construction and execution of human validation test procedures are still applicable (Islam 2013).

1.7 RESEARCH OUTPUTS

Conference proceedings published:

Van Der Westhuyzen, J.G.J. and Leuschner., F.W. (2014). A transparent look at the measurement and application of colour rendering in the use of LED light sources. *Proceedings of a Symposium on Sensors, MEMS and Electro-Optical Systems (SMEOS*

2014), Skukuza, Kruger National Park, South Africa, March 16-20, 2014, SPIE Proceedings Volume 9257.

Conference papers presented:

1. Van der Westhuyzen, J. G. J. and Minnaar, P. C. (2016). The design of a low cost Lumen meter for industrial applications. Paper presented at the Sensors, MEMS and Electro-Optic Systems (SMEOS 2016) conference, Skukuza, Kruger National Park, South Africa, 12-14 September 2016.

2. Van der Westhuyzen, J.G.J. Human colour perception change with age influences LED light source design. Paper accepted for oral presentation at Sensors, MEMS and Electro-Optic Systems (SMEOS 2018) conference, Skukuza, Kruger National Park, South Africa, 8-10 October 2018. (Manuscript number SM100-15)

Recent paper submitted to journal:
Van der Westhuyzen, J.G.J. and Leuschner., F.W. (2018). The effect of age on white light perception. Paper submitted to International Journal of Sustainable Lighting.

1.8 THESIS OVERVIEW

The thesis is divided into the following chapters and addendums:

- Chapter 2 provides an overview of related information as presented by researchers in the field. This includes media such as published journal articles, private and governmental reports, handbooks and reference to internet websites.
- Chapter 3 presents a description of methods used in this study. It also incorporates a discussion of existing tools currently used and an alternative design.
- In Chapter 4, results achieved in this study are presented. These are listed in the form of discussion, tables and graphs.
- Chapter 5 consists of a discussion of results especially wrt reference and comparison to similar studies.

- Chapter 6 presents the conclusion reached in investigating the role of the reference source in improving the Colour Rendering Index for visual perception optimisation.
- Addendum A consists of tables containing raw data as measured during the research period.
- Addendum B is a description of statistical method and results using the research data.
- Addendum C prsents a graph of the test booth inside paint spectral reflection characteristics.
- Addendum D presents some photos of results achieved for illustrative purposes.
- Addendum E presents a description of improvements that can be implemented to improve the double booth method used in many visual psychophysical research studies.

CHAPTER 2 LITERATURE STUDY

2.1 CHAPTER OBJECTIVES

The objective of this chapter is to present a summary of applicable and related literature studies. Literature studies are divided into three sections:

- Measurement of colour.
  - Section 2.2 lists and describes some prominent colour models.
- Laboratory colour appearance evaluation..
  - Section 2.3 describes practical methods used to evaluate colour perception. This includes different test setups such as chambers and rooms. Test charts and objects, observer screening, sources and field of view are discussed.
- Human factors
  - Section 2.4 discusses human traits applicable to this study. This includes psychophysical test methods, colour perception and age, chromaticity shift, colour perception and sex, colour perception in the periphery, illuminance levels and optical and photobiological safety.

2.2 MEASUREMENT OF COLOUR

The measurement of colour originated with the need to describe colour appearance and rendering scientifically. The description of colour was, and is, an attempt to describe how well an object looks under the illumination of a light source. Light sources change continually. During the industrial revolution, artificial light sources grew from gas to electricity and then further to a wide variety of gas, electricity and even a mixture of the two, including high-resistance conductors, glow and arc discharge lamps, open and closed flames and eventually solid state lamps.

Colours can be described by calculated coordinates on a chromaticity diagram. In a perfectly uniform colour space or area, the colour difference between two colours is proportional to the distance between two coordinate points. David MacAdam developed the MacAdam ellipses in 1942 to illustrate the non-uniformity of the 1931 xy chromaticity diagram (MacAdam 1942). MacAdam proposed elliptical shapes, plotted on the xy-chromaticity diagram, which approximated perceptual differences in colour, assuming constant luminance. A MacAdam ellipse for a particular colour point is defined to encompass one standard deviation of an observer, which is selected to be an individual with “normal” colour vision (CREE 2013). About 65% of all people would locate their perception of a colour corresponding to a point on the diagram within a MacAdam ellipse.

The first steps to measure colour or colour rendering included measuring of the SPD within defined spectral bands (Schanda 2003). An index for colour discrimination was proposed in 1980. This index was based on relatively small colour differences (Schanda 1980).

Semiconductor light sources grew through a number of technological developments to the point where white LEDs reached the consumer market. Their initial use was limited by cost, but as manufacturing methods became optimised, prices reduced and LEDs are becoming a household commodity. LEDs or SSL sources are expanding in many applications, which include not only residential applications, but also industrial, automotive, medical, entertainment, security and street lighting.

For colour-rendering the CIE test method remains the most widely accepted test method. (Method of Measuring and Specifying Colour Rendering Properties of Light Sources 1995) This fact is quite remarkable, as numerous other test methods have been developed, but these seem not to have been universally accepted yet. The CIE test method produces a measurable number, which is known as the CRI number. The colour rendering of a light source measures perception of colours when exposed to a test source and a reference source. Light sources that are considered to provide good colour-rendering are those that render colours of an object similar to what the colours of the object look like under a reference source simulating daylight. A daylight reference source may be simulated by a full photometric spectrum source such as an incandescent lamp. A source that renders a perfect daylight colour spectrum is allocated a CRI number of 100. The further the source is from rendering daylight colour, the lower the CRI number. The strange fact is that the CRI number may even be negative. The CRI method uses the first eight colour samples of the Munsell colour chart system. Although the Munsell colour charts were developed long ago, they are still in use and applicable. Ikeda (2001) developed a colour space model that considered non-linearity and also non-uniformity. According to Ikeda the original X, Y and Z coordinates developed for the Munsell colour chart are amazingly accurate and still relevant.

Rea and Freyssinier (2010) investigated both CRI and gamut area index (GAI) methods and made a convincing case for the impossibility of a single method of colour-rendering being developed. They argue that each method features unique strengths and weaknesses. No one method can be used as a single solution. More than one measurement method (in this case CRI and GAI) should rather be used, drawing on the strengths of each to arrive at a more inclusive solution. They also mention that lighting practitioners in architectural applications consider luminous efficacy to be less important than colour-rendering.

Alternative test methods are mainly based on many variations of the CIELAB and CIECAM models (Yaguchi 2001; Schanda 2003). Moroney *et al*. (2002) proposed CIECAM02, which is a revised version of CIECAM97.This model is also backwards compatible with CIECAM97. (The CIELAB hue circle is the uniform colour spaces circle published by the CIE in 1976. The CIECAM hue circle is the colour appearance hue circle published by the CIE in 2003.)

Some of the proposed alternative colour measurement systems are indeed advanced and fairly well developed. Such a system is the colour quality scale (Davis 2010). Researchers attempted to develop a system that can be used for all light sources. The aim is to integrate other dimensions of colour quality as well, but still produce a method where a single number is used to describe the quality of colour. This is an admirable and logical attempt to gain larger acceptance in the daily use of the proposed system.

Other attempts to produce alternative colour measurement systems include the flattery index (Judd 1967), the colour preference index (CPI) (Thornton 1974) and the colour discrimination index (Thornton 1972; Schanda 1978). The flattery index was modelled after the general colour-rendering index. It uses 10 of the original 14 Munsell colour samples. The general colour-rendering index uses only the basic eight Munsell colour samples of fourteen samples. (A 15th sample was added later.) It uses the same method to determine the reference illuminant. In practice many applications give a skin appearance colour of about one third of the total weight. The CPI was used especially in the evaluation of compact fluorescent lamps. Indeed, an attempt was formulated to merge some elements of the CPI and CRI into a single index (Schanda 1985).

An attempt that is more applicable to specific applications, such as the textile industry, is a spherical colour model, which was developed by Chen *et al.* (2013). The model uses the three coordinate components of a rotated spherical coordinate system to describe colour perception.

Yaguchi *et al*. (2001) developed their own colour-rendering index based on categorical colour names. The purpose of their study was to develop a system of colour categorisation rather than colour difference in evaluating the practical colour-rendering properties of light sources. They proposed a colour-rendering index based on categorical names rather than colour difference.

Guo and Houser (2004) completed a study where the colour rendering of light sources was evaluated using different methods of colour rendering measurement. The study was completed when SSLs were not readily available and LEDs are thus not included. The study is a comprehensive description of many of the methods developed in the field of colour-rendering. Guo and Houser (2004) also developed a score that allowed them to allocate a single number (or measure) to the description of colour rendering across all different methods applied. They do point out, however, that a single measure cannot address the problem of colour description, which spans many dimensions. The measurement algorithm designed by Guo and Houser does not allow for sources with a CCT of lower than 5000 K to be used. The CIE CRI system only allows for sources with similar CCTs to be compared and evaluated.

The CIE has also endorsed new techniques for measuring and quantifying colour discrimination, such as CIE ΔE 1994 and CIE ΔE 2000. ΔE involves many pages of calculations and requires detailed implementation instructions. Goldstein proposed pictorial representations of ΔE 2000 so that data can be described in terms of ellipses. (Goldstein 2012) These ellipses are non-MacAdam ellipses.

The CIE also realised that the standard test method may be problematic when applied to white LED light sources. In a technical report the CIE stated the following: “The conclusion of the Technical Committee is that the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this set” (Color Rendering of White LED Light Sources 2007).

Thompson *et al*. (2007) found that colour-rendering, more so than CCT, exhibited a close correlation with perception of brightness, such that if two light sources of equal colour temperature and different light levels were observed, the source with higher CRI appeared brighter.

Fotios completed a survey of previous studies to investigate the relationship between lamp colour properties and apparent brightness (2002). Observers were requested to state which environment was preferred for a workplace. The majority of observers preferred an interior lit by a source with a high colour-rendering number and colour temperature, despite the environment yielding significantly lower illuminance.

Most colour perception studies depend on human observers or evaluators to provide some feedback or input. Lee *et al*. (2005) proposed to explore colour preference using eye tracking. It is possible that these inputs may be subjective, therefore they attempted to design an objective method to obtain colour preference data. The relationship between colour preference and scan-path characteristics using eye-tracking was investigated. The results suggested that colour preference orders can be associated with fixation counts, return of fixations and fixation duration. They concluded that colour preference can indeed be indicated by eye movement.

The CIE Technical Committee (Committee Number TC 1-62) evaluated the colour quality of sources, especially white LED sources. They came to the conclusion that a new CRI should be developed. New and updated methods have been submitted to the committee. The number of metrics investigated by 2013 grew to nine (Dangol 2013).

Another applicable document published by the American National Standards Institute (ANSI) is called the SSL Chromaticity Specification, with tracing number C78.377 (Jiao 2015). This document was published in 2008 and is being updated. Jiao explains: "The intended purpose of C78.377 is to communicate between makers and users how indoor white color lighting is categorized, named and color variation tolerances are defined."

2.2.1 Summary

Table 2.1 presents a summary of some of the colour measurement methods developed.

Table 2.1 Colour Measurement Methods

Reference	Author(s)	Method	Description
(Judd 1967)	Judd	Flattery Index	Based on the SPD of the test source. Similar to CRI with the exception that reference colours are test samples viewed under a reference source and not computed colours.
(Thornton 1972)	Thornton	Colour Discrimination Index	The 1960 CIE chromaticity diagram is used with the eight test colours of the CRI. A gamut area is used to determine the colour discrimination of a test source.
(Thornton 1974)	Thornton	Colour Preference Index	Four fluorescent lamps were used to illuminate household objects; 267 observers rated the lamps in order of preference for colour, thus establishing the CPI index.
(Ikeda 1996)	Ikeda Yamashina Ichihashi	NC-IIIC Colour Space	Colour space NC-IIIC is introduced. The non-linear transformations of tri-stimulus values are synthesized and opponent colour response functions are developed. Hue, lightness and chroma can be specified independently.

Reference	Author(s)	Method	Description
(Ikeda 2001)	Ikeda	NC-IIIC Colour Space Adapted	Expands the NC-IIIC colour space to include opponent colour response capability with non-linear and non-symmetrical mechanisms.
(Jerome 1974)	Jerome	Absolute Colour Rendering	A method is developed that enables manufacturers to rate all lamps on the same base line regarding CRI. Experimental results not encouraging. Pre-LED era.
(Pointer 1986)	Pointer	Colour-rendering Presented through Numbers	Samples viewed under a reference illuminant are awarded numbers relating to hue lightness and chroma of the sample. The numbers are then combined to provide a difference measure between a set of samples observed under reference and test illuminants. Indices are calculated for red, yellow, blue and green and combined for a single number.
(Hisdal 1993)	Hisdal	Colour-Rendering based on the Colour Shift of Five Samples.	A set of colour samples is used with its complementary pairs. It is shown that if a group of colour samples include complementary pairs, a weighted sum of colour shifts can yield an index rating. Using a number of light sources (58) it is shown that five colour samples can be used rather than eight.
(Worthey 1982)	Worthey	Opponent Colours Approach	Opposite or complementary colours are any two hues that produce white or black (grey scale) when mixed. This method is developed regarding colour rendering.
(Lee, Tang & Tsai 2005)	Lee Tang Tsai	Eye tracking	A scan-path is implemented using eye-tracking characteristics to measure colour preference.

2.3 LABORATORY COLOUR APPEARANCE EVALUATION

How is colour perception of the human eye measured? Obviously, a practical method of measurement had to be devised. Whatever method is devised, this method must at least be able to satisfy the following requirements:

- It should allow humans with different colour perceptions to be measured.
- The test should be repeatable.
- The test should be simple and relatively uncomplicated.
- A minimum of performance figures should be calculated for the purpose of comparison.
- Other researchers should be able to duplicate the test and/or modify it.

A number of attempts are recorded. An excellent investigative overview of research methods was published by Fotios *et al*. (2009).

Fotios *et al*. (2009) investigated more than 60 studies in which SPD effects on spatial brightness were measured, using a variety of methods. Most methods employ varieties of a configuration where two test stations or booths are constructed and positioned next to each other. These test stations are normally in a cubicle form, which may vary in size. Many are in the order of 400 mm by 400 mm or larger. Full-size test rooms can be positioned side by side and these test rooms can then be stocked with a selection of furniture and typical office equipment in an attempt to simulate a realistic environment. Typical residential rooms or any other type of work area can be simulated using this method.

Fotios (2001) complemented the previous study with a study on brightness matching associated with the application of dimming, especially when side-by-side tests were implemented. Fotios described the use of a null-condition point where the stimuli from the two booths were perceived to be produced from two identical lamps. To counter any differences between the two interior spaces, stimulus presentation should be alternated between the two sides. Fotios investigated similar studies and came to the conclusion that a significant bias had been noted in null-condition brightness matching studies. Observers have a tendency to set illuminance on the low side in matched-pair comparisons.

Fotios and Cheal (2007) complemented earlier studies by investigating the effect of SPD on mesopic brightness conditions. For their experimental setups they used a full-size room and also side-by-side booths. The study found that bias regarding human brightness perception exists in side-by-side matching tests. This bias was claimed to be unexpected and was thought to be a response to contraction bias. It was calculated, however, that the bias had a very limited effect on the main results. It is noteworthy that Fotios and Cheal did not use any solid state light sources.

Narendran *et al*. (2002) conducted a human factors experiment in an effort to understand the colour-rendering properties of various LED-based reading lights. Human observers were tasked to rate their preference for a scene illuminated with test light sources (one type at a time) relative to an identical scene illuminated by a reference light source. Narendran *et al*. also employed the side-by-side booth approach. In their case the booth size was 380 mm by 380 mm. The evaluator was positioned 500 mm in front of the booths. The researchers used 30 evaluators whose ages ranged from 20 to 49. There were 15 male and 15 female evaluators.

Sandor *et al*. (2006) completed an evaluation again using the side-by-side booth configuration. No size description is provided but it is noted that diffusers were installed between the source and the chamber.

The use of real-life setups is also proposed by some researchers (Schanda and Madar 2007). They used realistic scenes for evaluation. A CIECAM2 model was used for adaptation of the illuminant and images were displayed on a calibrated CRT monitor for evaluation.

Spaulding *et al*. (2011) designed and completed three different experiments. They, too, felt that a real-life test setup was of value, since lighting preference can be very personal and often differs between people, applications and environments. The first experiment consisted of a complete facility, which was fitted with tunable LED panels. Thirteen evaluators performed daily tasks in this area. The CRI of the area was changed at specific intervals, at which time the evaluators had to answer certain questions that appeared on computer screens in front of them. For the second experiment, the typical double-booth method was implemented, although not side-by-side but back-to-back. The contents of the booths consisted of household objects. Three different CRI levels at three different intensity levels were used. For the third experiment, a typical life-sized office was constructed. The office was illuminated from the top and evaluators were exposed to one of four different lighting conditions. Each evaluator had to answer a set of predetermined questions.

Schanda *et al*. (2015) completed a thorough and ambitious study by evaluating real simulated life scenes in which office, home and shop lighting were evaluated. Full-scale test chambers were designed and constructed, which simulated a kitchen inclusive of a dining area, a living room and two realistic office areas. As test objects, the rooms were all fitted with appropriate equipment and furniture. Shop lighting experiments were executed in a real functioning canteen.

Practical evaluation of light sources is normally done in laboratory conditions. A large proportion of light sources are designed to be used outdoors and it thus makes sense that methods for outdoor evaluation should also be developed. Street lighting is very important, especially with designers turning to high power luminaires for this purpose. Sources of street lighting present special challenges for evaluation. These methods should be practical, but repeatable. Delta developed such a test in conjunction with the Rensselaer Polytechnic Institute (Taylor 2010).

Kostic *et al*. (2014) designed an illuminance test, which was completed at a walkway in an outside park. They illuminated an area with metal halide luminaires and a nearby area with LED luminaires. Both sources were selected to feature corresponding CCTs and CRIs. SPDs were also similar, as well as illumination levels. Sources were mounted such that evaluators were unable to identify the type of source. Humans were then asked to evaluate parameters regarding the sources. Most respondents declared that they favoured the metal halide source above the LED source regarding illuminance level, feeling of safety, feeling of comfort and colour of light.

Dangol *et al*. (2013) also used the side-by-side booth method, but using three booths instead of the customary two. The reference source (FL) was fitted in the centre booth and test sources (LEDs) in the side booths. They came to the conclusion that the “naturalness” of objects cannot be explained by the CIE CRI. Their results showed that observers do not prefer high CRI (higher than 95) LED sources over fluorescent sources, especially at a CCT of 2700 K.

Ying *et al*. (2006) developed an automated test setup. They used an integrating sphere, spectrometer and four independent power meters. The power meters were computer-controlled. They succeeded in measuring luminous flux, CRI and luminous efficiency. They were also able to analyse the colour characteristics of commercial RGB LED sources.

Just as LED light sources became widely accepted, thermal imaging is yet another technology that was continually developed to the point where most research institutions have access to thermal imagers and modern thermal imagers are relatively uncomplicated to use. It is thus logical that thermal imaging can also be used to measure certain parameters of LED light sources. Such a study was indeed completed by Siikanen *et al*. (2011). They used an infrared thermal imager to measure the surface temperature of LED tube luminaires and T8 fluorescent tubes. Both sources were mounted in a large integrating sphere in order to measure the total luminous efficacy of each source.

Thompson *et al*. (2007) designed a series of tests where the first phase included side-by-side booths. The booths were placed opposite each other, with the evaluator seated between the booths. A subsequent phase involved full-scale rooms. Evaluators were positioned at different angles and distances from the booths and rooms.

Wei *et al*. (2014) also used two related, but different methods. They designed a single booth mounted on a bearing, which enabled the booth to be rotated vertically. They also used the conventional side-by-side booth configuration for the second test, with dimensions of 533 mm x 381 mm x 813 mm, which does not follow the more usual rectangular configuration.

Ohno *et al*. (2013) designed a vision experiment on white light chromaticity for lighting to evaluate the Duv values perceived to be most natural by observers. (The Duv values can be calculated from a chromaticity diagram such as the CIE 1931 diagram. The Duv values are the plotted distances of chromaticity coordinates from the blackbody locus. Positive Duv values are above the locus and negative Duv values are below the locus). They started with a single booth layout where the observer had to report on different light levels. This was followed by life-size real-life rooms. The rooms were illuminated from the top with spectrally tuneable lights. The observer had to report on which light level and type appeared most "natural". They concluded that the chromaticity region below the Planckian locus is preferred well over white light, which is situated exactly on the Planckian locus. It is important to note that this observation was only tested for indoor environments and applications. They also evaluated the effects of two different wall colours, grey and brown, and found that the effects of different colours were negligible.

As already shown, a sizeable number of researchers focus on evaluation of colour-rendering. The ability of a light source to produce "pure" white light is also very important and not often researched. Houser *et al*. (2014) completed such a study. The team used two different LEDs (blue phosphorous LED (PLED) and violet PLED) and a halogen lamp as test sources. Objects covered with fluorescent whitening agents (FWA) were fitted in test booths and illuminated with the test sources. FWAs enhance the perception of white by chromaticity shifting towards the blue part of the spectrum and accentuating illuminance. Two side-by-side booths were used in the conventional layout. Five sets of booths were constructed and fitted in a pentagon pattern. Light sources illuminated test plates from the top and were dimmed using a mechanical iris. Sources were thus used at maximum power. The test plates consisted of nine calibrated plates. Evaluators were requested to compare plates in different sequences and to report accordingly. A diffuser was installed between the source and the test booth.

Sources under test or "test sources" are usually compared to "known" or rather "reference sources". Investigators use test sources of wide varieties, ranging from old technology to the latest LED sources. Colour perception of humans when sources are pulsed was also investigated. Fan *et al*. (2014) used the double booth test method to evaluate human perception on pulsed red and green illuminants. An experiment was completed to evaluate the influence of pulsed light on human colour perception. A red LED (640 nm) and a green LED (550 nm) were operated at pulsed currents with different duty cycles. The results showed that red light features a brightness enhancement effect when the duty cycle is less than 70%, whereas green light does not produce such an enhancement effect. It is thus deduced that the sensitivity of the human eye changes with the photometric spectrum and duty cycle.

2.3.1 Test charts and objects

Because of the difficulty of obtaining original CIE test samples, the CIE Technical Committee 1-33 recommended that samples of the Macbeth colour checker (MCC) should be used for visual experiments (McCamy 1976).

Yaguchi *et al*. (2001) used a set of Japanese Industrial Standard (JIS) colour chips specified with the Munsell colour system. They employed 292 colour samples, which consisted of samples found at value, chroma and hue levels. The size of each colour chip was 5.5 x 7 cm and it was positioned on a grey background.

Narendran *et al*. (2002) broke with convention and used no certified test charts. Instead, they used a magazine cover, two soda cans and a white plastic object, selected to represent a variety of colours.

Some researchers claim that the use of standard colour patches is not realistic and that the impression of the visual environment is important (Schanda 2007). Their solution is that the entire scene should be considered where colour solid distortion in different directions may have different appearances. Two scenes were used: a flower with foliage and a general indoor scene featuring colourful household wares.

Wei *et al*. (2014) used standard retail objects but added a test where human teeth and skin tone were evaluated. For this test they used two different races (Caucasian and Asian). Unfortunately African skin tone was not included.

2.3.2 Observer screening

Humans are to be used to evaluate colour experiments. It is thus important that human observers should be screened in advance to ensure that no individuals suffer from some of the medically documented colour perception deviations. Basic eyesight should also be tested to ensure that a minimum level of conformity is achieved.

The fact that some people suffer from deficient colour perception has been recognised long ago and the first paper on this subject was published by Dalton in 1798 (Dalton 1798). About 8% of all men suffer from some type of colour blindness, while only 0.5 % of women suffer from colour blindness (color-blindness 2017).

Fortunately, a number of test methods have been developed that can be used to screen individuals. Two of the most common methods used are the Ishihara test and the HRR pseudoisochromatic test. The Hardy-Rand-Rittler (HRR) pseudoisochromatic test was developed for colour vision (Rand 1956). As the name implies, the test was developed by Hardy, Rand and Rittler and it consists of a set of 20 coloured plates. The first six screening plates are used to identify the possible existence of a colour deficiency. The next 14 plates can be used to grade the severity of a deficiency and to differentiate between types of deficiencies. Cole *et al*. designed and completed a validation trail to compare the effectiveness of the two colour vision tests (Cole 2006). Their conclusion was that the Richmond HRR test is the better one. (The name "Richmond" is sometimes added because the Richmond Company originally manufactured the colour plates.)

Yaguchi *et al*. checked participants using Ishihara plates (Yaguchi 2001). Ishihara plates are the most commonly employed colour blindness test but not the most accurate one (color-blindness 2017). Wei *et al*. also used Ishihara plates (Wei 2014).

Narendran *et al*. (2002) mention the fact that evaluators were subjected to a pre-test colour screening but provide no further details. Sandor *et al*. (2006) used 10 young evaluators (six male and four female). They were subjected to a training session where Munsell colour chips of the same tri-stimulus values of the MCC were used.

Almost all the studies surveyed, except those of Yaguchi and Narendran, do not report on the type (if any) of colour screening applied.

For the sake of practicality, this study used an Ishihara computer model for basic colour deficiency screening. The model was checked using six different individuals with known colour deficiencies. As the model was used, it became clear that it would rather err on the safe side regarding this study. It is thus possible that more observers were eliminated than what was really necessary, but that was deemed acceptable.

2.3.3 Sources

Manmade light sources have formed part of human life for many centuries. Oil lamps have been designed and manufactured since the fourth millennium B.C. (Gardner 2014). Humans discovered long ago that fire can be controlled and one of the positive outcomes is the generation of light. Just as in modern times, ancient humans knew that light sources allowed man to engage in after-sunset activities such as working, playing, reading and social gatherings.

In an effort to maximise the efficiency of all light sources, research is focused on the design and construction of more efficient light sources. Worldwide, it is estimated that 19% of all electricity generated is used to power lighting systems in commercial applications. Illumination in commercial/office buildings uses 30% of a building's total power consumption (Albu 2013). Designers use different approaches to improve the luminous output of light sources. These range from improving fluorescent lamps, to replacing magnetic ballasts with more efficient components such as high-frequency ballasts, to the large-scale introduction of solid state lamps. Even in the field of solid state lamps, a large variety of design options are available to the illumination engineer.

A wide variety of different white light sources are available for the researcher to use. The possibilities are almost unlimited, but can basically be categorised into the following classes:

- Incandescent lamps,
- Fluorescent lamps,
- High intensity discharge (HID) lamps, and
- LED lamps.

Energy-efficient light sources such as LEDs have been developed as an option to replace traditional sources such as incandescent lamps. This replacement initiative is actively promoted, especially in developed countries, and in 2013 it was estimated that Europe should be free from incandescent lamps by the end of 2016 (Chamorro 2013).

It is generally regarded that the development of the LED occurred from 1960 to 1970 in the USA. The first observation of electroluminescence was published by Round in 1907. Another recorded fact is that Losev published a paper in 1927 in which he described the first recorded light emission from a point contact between a silicon carbide crystal and a metal wire. Losev also described the spectrum of the light and he reported on measured light thresholds. Losev published another 16 papers between 1924 and 1930 covering a comprehensive study on the LED and its applications (Zheludev 2007).

LED technology is not the only modern source being researched and developed. Researchers are also developing other sources that may feature competitive specifications and are even superior to LEDs in some applications. One of these sources is the high-efficiency fluorescent excimer lamp (Masoud 2013). This lamp is a high-efficiency xenon excimer lamp whose quartz tube transmits at a wavelength of 172 nm. Visible emission takes place at four distinct wavelengths, namely 400 nm, 440 nm, 550 nm and 590 nm. A fluorescent prototype white lamp was designed and tested and yielded an efficacy of 90 lm/W. Unlike most LED sources, this lamp is suitable for large-area illumination. Another advantage is that these lamps can be manufactured using established manufacturing methods developed for the mass production of conventional fluorescent and compact fluorescent lamps. (The lamp can be manufactured in both T5 and CFL configuration.) Its operating lifetime has experimentally been determined to be at least 5000 hours.

Yaguchi *et al.* (2001) used 14 different lamps, which included all types with the exception of LED lamps.

White light sources are best suited for most residential and in-door applications. This study focuses mainly on the investigation of white light sources. It is important to note that light sources containing other colours have practical applications as well. A variety of methods can be used to produce light of different colours.

Incandescent lamps or halogen lamps may be used as primary sources. White light is then transmitted through colour filters in order to achieve coloured lighting (Wyszecki 1982). Some of these sources feature a wide SPD envelope. Light generation in the blue spectral area may be limited, which is a disadvantage (Tominaga 2000).

Another way to produce coloured light is to use RGB fluorescent lamps. Coloured fluorescent RGB primaries can be added to achieve a wide range of chromaticity. The SPD of such a source is not a continuous distribution and includes sharp spikes (Tominaga 1996; Tominaga 1997).

RGB LEDs can be arranged in different patterns. These LED light sources can then produce a combined light of almost any colour, including white. Tanaka *et al*. (2011) constructed a matrix that included 12 red, 14 green and 12 blue LEDs. They also added 10 white LEDs. A computer controller and algorithm were developed to produce light of different colours.

In an effort to smooth the LED SPD, Schanda *et al*. (2015) constructed luminaires, which each contained 20 LED sources. The luminaire clusters consisted of 17 narrow-band LED sources with different colours, as well as three white LED sources, which were actually phosphor-covered converting blue LEDs. The peak emission wavelengths covered were

414, 424, 448, 465, 466, 504, 527, 533, 590, 592, 596, 624, 632, 636, 658, 667 and 691 nm. They also designed a computer-controlled current source, which was able to adjust the brightness of each source in 256 steps.

As RGB sources consist of individual LEDs of different colours, mixing and collimation may be difficult. These combined sources may produce colour shadows, multiple shadows and/or colour fringes. Cvetkovic *et al*. (2012) produced an optical design to ensure that properly mixed white light was achieved. They used moulded microlenses to provide Köhler integration. A shell with microlenses was designed to provide a homogeneous source when placed on an inhomogeneous multichip array.

White LED light from LEDs can be produced using one of two methods. White light can be generated by using blue or ultraviolet (UV) LED chips that are covered by a phosphor layer. Yellow light is then emitted from yellow phosphor due to the excitation from applied blue light (Wu 2012). Some of the emitted blue light is not absorbed by the phosphor and this mixes with emitted yellow light to produce white light (Kim 2004). The type of white light required can be altered by changing phosphor parameters such as particle size, particle density, layer thickness and refractive index (Bouchard 2012).
The second method used for generation of white light from LEDs is mixing base colours. Individual LED chips are used to mix base colours to achieve white light. The principle of additive colour mixing can thus be employed to achieve white light that consists of a number of spectral components (Zukauskas 2002; Zukauskas 2011). Narendran *et al*. (2002) used a selection of both types of LED sources in addition to halogen and incandescent lamps. Thompson *et al*. (2007) state that the problem is that the efficiencies of differently coloured LEDs are not the same. These differences may be sizeable and are related to different technologies used for each type of semiconductor (Thompson 2007). The designer who wants to build a white LED source using a combination of individually coloured LEDs should take note of this fact in order to optimise efficiency calculations. It is true, however, that multichip polychromatic LEDs can be more efficient than their phosphor-converted competition because no down-conversion process is required (Shur 2011).

Zukauskas *et al*. (2011) describe optimisation methods for the optimum LED source combination for the construction of a tetrachromatic source. They suggest four coloured LEDs with peak wavelengths in the following sectors: 410 – 490 nm, 490 – 540 nm, 540 – 610 nm and 610 – 680 nm. Their final selection is the following combination: 452 nm, 523 nm, 589 nm and 637 nm.

Although currently widely manufactured and used, phosphor-converted LEDs suffer from some disadvantages. A down-conversion process is required and this means that some energy is wasted. Ageing of phosphor layers together with unequal temperature distribution on chip and layer may result in an unpredictable chromaticity shift. A final problem is the fact that different types of phosphor layers can only produce a limited number of illumination environments, whereas future requirements will demand an almost limitless number of spectral compositions (Shur 2011).

He *et al*. (2010) generated a set of computer models to simulate the CRI and luminous efficacy (LED) of different types of white LED sources. In their simulations, they used various models of RGB white LEDs and also phosphor-doped white LEDs. In addition to the standard single UV chip model doped with yellow phosphor, they evaluated UV chips doped with multiple types of phosphor. According to their simulation, a single blue chip (450 nm) doped with green phosphor (507 nm), yellow phosphor (580 nm) and red phosphor (655 nm) should render a CRI of 97 and a luminous efficacy of 250 lm/W. These are theoretical models where four discrete wavelengths are used for the generation of white light. Practical implementation may not be easy.

Likewise, Murphy investigated the theoretical limits to luminous efficacy for perceived white light sources. He found that the maximum efficacy is in the range of 250 to 350 lm/W. Murphy (2012) also found that the colour temperature of a light source has only a limited impact on the range of values typically encountered.

Sandor *et al*. (2006) used a variety of incandescent, halogen and LED sources. They divided their sources into three main classes for experimental purposes. These were classified as groups with a CCT of 2700 K, 4000 K and 6500 K.

Houser *et al*. (2014) used three sources in a study on whiteness perception. These were a blue PLED, violet PLED and a filtered halogen lamp. It was discovered that the blue PLED failed to excite some of the FWAs properly. The filtered halogen lamp and the violet PLED fared better and the perception was that the blue phosphorus converted LED is not the best source to use for the rendering of pure white. This is interesting, as many of these types of sources are used in commercial applications where white light illumination is required. The team concluded that proper white rendering can only be achieved by a thorough design of the source spectrum.

Fotios and Cheal (2007) did not use solid state light sources but only high-pressure sodium (HPS), metal halide and CFL sources. It is interesting that brightness was adjusted using a mechanical iris instead of altering current (Figure 3.4). Fotios and Cheal used the HPS as reference source and compared the lighting of this source to the lighting of sources with reduced efficacy but increased CRI. These test sources consisted of metal halide and CFL lamps.

Adjustment of source intensity is another research area. Users of traditional sources such as incandescent and halogen lamps became accustomed to the fact that these sources change colour towards the red part of the spectrum when current through the sources is decreased. As the intensity of the source is minimised, the source emits a reddish colour, which many humans perceive as a pleasant atmosphere. Intensity adjustment of solid state sources such as LEDs manifested in ambient light, which rendered unnatural colours, especially with an excessive blue component and a limited red component. To compensate for this, designers started to mix different colours of LEDs. Essentially, different components of RGB LED sources are mixed with different RGB weighted values and the end result may be a huge variety of colours. The problem with this method is that it is rather complicated. A feedback system must be designed that measures the “mixed” result. A control system must then be used to calculate relative drive currents in order to achieve a dimmed atmosphere that is “reddish” in nature.

Recent developments show promising results in simplifying the method of intensity adjustment regarding LED sources. Bauer *et al*. (2014) developed a composite coating, which consists of liquid crystal combined with polymeric material. Scattering of light through this coating is heat-dependent. When a higher current (more heat) is applied to the LED, light is scattered differently from when a lower current (less heat) is applied.

When a higher current is used, the LED emits more light in the blue region, which has the effect of a "colder" light source. When the current is decreased, blue is reflected back from the coating, which enables more red to be emitted and the source appears "warm".

Solid state or LED sources are mostly powered by using continuous current. Fan *et al*. (2014) investigated human perception when pulsed LEDs are used. They used the traditional side-by-side booth configuration. One booth was fitted with a LED module operating in DC mode. The other booth was fitted with a LED module that was pulsed at 100 Hz. The duty cycle ratio of LED module 2 could be adjusted from 10% to 90% in steps of 10%. The observer was able to see both booths through two holes for comparison purposes. Red and green LEDs were used in this experiment. It was concluded that brightness can perceptually be improved when pulsing a red LED with a duty ratio of 20%. Pulsing a green LED proved to have no enhancement effect for the human eye.

2.3.4 Field of view

Any test setup must be designed to allow the evaluator or observer a specific angle of viewing. Although, the human eye has a complete field of view (FOV) of almost 180°, the FOV should be less for test setups in order to force the evaluator to concentrate on selected test objects. Another reason is pure practicality of construction, to determine which FOV is too wide or too narrow. Another reason for using a smaller FOV is that research has shown that a significant range of colour distortions are unnoticeable when operating outside a human's main FOV (Thompson 2007). For the completion of their tests, Thompson *et al*. (2017) used a FOV of 10° and 20°.

Side-by-side test booths are often constructed in cubicle form, which may vary in size. The typical size spans from a 380 mm three-dimensional square to 660 mm (Narendran 2002; Fotios 2007; Houser 2014; Wei 2014). The double-booth method can also be altered to use the booths in a back-to-back configuration (Spaulding 2011) or mounted on a rotating base (Wei 2014). The observer is positioned in front of the double booth and the distance is selected to ensure a FOV of around 40°. A number of researchers choose booth dimensions and viewing distances such that a FOV of around 40° is achieved (Narendran 2002; Fotios 2007; Houser 2014; Wei 2014). One explanation for this FOV figure is presented by Haller (Haller 2006). According to Haller (2006), the FOV of the human eye is about 150° (horizontal) by 120° (vertical). This angle includes peripheral vision. To accomplish such a wide FOV, it is necessary to move the head. If the head is kept stationary without motion, a FOV is achieved that is called the field of fixation. The fixation FOV varies from 40° to 50°.

Another way to explain the origin of a 40° FOV figure is to consider the distribution of rods and cones in the human retina. Colour-sensitive receptors (or photoreceptors) are presented by cones. The fovea is the area containing the highest number of photoreceptors. This is thus the area where the image is assessed most acutely. According to DiLaura *et al*. (2011), the fovea area corresponds to an included FOV of 40°. It can thus be deduced that researchers designed the test booth FOV to be similar to the fixation FOV and to correspond to the fovea FOV.

2.3.5 Efficacy

Although this study includes mostly investigations into colour evaluation, any modern light source should be evaluated for efficacy and efficiency. Energy efficiency of lighting is measured using a figure of merit called luminous efficacy, which is measured in lumens per watt (Murphy 2012). Inefficiency can originate from inefficient production of output photons relative to input power and distribution of photons outside the visible spectrum. Incandescent lamps are very efficient in producing photons, but most of the output photons are in the near infrared spectrum, which means they are not visible to the human eye. Luminous efficacy also encompasses visible and total radiation. The spectral part is measured in lumens per watt. The electrical part is the ratio of luminous power output to electrical power input and is thus unitless.

Efficacy values are sometimes published on data sheets of commercial products. These values are usually the values for the bare LED chip. They often do not include losses, which are part of the commercial product. This means that commercial efficacy values are often exaggerated (Lighting Global 2010).

2.3.6 Summary

A summary of visual perception measurement parameters is presented in Table 2.2.

Table 2.2 Summary of visual perception measurement parameters.

Author(s)	**Method**	**FOV (incl)**	**Source and Illuminance**	**Test Object**	**Evaluators and Screening**
(Narendran 2002)	Double booth (380 mm x 380 mm)	40°	RGB LED P LED Halogen Incandescent 200 lux	Soda cans Magazine cover Household objects	30 15 m, 15 f Age 20-49 Yes, NA
(Sandor 2006)	Double booth	NA	RGB LED Fluorescent Incandescent P LED Halogen 350 – 400 lux	MCC	10 6 m, 4 f Yes, FM100
(Yaguchi 2001)	NA	NA	HID Incandescent Fluorescent NX, NH, MHL, H, HF 1000 lux	JIS colour chips with Munsell system	4 NA NA Yes, Ishihara plates.
(Schanda 2007)	Real life scene Indoor	NA	RGB LED P LED Fluorescent	Flower with foliage Household goods	NA NA, NA Yes, FM100

Author(s)	Method	FOV (incl)	Source and Illuminance	Test Object	Evaluators and Screening
(Taylor 2010)	Real life scene Outdoor	NA	LED		26 NA, NA NA
(Spaulding 2011)	Real life scene Indoor		LED Panel 300 lux	Complete facility	13 NA,NA NA
(Spaulding 2011)	Double booth (back to back)		LED Panel	Soda cans Cereal boxes Fruit Flowers Painting	25 NA, NA NA
(Spaulding 2011)	Real life scene Single office		LED Panel Fluorescent Incandescent	Office scene with furniture	125 NA,NA NA
(Thompson 2007)	Double booth	10°	LED with changing CRI. 250 lux	Color-Aid	10 6 male 4 female
(Thompson 2007)	Real life scene	20°	LED with changing CRI.		30 11 male 19 female
(Wei 2014)	Single booth Rotating base (530 mm x 530 mm x 79 mm)		MR 16 lamp PLED Ra85 500 lux	Skin tone and teeth evaluation	48 33 male 15 female Age 18 -25 Yes, Ishihara plates.
(Wei 2014)	Double booth (533 mm x 381 mm x 813 mm)		MR 16 lamp PLED Ra97 500 lux	White shirt and 8 patches of eye makeup (retail environment)	48 33 male 15 female Age 18 – 25 Yes, Ishihara plates.
(Fotios 2007)	Double booth (575 mm x 680 mm x 660 mm)	38° x 37°	HPS and CFL Metal halide 1,4 lux to 15 lux	Four 60 mm high pyramids, red, green, blue and yellow card boards.	21 7 male 14 female, Age 18 – 54

Author(s)	Method	FOV (incl)	Source and Illuminance	Test Object	Evaluators and Screening
(Schanda 2015)	Real life scene Shop Kitchen Office Living room		Tungsten halogen P LED RGB LED	Furniture Real life objects	Not listed
(Ohno 2013)	Single booth Real life scenes		Spectrally tunable light sources 300 lux	Furniture Real life objects Fruit and vegetables MCC	18 11 male 7 female Age 20-70 Yes, Ishihara
(Dangol 2013; Islam 2013)	Triple booth side-by-side 1 m (h) x 0.5 m (w) x 0.5 m (d)	42°(H) x 61°(V)	LED 2700 K 4000 K 6500 K Fluorescent light	Coloured picture Wood Smartphone Hand (skin) Text Coke can MCC	60 20 male and 20 female (20-40 y) 10 male and 10 female (50-65 y)
(Moore 2002; Moore 2002)	14 open plan office buildings		Luminaires with CFL	Real life office objects and work areas	
(Houser 2014)	Double booth (530 mm x 530 mm x 790 mm)	30° - 45°	Blue PLED Violet PLED Filtered Halogen 300 lux	Nine calibrated commercial white plates	39 18 female & 21 male. (19-25) Yes, Ishihara plates.
(Bartleson 1960)	Investigates evaluators' ability to memorise colours of natural objects regarding average chromaticity, saturation and lightness.			931 Munsell colour chips These were correlated with ten common natural objects.	50 evaluators

Author(s)	Method	FOV (incl)	Source and Illuminance	Test Object	Evaluators and Screening
(Rea 2010)	Single booth		Halogen lamps PLEDs 6 coloured LEDs Composite source350 lux	Colour checker chart Grocery store fruit and vegetables	18 evaluators 10 male 8 female (21-38 y) Yes, Ishihara plates

2.4 HUMAN FACTORS

The purpose and aim of lighting is to enhance and support the performance of visual tasks.

Except for eating, lighting has the greatest influence on the ability of humans to function well regarding work, relaxation, private life and health. The exact influence of light on many human parameters is indeed difficult to measure. Numerous studies attempted to measure a variety of human living parameters with regard to light levels and quality. It was established that humans will overwhelmingly choose to work or sit next to a window with an outside view, when given a choice (Aries 2015). The reason for this cannot be explained, but it has been established that humans prefer natural light (or daylight) rather than artificial lighting. The designer of artificial light sources should thus take human factors into consideration.

The existence of light influences all aspects of daily life and work for humans. Pechacek *et al*. (2008) argue that light has an effect on people's physical, physiological and psychological well-being.

The part of the electromagnetic spectrum visible to the human eye is called the "visible region" or spectrum. (This is flanked by the infrared region and the ultra-violet region.) Most scientists define the visible region to span from 380 nm to 780 nm. This is not a set figure and definitions may vary. Guo and Houser (2004) used the spectrum from 360 nm to 830 nm for their calculations.

The study of the human eye’s response and interaction with visible light is known as photometry. The spectral response of the human eye was characterised more than 90 years ago and the resultant photopic function is the well-known V(λ) luminous efficiency function. The scotopic luminous efficiency function V’(λ) complements the photopic function and the two overlap to form the mesopic function.

Rea *et al*. (2004) point to the problem that the current photometric system has shortcomings. It is especially under low light conditions or mesopic conditions that the measurement of light sources becomes problematic. These are light sources used in special night/twilight applications. Human light perception studies have shown that traditional photometric measurements on mesopic light sources yield unreliable results concerning light levels and object discrimination (safety). Rea *et al*. thus developed and proposed a uniform photometric system. This study is focused on the research of colour perception and mesopic light sources are therefore only mentioned but not applied.

This chapter provides an overview of parameters involved in the use of human observers when measuring vision performance and colour perception.

2.4.1 Psychophysics

Illumination engineering relies on pure physical principles. These principles are established and used in research and development as the tools that enable technology to fulfil needs in a human world. It is, however, the human observer who uses illumination devices and it is thus important that human response to these products be measured. Results achieved from these measurements can, in turn, be used by the illumination designer to optimize the design of illumination systems. This is thus the study of psychophysics. Fechner was the first to realise the importance of psychophysical methods in audiology and vision science (Bijl 2003).

For the purpose of visual research and investigation, DiLaura *et al*. (2011) define psychophysics as follows: “Psychophysics is a sub-discipline of psychology that analyses perceptual processes by studying the relationships between physical stimuli and a human response, the response being given by either the report of a perception or the performance of a task.” Psychophysical experiments are designed and implemented to measure a subject’s response when stimuli are applied with a variation of properties. Psychophysical procedure, as used in this study, is thus the tool used for measuring and evaluating perception.

According to DiLaura *et al*. (2011) measurements and results achieved by psychophysics can be used in illumination engineering and lighting design to assist in the following ways:

- Formulate lighting design criteria.
- Optimise lighting design methods.
- Provide a basis for analysis tools.
- Minimise poor lighting designs.
- Assist in the design of lighting test equipment.

According to Pelli and Farnell (1995), psychophysical experiments yield two kinds of decision tasks, namely judgements and decisions, and the one is regarded as the inverse of the other.

Visual stimulation measurement methods can be divided into the following procedures and activities (Pelli 1995; Bijl 2003).

- Adjustments
  - Threshold

    An observer adjusts a stimulus contrast to more or to less to the situation where a contrast difference is not observable.
  - Nulling

    An experimental method is used to produce a distorted stimulus. The observer adjusts the stimulus until the distortion is cancelled.
  - Matching

    Two stimuli are presented to the observer who is requested to adjust one to match the other.

- Magnitude production

  The observer can adjust a stimulus and is presented with a numerical criterion to which the stimulus must be matched (for example: Illumination the same as that of a 100 W halogen lamp.)

- Judgments
  - The ideal observer

    The observer is presented with a stimulus and requested to use the information for a classification that will yield the most accurate performance. More than one response may be possible.

  - Yes-No

    This is one of the most popular methods. It can be used in detection and discrimination tests. The observer may only respond with a “yes” or “no”. “Was it visible?” “Is the left-side box brighter than the right-side box?”

  - Rating scale

    A rating scale is used to describe a stimulus. A set number of alternative rating numbers (often five) or a continuous scale may be used. “Number one is perfectly red and number five is perfectly red with other numbers a mixture of the two colours.”

  - Two-alternative forced choice

    The observer must choose between two numbers. These may relate to dark/light, blank/non-blank, up/down, left/right etc. Sequential stimuli may be presented randomly and/or in a set pattern.

  - Magnitude estimation

    Magnitude estimation and the rating scale are closely related. With magnitude estimation, the observer is requested to rate a stimulus using a number. Many different stimulus parameters are tested, whereas the rating scale tests a few stimulus parameters a number of times.

  - Response time

    The time taken for the observer to judge a parameter is measured and a stimulus test is designed such that response time is analysed and measured.

- Stimulus sequencing
  - Method of constant stimuli

The stimulus presented to the observer is constantly changed and the observer is continuously exposed to alternative runs, which are random trials of the same information.

- Sequential estimation methods

  Sequential estimation methods are expansions of the method of constant stimuli. A high number of trials are required to achieve a reliable threshold number. This method only became possible with the advent of computer technology, which made the design of evaluation algorithms possible. The designer should, however, keep the test programme relatively short.

In the past, research using psychophysical methods has concentrated on measuring thresholds (Pelli 1995). The reason for this is that observers are in favour of comparing different levels of visual input.

For the purpose of this study, experiments were designed where a stimulus was applied and the outcome was recorded and evaluated. Observers were required to react to a stimulus and make a decision of which the output was measured.

2.4.2 Chromaticity shift

Most humans are able to distinguish between sources with different levels of illumination and sources with different colours. Indeed, Wei *et al.* (2014) showed that for humans, colour perception and appearance are closely related to illuminance levels. Chromaticity shift, or colour shift, is not that easy, as it usually occurs over time periods, which may be months or even years. This phenomenon is not new, but it may be argued that the problem really becomes visible with the use of modern light sources. In the past, a room would often be fitted with a single source such as a fluorescent/tungsten lamp. Chromaticity shift gradually changed the emitted colour (and illuminance) but that was acceptable to the user.

Modern light sources such as LED sources are usually fitted in groups, in an effort to gain more evenly distributed illumination on subjects. If the chromaticity (and illuminance) of the sources drifts and this process is uneven, the human eye becomes a very effective tool in the measurement of differences of performance and such a scenario may indeed be undesirable.

Speier *et al*. (2006) completed a very thorough investigation into the colour temperature of tunable white LEDs. They investigated a number of concepts relating to the tuning of white LEDs. They came to the conclusion that each concept presents a unique set of advantages and disadvantages and the optimal solution depends on the application.

The fact is that most light sources display an amount of chromaticity shift, which will eventually be very visible to humans. All phosphor-doped or -equipped light sources display drift of chromaticity. Cold cathode fluorescent lamps used for panel back lighting display chromaticity drift (Jiang 1995).

Phosphor-doped LEDs degrade with time and drift towards the blue colour of the spectrum. White LEDs are temperature-dependent and the chromaticity of white LEDs tends to depend on junction temperature (Nichia Corporation 2017).

RGB LEDs are not free from chromaticity shift. As the junction temperature of a device increases, flux decreases and the CCT of the device decreases, thus moving towards a warmer colour temperature (CREE 2013). As the forward current of a device increases, flux increases and the CCT of the device increases, thus moving towards a cooler temperature. Consistency of colour and CCT of a number of LEDs can only be ensured if LED devices are procured in manufacturing batches (CREE 2013).

2.4.3 Colour perception and age

Most industrialised nations have ageing societies with increasing populations over the age of 65. This is the fastest growing segment of society in many countries (Chader 2013). The number of seniors in the USA is currently estimated at approximately 40 million. This number is expected to grow to 90 million by 2050. Most major eye diseases and sight retardations are age-related. It is thus logical to consider colour perception related to ageing. The fact is that a significant size of the market for modern light sources will belong to the senior segment. Colour production of light sources should therefore at least consider the needs of seniors.

The effect of light source colour production on age has enjoyed very limited attention from researchers and study groups to date. The effect of colour on age has been studied by a number of researchers. Dorcus (1926) completed one of the most comprehensive studies in an effort to determine colour preference related to age. He was able to use 1 235 evaluators, of whom 40 were older than 60 years of age and 297 were children. The colour samples he used were purple, blue, green, yellow, orange and red. His conclusion was that all age groups have exactly the same colour preferences.

A more recent study was completed by Ou *et al*. (2012) to investigate the effect of colour emotion as people grow older. They designed two experiments where evaluators were requested to respond to stimuli of different colours. One group of 72 evaluators consisted of a young group with a mean age of 24.5 years and an older group that had a mean age of 64.8 years. Ou *et al*. came to the conclusion that colour emotion may indeed change as people grow old. The reasons for this may, however, include a number of factors such as different psychological environments and a change in social requirements applicable to different life stages.

Colour perception and vision studies using children in modern times are rare indeed. One possible reason is that legal approval procedures when using children as observers tend to be complicated and time-consuming. Taylor *et al*. (2013) nevertheless conducted an experiment to compare colour “preferences” of infants and adults. They came to the conclusion that adults prefer blues and like green-to-yellow least. Infants have a stronger preference for dark yellow and a lower preference for blue than adults. It is strange that crystalline lens transmission was not considered at all.

Spectral transmission of the human crystalline lens changes with age because the optical density of the lens increases progressively with age. Transmission of short-wavelength light decreases with age and this causes the lens to appear yellower (Weale 1988; Lutze 1991; Delahunt 2004; Elliot 2007). The decrease of transmission includes colour and total transmission of visible light. The change in transmission already commences between 40 years and 59 years of age, but is most prominent above 60 years of age. Artigas *et al*. (2012) designed a series of experiments to measure the change in transmission. It was found that spectral transmission decreases dramatically after the age of 70. The crystalline lens of older people filters most of the UV part of the spectrum. The age group from 40 to 59 years typically loses 40% transmission at 420 nm and 18% transmission at 580 nm. It is true that results may vary to a great degree, as age may not be the only factor affecting the results. It has been shown, however, that transmission of the lens in the blue part of the spectrum decreases with age. The authors do state that more measurements should be completed.

Boettner *et al*. (1962) measured the crystalline lens transmission of nine eyes spanning an age of four weeks to 75 years. The lens of the four-week-old child started transmission at 300 nm. At 450 nm the infant lens reached a transmission figure of 90%. A 53-year-old lens achieved transmission of 50% at 450 nm, whereas that of the 75-year-old lens decreased to 18%.

Brøndsted *et al*. (2013) investigated the implications of circadian rhythm when applying short wavelength light filtering to the natural human lens and intraocular implant lenses. For this study, lens transmission was measured from human donors. A total of 29 lenses from 16 donors were measured, with ages ranging from 18 to 76 years. The study noted that transmission of the 76-year-old lens was 33% less than that of the 18-year-old lens. Spectral information was not provided.

Light sources in working environments are especially important. Older workers, on average, need higher levels of illumination to perform a task than what younger workers will need for the same activity (Van Bommel 2004). It is known that the colour of the lens moves towards yellow, which means that blue transmission deteriorates. This effect can be severe. It was discovered that where a person of 40 years old needs about 100 lux of illumination for a moderately difficult task, a person of 60 years old may need about 500 lux of illumination for the same task.

Chamorro *et al*. (2013) investigated the effect of LED radiation on human retinal pigment epithelial cells. The cells were exposed to three light-darkness cycles of 12 hours each. LED sources used for exposing the cells were blue (468 nm), green (525 nm), red (616 nm) and white LED. Chamorro *et al*. demonstrated that LED lighting can damage RPE cells. Their results showed that the rate of cell death was 86% for blue, 84% for green, 66% for red and 89% for white radiation. White radiation included a significant blue part of the spectrum.

Some illnesses may also contribute to a decrease in transmission of the human lens. Lutze and Bresnick (1991) showed that the decrease of transmission, especially at shorter wavelengths, is accelerated in diabetic patients.

2.4.4 Colour perception and sex

The difference between colour perception of human males and females was investigated by Murray *et al*. (2012), who presented a summary of more than 45 studies on the topic of male and female colour perception differences that were surveyed. They stated: “As can be appreciated from the above, there is no clear evidence for either the presence or absence of sex-related differences in color vision.” The common factor in all previous studies was that central colour vision, using a variety of methods, was evaluated. Murray *et al*. conducted tests to assess colour vision in the peripheral regions of the visual field. They concluded their study by investigating the hue and saturation shifts in the peripheral retinal areas of males and females. It was concluded that a difference in colour vision in the near retinal peripheral area does exist; a significant difference was found in the green to yellow area of perceived saturation in the chromatic axis angles from 225° to 240°.

Women are often thought to have superior colour vision simply because they are more articulate than men in the description of colours. In experiments, men use more basic terms than women to describe colour, whereas women use more elaborate terms to describe colours because they tend to have a more complete colour vocabulary than men (Nowaczyk 1982; Rodriquez-Carmona 2008).

2.4.5 Colour perception in the periphery

Because of the construction of the eye, as well as the placement of rods and cones, it can be deduced that colour perception probably changes over the visual field. The foveal region produces the best colour perception and it is assumed that colour perception decreases in the peripheral area. The question arises how much colour perception is lost in the periphery and at what angles. Hansen *et al*. (2009) completed a study to investigate colour perception in the periphery and found that colour stimuli can be reliably detected and identified at an angle of 50°. They commented that earlier studies underestimated this range. Moreland and Cruze (1959) found experimentally that colour perception reduces at an angle from the fovea to the point that dichromatism is measured from 25-30° and monochromatism can be expected from 40 to 50°. Abramov *et al*. (1991) found that the size of the optical stimulus influences peripheral colour perception. By increasing the size of the stimulus they achieved fovea-quality colour vision up to 20° but even large stimuli were unable to yield high-quality hue lines at angles larger than 40°.

Unfortunately, only five (younger than 41, and both male and female) observers were used in the study by Hansen *et al*. and they also reported that not all observers took part in all tests, which makes the sample size unreliably small.

2.4.6 Illuminance levels

For the purpose of this investigation, illuminance levels should be specified. Illuminance level is a subjective parameter on which evaluators and workers may have different opinions. The standard CIBSE Lighting Guide 7: Lighting for Offices and CIBSE Code for Interior Lighting 1994 lists some recommendations. This code specifies that general office desk work areas should be illuminated at a lighting level of at least 500 lux. Computer work station areas should be illuminated at levels ranging from 300 to 500 lux. An open-plan work area is recommended to feature light levels of at least 750 lux (Moore 2002).

Moore *et al*. (2000) investigated the validity of the specified levels of illumination to determine whether these light levels were realistic. They published results that showed that most office workers (desk areas as well as workstation areas) prefer to work in an area where light levels range from 100 to 300 lux. About 25% of people prefer the range from 300 to 500 lux and another 20% prefer to work in an area illuminated at a level of even less than 100 lux. These results are surprising, as the light levels are significantly lower than those suggested by Health and Safety recommendations.

A comprehensive industrial, workspace and office illumination study was completed by Van Bommel *et al*. (2004). This study used the EN 12 464-1 standard as guide in the evaluation of illuminance levels (EN 12 464-1 Light and Lighting – Lighting of work places. Part 1: Indoor work places). This standard is a European indoor lighting standard. Of specific application to this study is the fact that EN 12 464-1 even specifies illumination levels for specific tasks. Illumination levels are similar to those specified by Moore (2002), except that more detail is added. EN 12 464-1 specifies an illumination level for colour inspection in industry. This level is specified to be 100 lux. As mentioned by Moore, indoor office and workspace light levels should be between 100 and 300 lux. It was thus decided to consider the suggested light levels for colour sample inspection (100 lux) and indoor work space light levels (100 – 300 lux) to specify a reference and test illumination level of 150 lux for the experiments described in this report.

An additional aspect (which is not investigated in this report) is the effect of illuminance levels on human behaviour. McCloughan *et al*. (1999) completed a study investigating the impact of illuminance levels on the psychological mood of humans. They found that lower light levels (280 lux) are more likely to induce positive behaviour than high light levels (770 lux). Very high light levels (1500 lux) were responsible for inducing negative behaviour. The study also showed that very big differences in perception can be found between individuals and that differences also exist between sexes. Colour temperature (CCT) also plays a part and it was found that negative mood experienced by women tend to decrease under illumination of a warm source (2950 K). In contrast, men experiencing negative moods needed a cool lamp (4000 K) to enhance their moods. The experiments were completed using lamps with high CRI numbers.

2.4.7 Optical safety

LED sources are known to emit a sizeable amount of light in the blue spectrum. Waves in the electromagnetic spectrum carry more energy if the wavelength becomes shorter. Thus, the term “blue light hazard” was introduced. As the term implies, the possibility of eye damage due to LED-induced light is investigated. The photometric spectral area from 380 nm to 500 nm is known as “high-energy visible light”. The extent to which blue light poses a danger to the human retina is debated among academics, ophthalmologists, engineers and even government departments. Some role players feel that the risk of possible damage is highly unlikely or almost non-existent (US Department of Energy. Energy Efficiency and Renewable Energy. October 2014). Other researchers claim to be able to present convincing proof that blue light induces not only retinal damage, but corneal and lens damage as well (Smick 2013). A study was even completed using rats. A number of rats were exposed to LED sources for nine days. A similar number of rats were exposed to traditional sources for the same period. Both groups displayed retinal damage, but according to the authors, the group exposed to LED sources displayed measurably more retinal damage (Lougheed 2014).

The best method used to measure and evaluate blue light hazard is another area of contention. Schulmeister *et al*. (2013) developed a simplified method for the assessment of UV and blue light hazards of lamps. They characterized 110 lamps used for lighting in the UV and visible spectral region. Although their results were preliminary, they were able to specify exposure limits for UV lamps and derived transformation factors for blue light hazard.

2.4.8 Material safety

The ability of LED light sources to damage materials such as museum artefacts was investigated (US Department of Energy. Energy Efficiency and Renewable Energy. October 2014). This aspect is not investigated in this study. It is mentioned for completeness to indicate that LED sources for display applications should be carefully selected.

2.4.9 Photobiological safety

The circadian rhythm of humans is well documented. The 24-hour cycle or rhythm dominates a variety of human aspects such as physiology and behaviour. A time period of about 23 to 25 hours characterises the human circadian rhythm. An external environmental light input with a light and dark cycle is needed to adjust the internal human clock to a periodic cycle of 24 hours (Pechacek 2008).

The possibility of LED light sources to influence the human circadian rhythm was investigated (US Department of Energy. Energy Efficiency and Renewable Energy. October 2014).

For most of ophthalmic history, the sensory system in the human eye has been accepted to consist of two types of photoreceptors. These are rods and cones. The existence of a third photoreceptor has been researched and evidence suggests that such a receptor does indeed exist. These receptors are called intrinsically photosensitive ganglion cells. These receptors communicate directly with the brain, using an alternative nerve path, and are less sensitive to light than cones and rods. They are, however, able to register ambient light.

Because these receptors are thought to play a major role in the 24-hour light/dark cycle, they are referred to as circadian photoreceptors. They also play a role in controlling pupil size and assisting with the release of melatonin.

Although circadian photoreceptors do not contribute to colour perception, they are assumed to assist the eye in execution of mesopic vision (King 2000; Devlin 2001; Reppert 2002).

Barrosso *et al*. (2014) attempted a study to determine how the effects of lighting conditions are measured and standardised in order to describe some parameters influencing the circadian system. They chose a hospital environment to investigate the relationship between lighting and circadian rhythms. A set of lighting metrics was developed for use in comparative applications when the impact of light levels on circadian physiology was studied.

The question of what the input parameters influencing the circadian system are was also addressed by a number of writers. Pechacek *et al*. used a hospital environment to determine experimentally light parameters that may be beneficial to the healing of patients. Pechacek (2008) and Rea (2011) list some input parameters that are important to the human circadian rhythm. (There may be more.) The discovery that the circadian system is influenced by previous photic history was studied by Chang *et al*. (2011). These parameters are:

- Intensity or quantity,
- SPD,
- Duration,
- Spatial distribution,
- Timing, and
- Photic history or history of light exposure.

Rea and Figueiro (2011) claim that the output of the circadian system influences the following human parameters:

- Sleep and awake cycle,
- Core body temperature, and
- Hormone production.

2.5 ILLUMINATION AND WILDLIFE BEHAVIOUR

The effect of illumination sources on wildlife is not investigated in this study. It is important to know, however, that research on the effect of modern illumination sources on the behaviour of wild animals is a fast-growing study discipline. Indeed, Hecht (2015) states that the use of modern external light sources, especially solid state sources, may have an impact on wildlife populations in unplanned ways.

The effect of a light source on specific wildlife depends heavily on the SPD of the light source used. Hecht mentions that UV attracts insects and is visible to birds and reptiles, while also affecting animal circadian rhythms. Blue repels some bats and attracts insects and some predators. Blue is also known to affect some animal circadian rhythms and it is thought to be responsible for the lowering of melatonin production. Green light sources may attract some amphibians and affect some bird migration. Yellow light sources feature low insect attraction and may be responsible for the interruption of night foragers. Red light sources may affect the photoperiodism of plants and may also be responsible for change in the growth of bird gonads. ("Colours" mentioned in this section may not represent mono-colour sources but rather wide-band sources with dominant wavelengths as described in each case.)

An innovative use of solid state light sources was demonstrated when a rural boy from Kenya found that flashing LEDs positioned around livestock successfully kept lions away from hunting farmers' animals (Thomas 2013). This solution presented a double advantage for both rural farmers and the Kenyan tourism industry. On the one hand, farmers benefitted because lions did not kill their livestock anymore. On the other hand, the tourism industry benefitted because farmers now had no need to kill lions. Unfortunately the physics concerning this novel solution remains to be studied. Some of the questions concern the parameters involved in keeping lions at bay, such as the influence of wavelength, intensity and flashing frequency.

Some of the claimed effects at specific wavelengths may not be widely accepted by illumination scientists because of incomplete research. Research involving animal behaviour is difficult and often problematic to structure and repeat.

Research investigating dark/light influences on animal behaviour as described by Roedel *et al*. (2006) is readily available. Research investigating the effect of illuminant colour on animal behaviour is not commonly available. It is thus no surprise that the writers of a report state: "Although there's no way to truly know what non-human animals actually perceive, scientists can examine the cones inside the eyes and estimate what colours an animal sees" (www.colormatters.com 2015). Baraniuk (2015) describes a number of methods that can be used to determine animal colour perception but these all rely on deduction rather than measurement.

The study area of animal behaviour certainly deserves attention, as the designer of illumination sources should be aware of parameters that may influence animal behaviour negatively.

2.6 CHAPTER SUMMARY

This chapter provides an overview of literature studies relating to:

- Measurement of colour
    - Although a number of colour models have been developed, Section 2.2 shows that the CIE test method is still accepted. Using this method, a colour-rendering number is used to describe the colour quality of a source. The colour quality scale is an expansion of this method and gaining industrial acceptance.
- Laboratory colour appearance evaluation
    - Section 2.3 lists configurations to investigate colour perception studies and finds that these include test booths or rooms of various sizes. Reference sources used include different types of sources. A test setup is often designed to feature a 40° field of view.
- Human factors
    - Psychophysical test methods for audiology and vision science are established and accepted as presented in Section 2.4.1. Section 2.4.2 shows that most light sources display some chromaticity shift over time, which is clearly visible to humans. Colour perception change wrt age is expected because of the yellowing of the human crystalline lens with age, but has not been confirmed, as discussed in Section 2.4.3. Section 2.4.4 discusses the fact that colour perception differences between males and females could not be confirmed. Section 2.4.6 discusses illuminance levels and reports that many office workers prefer levels lower than established standards. Section

2.4.7 discusses LED “blue light hazard” and mentions that scientists do not agree on the extent to which blue light poses a danger to the retina.

CHAPTER 3 METHODS

3.1 CHAPTER OBJECTIVES

This chapter provides an overview of existing test setups and an improved method is proposed.

- Sections 3.2.1 to 3.2.4 discuss the practical layout of existing designs.
- Sections 3.2.5 and 3.2.6 present alternative improved designs.
- Section 3.4 discusses light sources used as reference and test sources.
- Section 3.5.2 calculates the acceptable observer sample size.
- Sections 3.5.2 to 3.5.4 lay out test procedures.

3.2 TEST BOOTH DESIGN

As part of the experimental evaluation, a practical setup had to be designed and manufactured. A number of configurations were designed and these are discussed. Most of the designs are based on existing setups or use elements of existing setups as used by other researchers in an attempt to correlate results. A final configuration is proposed, which is unique. All test booth systems incorporate the following elements:

- Enclosure to house light sources and test samples,
- Reference light sources,
- Test light sources,
- Colour checker reference colour charts,
- Light control to change test source parameters,
- Power source to power light sources,
- Illuminance meter (Lux meter) to measure light levels inside booth, and
- Photometric spectrometer to measure light source SPD and CRI.

3.2.1 Test booth with domed roof

Figure 3.1 shows the configuration of the test booth, which is divided into two chambers. Both test and reference light sources transmit towards the dome, where diffuse reflections ensure constant illuminance of ambient light reaching the test samples. A diffuser may be added to the bottom of the dome in an effort to improve light distribution. The evaluator has to compare the light characteristics of the two chambers. The evaluator can adjust the light levels and quality of the reference source. The disadvantage of this configuration is that the domed roof may be difficult and expensive to manufacture.

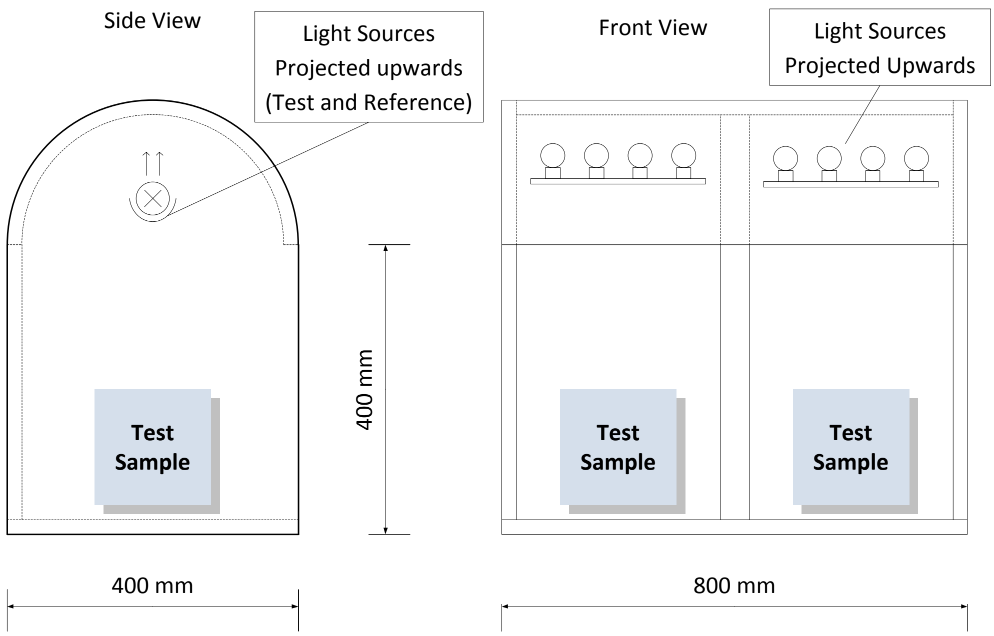

Figure 3.1 Domed roof with upward projecting sources.

3.2.2 Test booth with 45° slanted roof

Figure 3.2 shows a configuration that is similar to the one described in Section 3.2.1. The slanted roof may be easier and cheaper to manufacture. Light levels may not be as well distributed.

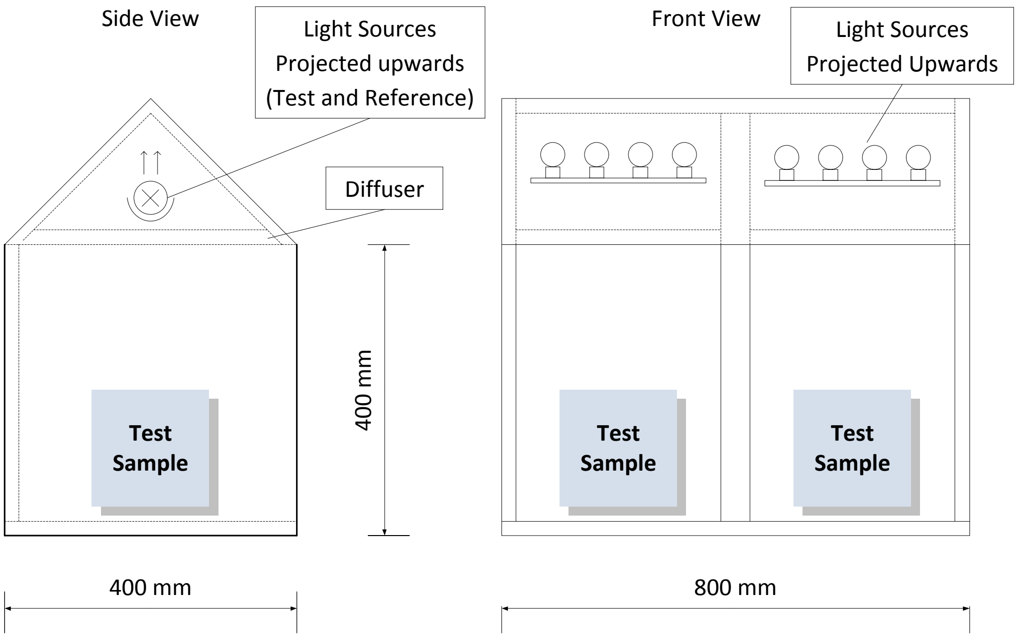

Figure 3.2 45° Slanted roof with upward projecting sources.

3.2.3 Test booth with sources behind a back screen

Figure 3.3 shows a slanted roof with light sources fitted behind a back screen and projecting upwards. This configuration is relatively uncomplicated and easy to manufacture. Light distribution may benefit from a diffuser.

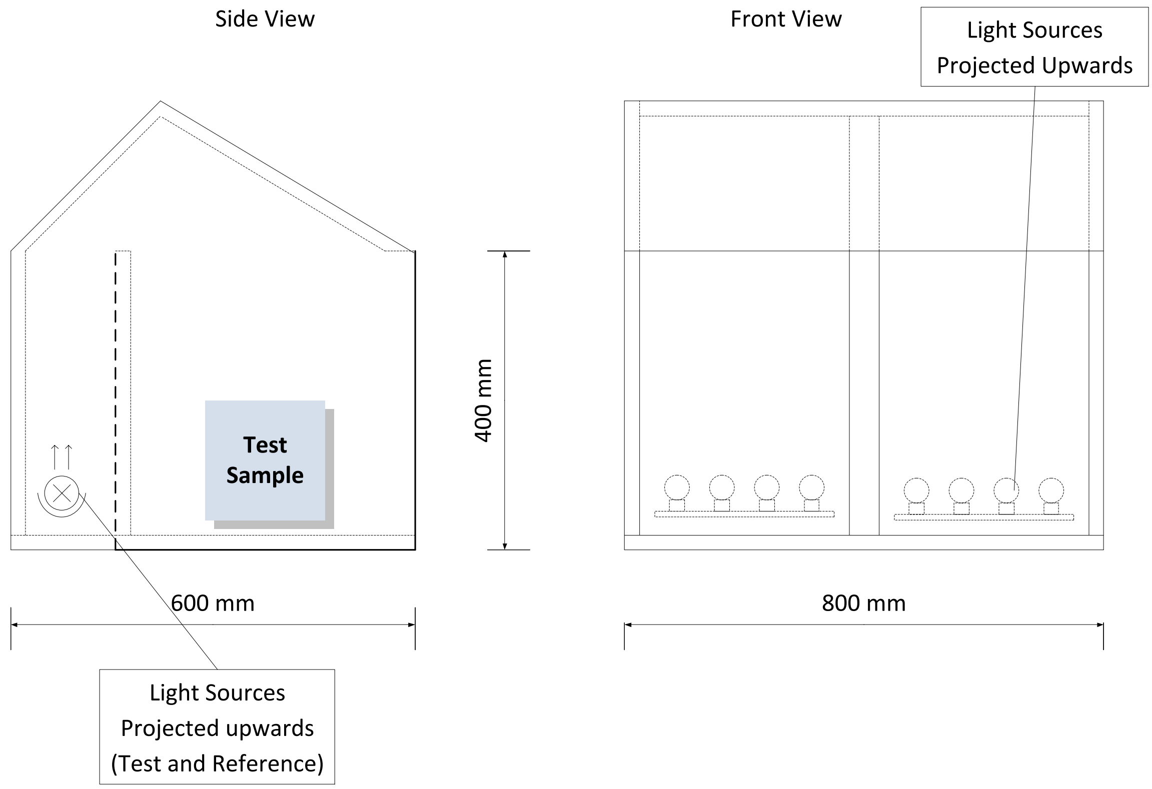

Figure 3.3 Slanted roof with upward projecting sources behind a back screen.

3.2.4 Test booth with sources behind back screen and adjustable iris

Figure 3.4 shows a slanted roof with light sources fitted behind a back screen and projecting upward. The light sources do not form an array as described in previous figures; rather a single source is fitted in a “pipe”. The pipe is then fitted with an adjustable iris. This means that illumination of both the reference and test source remains constant, as current through the sources is not altered. The mechanical iris is used to change light levels reaching the slanted dome and eventually the test sample. This layout is similar to the one designed and used by Fotios and Cheal (2007).

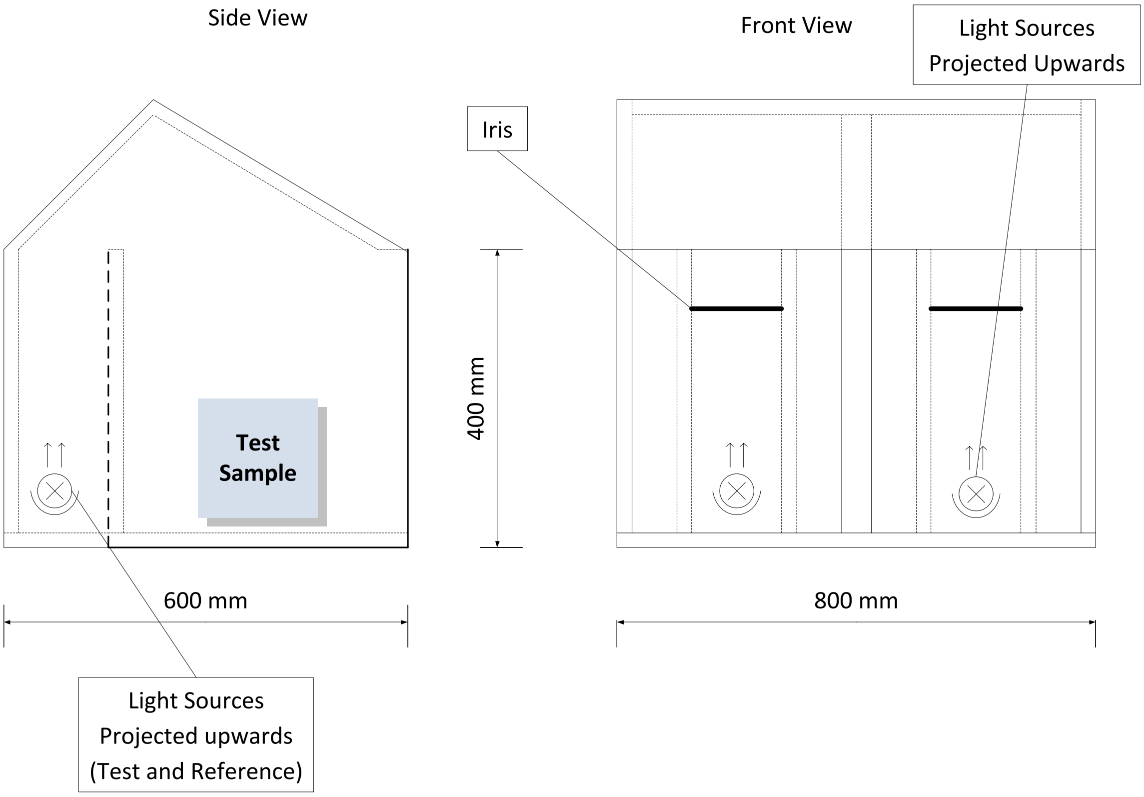

Figure 3.4 Slanted roof with back screen, upward projecting sources and adjustable iris.

3.2.5 Test booth with spherical dome and front illumination

Figure 3.5 presents a setup of a test booth where illumination is not vertically from the top but at an angle from the top and towards the test sample. In this setup, the sample is positioned vertically. This enables the evaluator to observe the sample directly from the front and the eye perceives the sample not to be at an angle relative to the body or, if at all, a very small angle. Construction of this setup is complicated, as manufacturing an even, smooth dome is vital. Light sources are mounted in clusters and face upward.

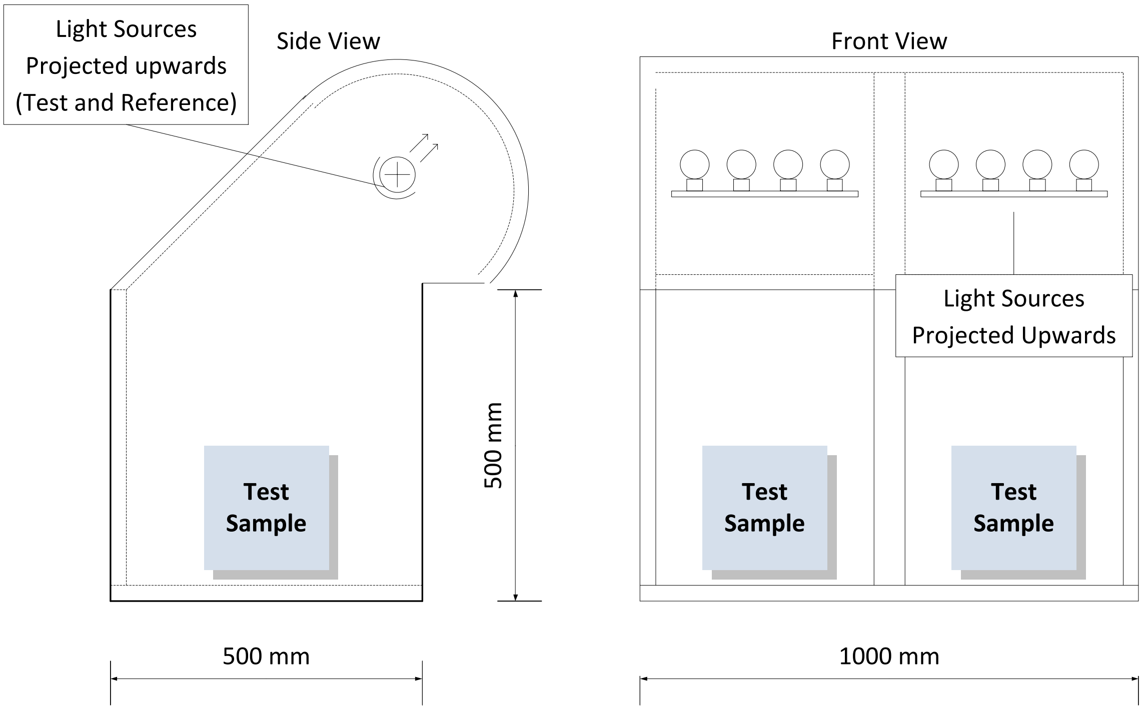

Figure 3.5 Spherical dome with front illumination.

3.2.6 Test booth with split scene setup

Figure 3.6 presents an impression of a setup where two test booths are used (top view). The spherical dome test booth with front illumination should be employed, as the test samples are mounted vertically. The one test booth houses the reference sample and the other houses the test sample. The split scene is used to ensure that both test and reference samples appear on the same eye line. The evaluator looks at the samples using a 45° rotating mirror and can alternate between reference and test view.

The split scene setup was designed and constructed. It thus consists of three booths. The two side booths can be positioned in a conventional layout so that existing colour perception test procedures can be duplicated. The booth with rotating mirror can be positioned in the centre to add a new and unique test procedure. Figure 3.7 presents the design of a side section test booth.

The side section test booth is similar to the design of the spherical dome test booth, as described in Figure 3.5. The light sources (test and reference) are both mounted so that

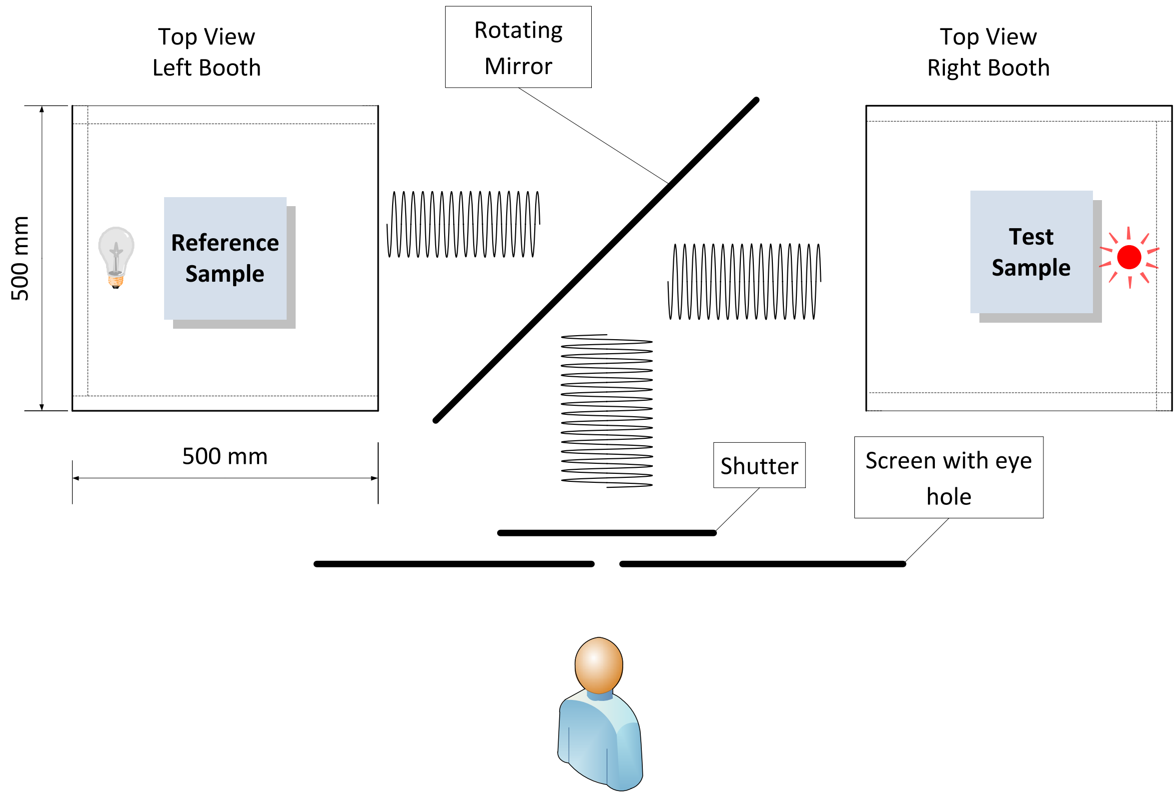

Figure 3.6 Test booth with split scene setup.

light is projected towards the dome. The dome produces diffuse illumination on the sample. Figure 3.8 presents a top view of the mirror rotating section of the split scene setup.

The completed product after construction is shown in Figure 3.9. This front view shows the rotating mirror section in the centre. The rotating mirror section houses the 45° rotating mirror, activated by a handle on the top. This section is flanked by the two conventional test booths with openings towards the mirror assembly. The eye piece can be seen in the front of the mirror unit.

The two conventional test booths are shown in Figure 3.10. In this position the two test booths can be used in the conventional manner as described and used by a number of researchers (Narendran 2002; Sandor 2006; Thompson 2007; Wei 2014).

The conventional test booths are equipped with domed roofs to ensure diffuse lighting.

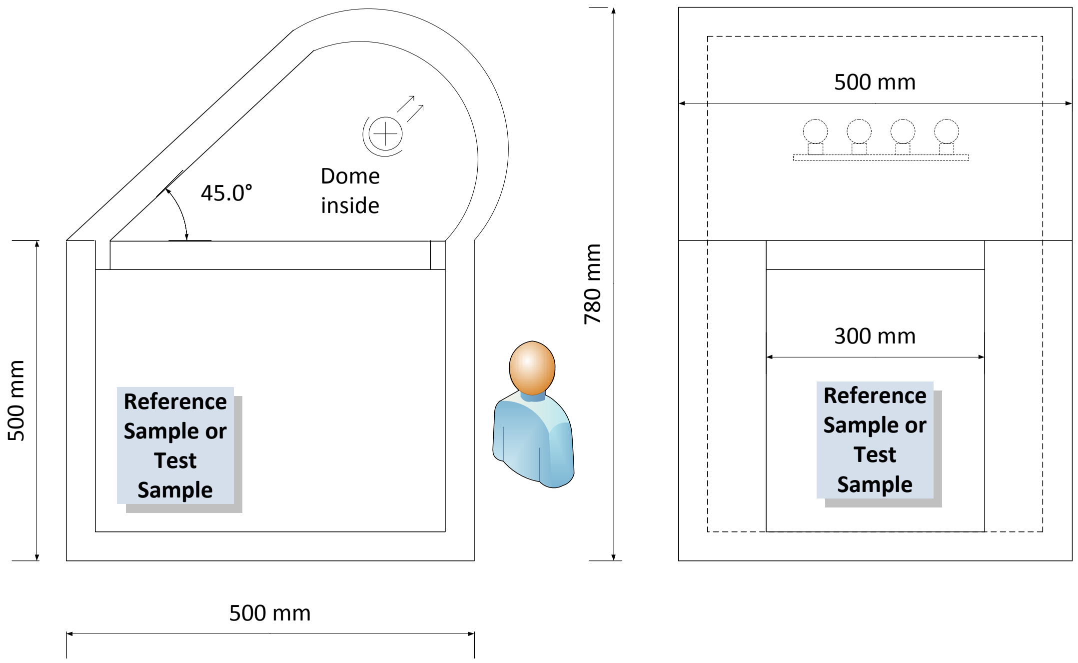

Figure 3.7 Side section booth of split scene setup.

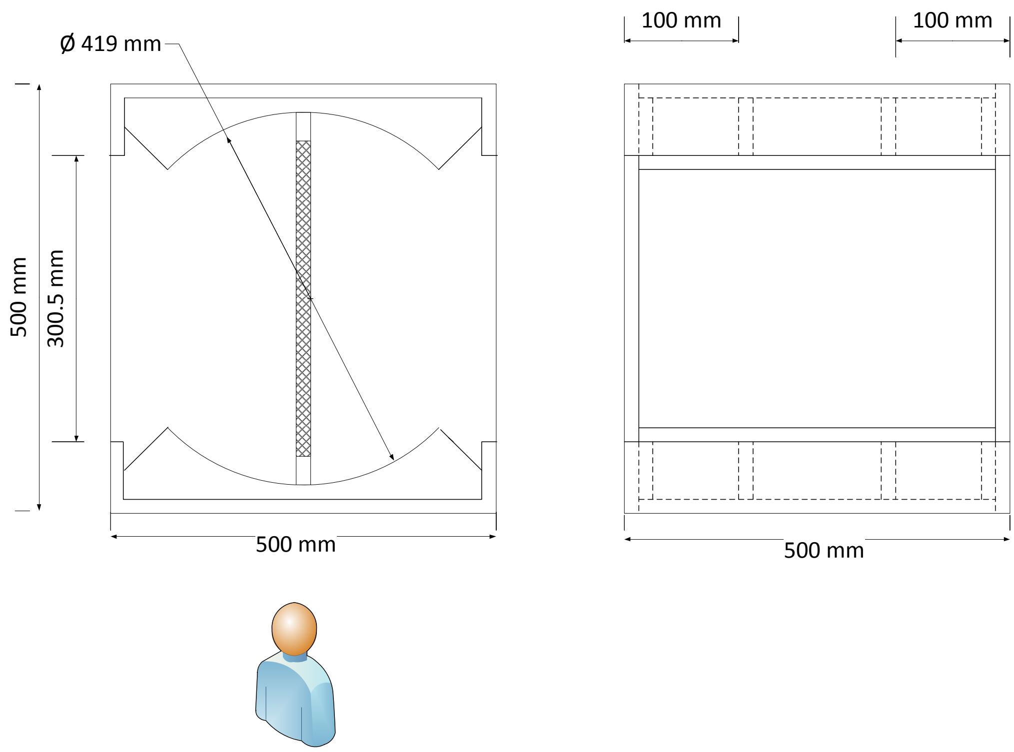

Figure 3.8 Top view of mirror rotating section.

Figure 3.9 Front view of assembled test setup. This shows the side booths on both sides of the rotating mirror section. The eye piece is in the centre of the mirror section and the rotating mirror lever can be seen on top.

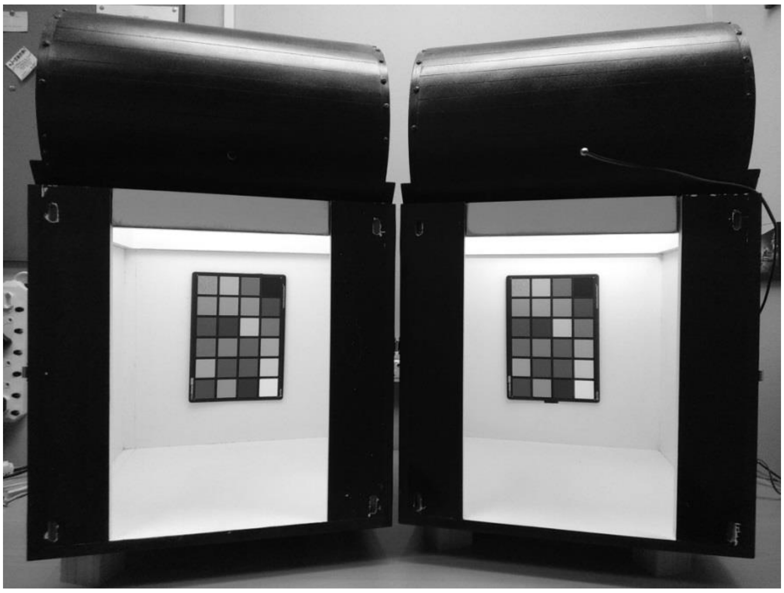

Figure 3.10 Front view of conventional test booths. The MCC's can be seen on the vertical walls of the booths. The top sections can be seen where sources are mounted.

The conventional test booths can also be used in a back-to-back configuration, as described by Spaulding *et al*. (2011). The back-to-back configuration is not shown.

Figure 3.11 presents a side-to-front view of the rotating mirror section only. Although a front-plated mirror would be the best design, a rear-plated mirror was used because of cost. It is not considered to present a major problem in this specific application. The spectral effect of the mirror added to the optical path is investigated in Section 4.6.

Figure 3.12 shows a top view of the mirror section flanked by the two conventional test booths. The domed roofs were removed for this photo.

Figure 3.11 Rotating mirror section. The rotating mirror can be seen on left and eye piece entrance is visible on the left.

3.3 LIGHT SOURCE CHARACTERISATION

This section describes the two methods that can be used for light source characterisation. The use of goniophotometers is common in most photonics laboratories. Vidal *et al*. (2011)

employed the goniomphotometricetric method to determine luminous flux for high-intensity white LED sources. The determined total luminous flux was corrected for spectral mismatch owing to a difference between the spectral responsivity of the photometric detector and the calculated V(λ) function.

This study did not use a goniophotometer but rather an integrating sphere setup. In order to measure various colour-related light source parameters, advanced laboratory measurement equipment is available. Such an instrument is the Konica Minolta CS-2000 spectroradiometer, which is used with custom software CS-S10w. For the purposes of this study, a test setup as shown in Figure 3.13 was used.

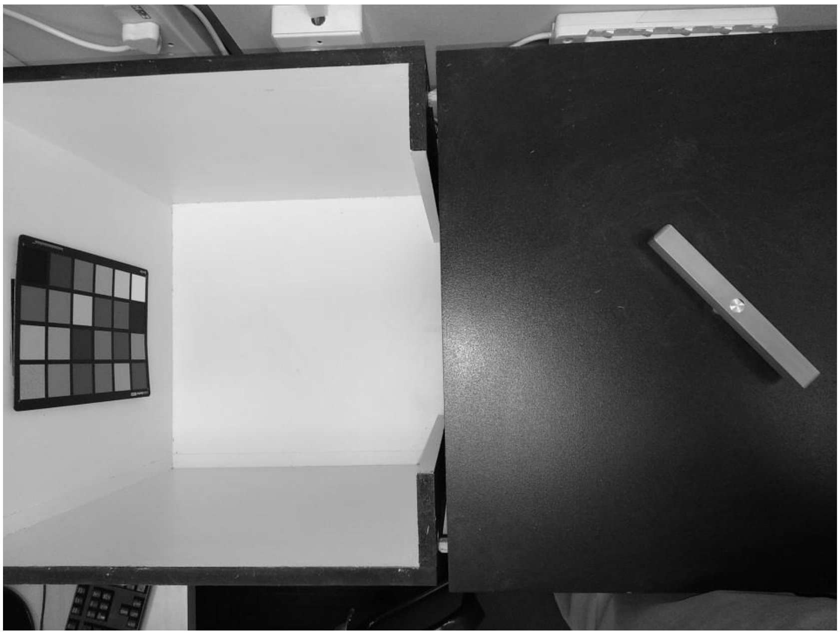

Figure 3.12 Top view of mirror section flanked by the left-side test booth. The test booth dome is removed and the MCC can be seen on the vertical wall of the booth. The rotating mirror handle can be seen on top of the mirror section.

The test or reference light source can be positioned in the primary integration sphere. Some of the integrated light is transferred to the secondary integration sphere. The Konica Minolta measurement apparatus is then focused on an aperture in the side of the secondary sphere and a measurement is taken.

Test methods used for the measurement of photometric as well as electrical characteristics is based on the "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products" by the Illuminating Engineering Society (IES) (Illuminating Engineering Society 2008). The IES method (section 9.1, page 4) prescribes the use of a single integrating sphere and an internal baffle is used to screen direct illumination from the entrance of the radiometer. The method used in this study uses a dual integrating sphere where the source is positioned inside the primary sphere and the entrance of the radiometer is aimed at the secondary sphere. The primary and secondary spheres are positioned as shown in Figure 3.13.

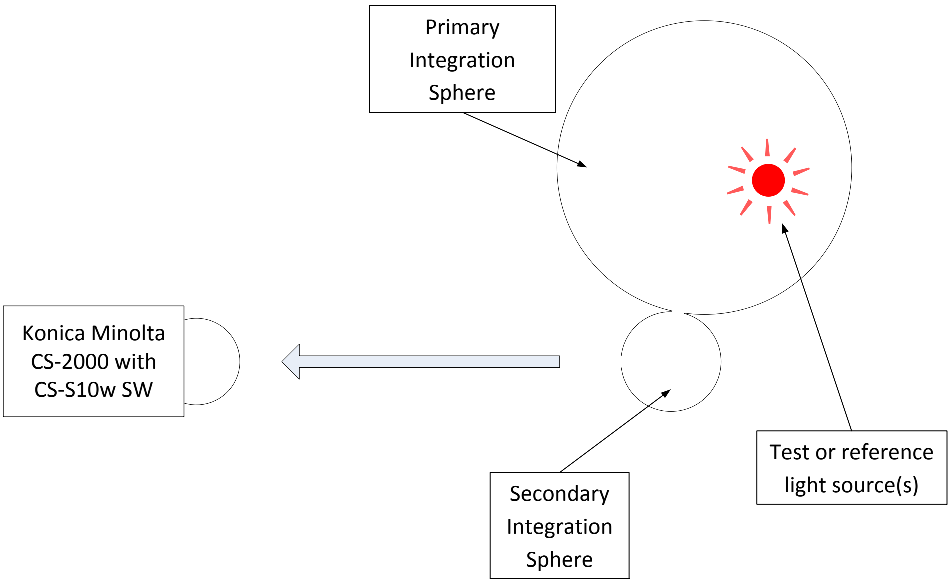

Figure 3.13 Colour characteristics measurement set-up.

3.4 LIGHT SOURCES

For the purpose of this study, two light sources were used. These are labelled a reference source and a test source. The purpose, characteristics and design of each source are described in this section.

3.4.1 Reference source

The reference source consists of a halogen lamp. The basic driving circuit is shown in Figure 3.14.

The reference source consists of a 50 W halogen lamp. The current through the source is not pulsed and can be adjusted.

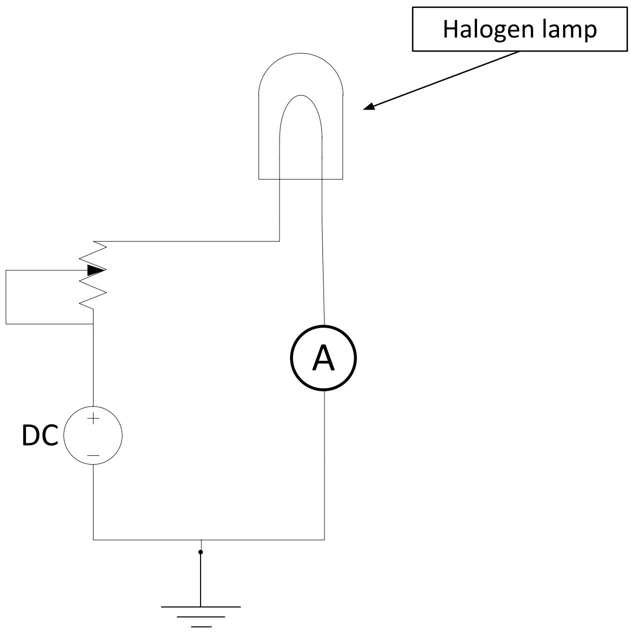

Figure 3.14 Reference source circuit showing a DC source, rheostat, ammeter and halogen lamp.

3.4.2 Test source

A tetrachromatic source was constructed and applied in a number of unique colour perception tests. The aim was to adjust SPDs to deliver a CCT of close to 4500 K as defined by ANSI standard C78.377 (Jackson 2011).

In order to achieve most of the visible spectrum, three LEDs (RGB) are needed. It was preferable to have more spectral control and another LED (amber) was therefore added. This ensured that not too many options were available for evaluators, which might complicate the test procedure. A recent study by Yao (2015) investigates the theoretical analysis of a source consisting of four coloured LEDs. A solution regarding specific LED wavelengths is not provided, but it is stated that a combination of wavelengths depends on the specific application, such as indoor, outdoor, road lighting and lighting properties required under mesopic and photopic conditions.

For this study, spectrum spread was selected to be evenly spaced throughout the visible spectrum as far as was practically possible.

The composite LED test source consists of components as listed in Table 3.1. The wavelength range is presented as supplied by the manufacturer.

Table 3.1 LED specifications.

Dominant Wavelength (nm)	Wavelength Range (nm)	Forward Voltage	Current Range (non-pulsed)	Transmission Angle	Part Number
455	449 - 461	3,2 V	100 mA - 1000 mA	120 °	OSRAM LDW5SM-4S4T-35
528	513 - 537	3.3 V	100 mA - 1000 mA	120 °	OSRAM LTW5SN-KYLY-25
590	583 - 595	2,6 V	100 mA - 1000 mA	120°	OSRAM LYW5SM-HZJZ-46
657	646 - 666	2,6 V	100 mA - 1000 mA	170°	OSRAM LHW5AM-1T3T-1

The LED composite source circuit layout is presented in Figure 3.15.

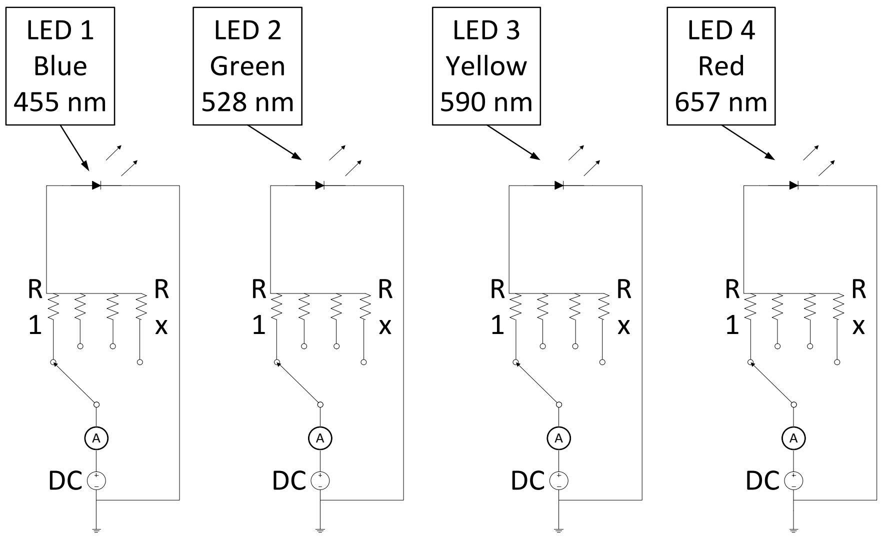

Figure 3.15 Test source circuit showing discreet current selector resistors, DC current sources, ammeters and LEDs.

To ensure the stability of light output, the LEDs were properly mounted on heat sinks as prescribed by the manufacturer (OSRAM 2013). The manufacturer also provided data on the stability of light output over time (OSRAM 2014). These data show that a change in LED light output can be expected after 20,000 hours of usage. LEDs used in this evaluation were not switched on for longer than 20 to 30 minutes a time (for each psychophysical evaluation, which includes a stabilisation time of 10 minutes.) The total on-time (all psychophysical evaluations included) was calculated to be 90 to 120 hours. The manufacturers' data sheet does not include data on light and/or wavelength change at 120 hours of usage. It is thus not expected that light output/wavelength shift will make a significant contribution within the period of evaluation. LED light output stability also depends on the current used relative to the maximum current specified for the LED. Continuous high currents affect the time that a LED can deliver stable light output negatively. During this study, peak currents never exceeded 50% of the specified maximum current. Because observer groups are tested concurrently, any possible degradation in LED performance will affect both groups in the same way and no group will thus be at an advantage/disadvantage.

3.5 PROCEDURE

The test procedure is described in this section. Two groups of evaluators are used. One group consists of people younger than 40 years of age (and older than 18 years of age). This group is representative of evaluators used by previous study groups (as described in Table 2.2. Another group consists of people older than 50 years of age and preferably not older than 70 years of age. The reason for this is to investigate the effect of age on colour perception, as described in Section 2.4.3.

The test procedures as described in Sections 3.5.2 and 3.5.3 should be completed using the same evaluators but on different days in an effort to reduce the effect of “colour perception memory”.

3.5.1 Observer sample size

Observers suitable for a psychophysical evaluation should be defined in order to calculate the minimum sample size valid for statistical analysis. For this study, it was decided to exclude the following people:

- People with significant visual impairment (not low vision, which is acceptable),
- People with colour vision impairment (as established by the Ishihara screening test), and
- People younger than 16 years of age. (This group was excluded in the first test but a future study is planned that will include this group. Children are rarely included in comparable studies, probably because of complicated legal authorisation procedures.)

The population size is thus the above-mentioned groups subtracted from the world population. The United Nations estimates that the world population reached seven billion people in October 2011 (7×10^9). It is estimated that there are 40 million people who are blind or significantly visually impaired (Chader 2013). The number of children younger than 15 years of age is generally thought to constitute about 30% of the population. Indeed, UNICEF estimates the number of children to be between 1.9 and 2.2 billion. The established figure for male colour deficiency is 8% of the population and that for females 0.5%, which has remained fairly constant since originally researched by Dalton (Dalton 1798). (This may actually differ between races and nations, but should be close enough for this study.) If one assumes a 50% male and 50% female world population division, the population not included in the previously mentioned groups is calculated to be 4 billion people (4×10^9).

With the population size determined, the margin of error, confidence level and standard deviation can be selected to calculate the minimum sample size (Israel 2013). For this study the population size can be regarded as very large (more than 10 000). This is to be expected when human characteristics are studied. It is normal practice to start calculations using a confidence level of 95% and a margin of error of ±5%. Using these input values, the sample size required is calculated to be 384.

Israel (2013) states that the sample sizes of similar studies should also be considered to provide guidance. Sample sizes used in comparable studies are presented in Table 3.2. Table 3.2 lists some of the same studies as those presented in Table 2.2. The largest sample size listed is 48. Table 3.2 also lists the level of confidence achieved for different sample numbers, assuming a population size of 10 000 and a margin of error of ±10%. It is important to note that the boundary conditions of the listed studies are not known. This may be different from the conditions of this study, which may drastically reduce the population size and thus increase the level of confidence and narrow the margin of error.

Table 3.2 Sample sizes from similar studies.

Item	**Experiment designation** *(Note 1)*	**Number of observers**	**Level of confidence (%)** *(Note 2)*	**Reference**
1	Experiment 1	20	63	(Narendran 2002)
	Experiment 2	10	47	
2	2700 K CCT – 6500 K CCT	10	47	(Sandor 2006)
3	Section 4.1	25	68	(Spaulding 2011)
4	Section 3 Phase 1	10	47	(Thompson 2007)
5	Section 3.3.2	24	67	(Wei 2014)
	Section 3.3.3	48	84	
6	Section 2	21	64	(Fotios 2007)
7	Section 2.1	40	80	(Houser 2014)

Note 1: A research article may describe more than one test procedure. This column labels a specific procedure as it is labelled in the article.

Note 2: The level of confidence was reverse-calculated using a population of 10 000 and a margin of error of ±10%. (The boundary conditions of similar studies are not known and this may influence sample size and level of confidence.)

The number of observers who participated in the study described in this document is 36, which translates to a confidence level of 77% and a margin of error of ±10% when using a large population. In view of comparable studies, the sample size of 36 is thus regarded as acceptable. (The number of observers that took part in some of the tests was actually 44, as described in Section 4.3.1.)

3.5.2 Split test booth test procedure

The test booth with split scene setup is used, as described in Section 3.2.6. and Figure 3.6.

The test procedure is as follows:

(a) The evaluator is subjected to an Ishihara colour-blindness screening test. This is completed interactively on a tablet PC.

(b) The reference source is adjusted to a level of 150 lux, as measured at the MCC. (Figure 3.14)

(c) The evaluator looks through the eyepiece (Figure 3.11) at the MCC in the LED test booth or halogen reference booth by rotating the mirror.

(d) The mirror is rotated to enable the observer to evaluate the MCC of the test and reference chamber.

(e) The observer may toggle the mirror as many times as required.

(f) The evaluator adjusts the four coloured LED sources inside the test chamber until the colours of the 24 blocks on the MCCs in both test chambers are perceived to be matched.

(g) The facilitator notes the test source inputs and measures the following:

   a. Light level (lux),
   b. Forward current,

(h) The facilitator duplicates the source, using selected currents, and measure the following parameters using the test procedure described in Section 3.3.

   a. CCT,
   b. General CRI value (R_a),
   c. CRI values (R_1 to R_{15}),
   d. Values of x and y,
   e. SPD, and
   f. Duv values.

3.5.3 Side-by-side test booth procedure

The test booth with side-by-side setup is used, as described in Section 3.2.5. and Figure 3.10. The test booth containing the test source is positioned on the right-hand side of the observer’s view, while the test booth containing the reference source is positioned on the left-hand side of the observer’s view.

The test procedure is as follows:

(a) The evaluator is subjected to an Ishihara colour-blindness screening test. This is completed interactively, using a tablet.

(b) The evaluator looks at the LED test booth.

(c) The evaluator adjusts the four coloured LED sources inside the test chamber until colour is perceived to be “white” by considering only the white block on the MCC. (The reference source is not used for this test and only one test booth is thus used.)

(d) The facilitator notes the test source inputs and measures the following:

a. Light level (lux),
b. Forward current,

(e) The facilitator duplicates the source, using selected currents, and measure the following parameters using the test procedure described in Section 3.3.

a. CCT,
b. General CRI value (R_a),
c. CRI values (R_1 to R_{15}),
d. Values of x and y,
e. SPD, and
f. Duv values.

(f) The reference source is adjusted to a level of 150 lux (Figure 3.14). The reference source illuminates an MCC inside the reference test chamber.

(g) The evaluator looks into the chamber with the reference source, at the MCC.

(h) The evaluator looks into the chamber with the test source, at the MCC.

(i) The evaluator adjusts the four coloured LED sources inside the test chamber until the colour corresponds with that in the reference test chamber.

(j) The evaluator may alternate between chambers as many times as required.

(k) The facilitator notes the test source inputs and measures the following:

a. Light level (lux),
b. Forward current,

(l) The facilitator duplicates the source, using selected currents, and measure the following parameters using the test procedure described in Section 3.3.

a. CCT,
b. General CRI value (R_a),
c. CRI values (R_1 to R_{15}),
d. Values x and y,

e. SPD, and
f. Duv values.

3.5.4 Side-by-side test booth procedure with time lapse

The test booth with side-by-side setup is used, as described in Section 3.5.3 and Figure 3.10. The test booth containing the test source is positioned on the left-hand side of the observer's view while the test booth containing the reference source is positioned on the right-hand side of the observer's view. The remainder of the procedure is as described in Section 3.5.3. This procedure was repeated (using the same observers) one year after the procedure described in Section 3.5.3 to evaluate observer colour perception repeatability.

3.6 CHAPTER SUMMARY

In this chapter, existing test setups were discussed and alternative designs were proposed. The test methodology was specified.

- Sections 3.2.1 to 3.2.4 discuss the practical layout of existing designs, which are used by various researchers for comparative studies investigating light and colour characteristics.
- Sections 3.2.5 and 3.2.6 present alternative improved designs. Section 3.2.5 presents a test booth design with improved test object illumination. This configuration can be used in single and double booth layouts. Section 3.2.6 presents a double booth design with a central rotating mirror to ensure that the observer has a central optical path for comparative studies.
- Section 3.4 discusses light sources. The reference source used is a 12 V halogen lamp. A tetrachromatic source was designed to be used as test and reference source. The source consists of four LEDs with wavelengths at 455 nm, 528 nm, 590 nm and 657 nm, of which the intensities are adjustable.
- Section 3.5.2 calculates the acceptable observer sample size and compares it with sample sizes of similar studies. The number of observers used varied from 36 to 44, depending on the test. Observer numbers of similar studies vary from 10 to 40.

- Sections 3.5.2 to 3.5.4 lays out test procedures. Observers are required to follow the step-by-step procedure.

CHAPTER 4 RESULTS

4.1 CHAPTER OBJECTIVES

The purpose of this chapter is to provide results of measurements.

- Section 4.2.1 provides results achieved when measuring the sun, regarded as the ultimate light source. The photometric spectrum of the sun is compared with calculated blackbody radiation curves.
- Section 4.3.2 presents results of the Ishihara colour screening test for observers.
- Section 4.3.3 presents results achieved when two observer age groups were subjected to a white perception test.
- Sections 4.3.4, 4.3.5 and 4.3.6 present results achieved when two observer age groups were subjected to colour matching tests, using two different test methods.
- Section 4.3.7 presents colour matching results achieved with two different age groups and measured one year apart to evaluate repeatability of colour matching tests.
- Section 4.5 presents a summary of losses measured at tetrachromatic wavelengths.
- Section 4.6 shows the results of SPD curves multiplied by the photopic luminosity curve.
- In Section 4.7, wavelength shift when using a mirror in the optical path is investigated.

4.2 LIGHT SOURCE CHARACTERISTICS

Results regarding light sources are presented in this section.

4.2.1 The ultimate source

The ultimate light source is assumed to be the sun. It is thus logical that the characteristics of the sun should be measured, as any design of a man-made source should strive to mimic that of the sun. Characteristics of the sun, as measured on earth, depend on the time of day, the time of the year, earth coordinates where they are measured and also weather/atmospheric conditions. Compiling a complete set of the sun's characteristics would thus entail a comprehensive study and is not included in this report.

In an effort to generate a set of specifications for the perfect source, it was decided to measure the visible spectrum of the sun. A Konica Minolta spectroradiometer was fitted with a wide angle diffuser lens. A test was completed on 6 September 2016 at the University of Pretoria. The spectrometer was first directed to measure the sky without the sun included in the FOV and secondly to measure the sky with the sun included in the FOV.

The results are presented in Table 4.1 and Table 4.2.

Table 4.1 Basic parameters for sky and sky/sun as illumination sources.

Parameter	**Sky**	**Sky and sun**
R_a	99	99
CCT	7 998 K	5 337 K
Dominant λ	483 nm	562 nm
Peak λ	451 nm	481 nm
x	0.2939	0.3364
y	0.3096	0.3477
Duv	0.0033	0.0017

Table 4.2 Sun results with CRI measured against approximate Munsell colour samples.

CRI values	Appearance under daylight (Chroma-Q Product Support 1997-2016)	Sun
R_1	Light greyish red	100
R_2	Dark greyish yellow	99
R_3	Strong yellow green	99
R_4	Moderate yellowish green	100
R_5	Light bluish green	99
R_6	Light blue	99
R_7	Light violet	99
R_8	Light reddish purple	99
R_9	Strong red	99
R_{10}	Strong yellow	99
R_{11}	Strong green	99
R_{12}	Strong blue	99
R_{13}	Light yellowish pink (skin)	99
R_{14}	Moderate olive green (leaf)	99
R_{15}	Asian skin	100

Results of the sun/sky and sky characteristics measurement are presented in Figure 4.1. This measurement only covers the photometric spectrum (380 nm – 780 nm), as it is in this region where light sources for photometric illumination are specified.

In order to isolate the contribution of the sun, the “sky” is subtracted from the “sun/sky”. This result is presented in Figure 4.2.

The CCTs of the sun/sky, sky and calculated environments can be used to represent a light source with corresponding CCT and these results are presented in Table 4.3.

The CCT figures can thus be used as part of a specification to describe a similar light source than that of the sky/sun. Sky and sun measurements can also be used to calculate blackbody radiation for specific temperatures.

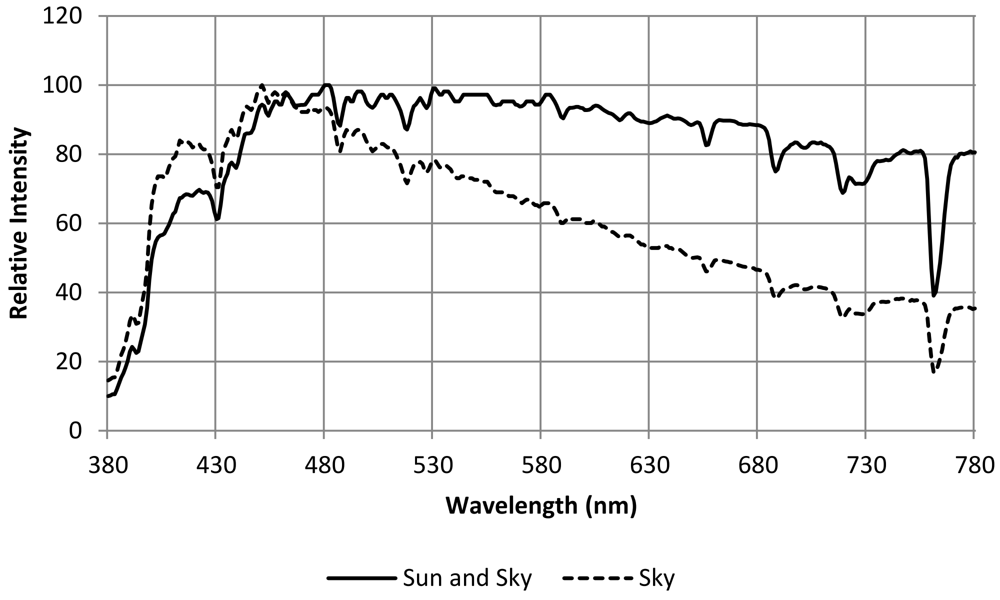

Figure 4.1 SPD of sun/sky and sky in visible region.

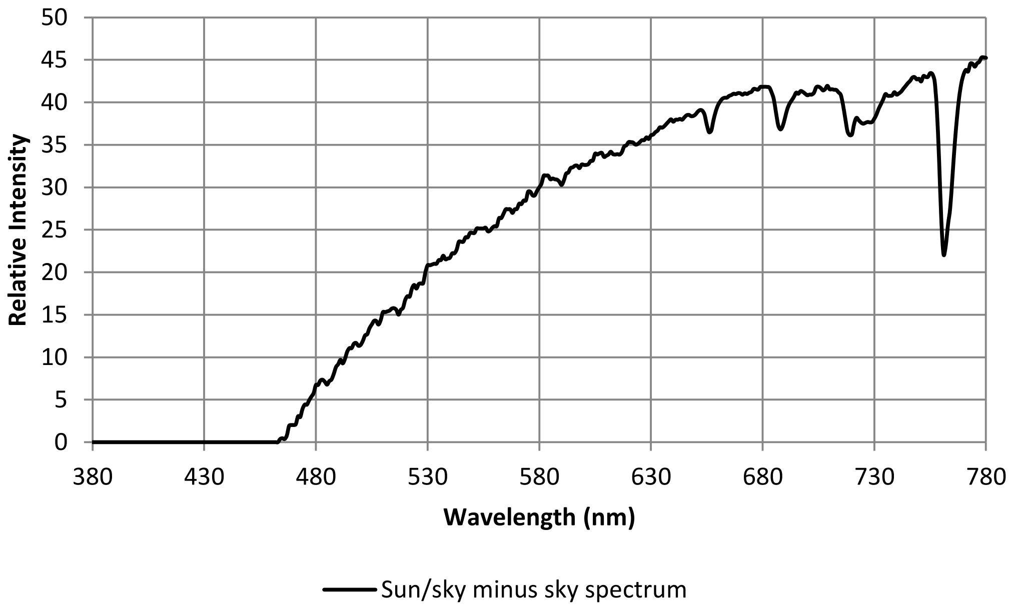

Figure 4.2 Calculated sun spectrum (sun/sky minus sky)

Table 4.3 CCTs of measurement areas.

Area of interest	CCT
Sky/sun	7 998 K (Measured)
Sky	5 337 K (Measured)
Sun	2 661 K (Calculated)

The sun can be described as a blackbody radiation source. Blackbody radiation can be calculated in the spectral range from 380 nm to 780 nm. Blackbody radiation is calculated using Planck's radiation law, Wien displacements law and Stefan-Boltzman's law (Finger Lakes Institute 2016) (minerva.union.edu 2016).

Planck's radiation law applies wavelength and temperature to calculate the intensity of radiation per unit surface area that is emitted by a blackbody.

$$E(\lambda T) = \frac{2hc^2}{\lambda^5} \times \frac{1}{e^{\frac{hc}{kT}} - 1} \tag{4.1}$$

where *h* is Planck's constant, *k* is Boltzmann's constant, *c* is the speed of light, λ is the wavelength (in cm), *T* is the temperature (in Kelvin) and $E(\lambda T)$ is the Energy Intensity.

The Stefan-Boltzman Law is presented as:

$$E = \sigma T^4 \tag{4.2}$$

where σ is the Stefan-Boltzman constant and *E* is the total energy emitted from a blackbody at all wavelengths.

The Wien Displacement Law is given as:

$$\lambda_{max} = \frac{2\,897\ \mu m\ °K}{T} \tag{4.3}$$

where λ_{max} is the Blackbody peak radiation at μm and *T*.

Figure 4.3 shows the blackbody radiation curves calculated at the three source temperatures.

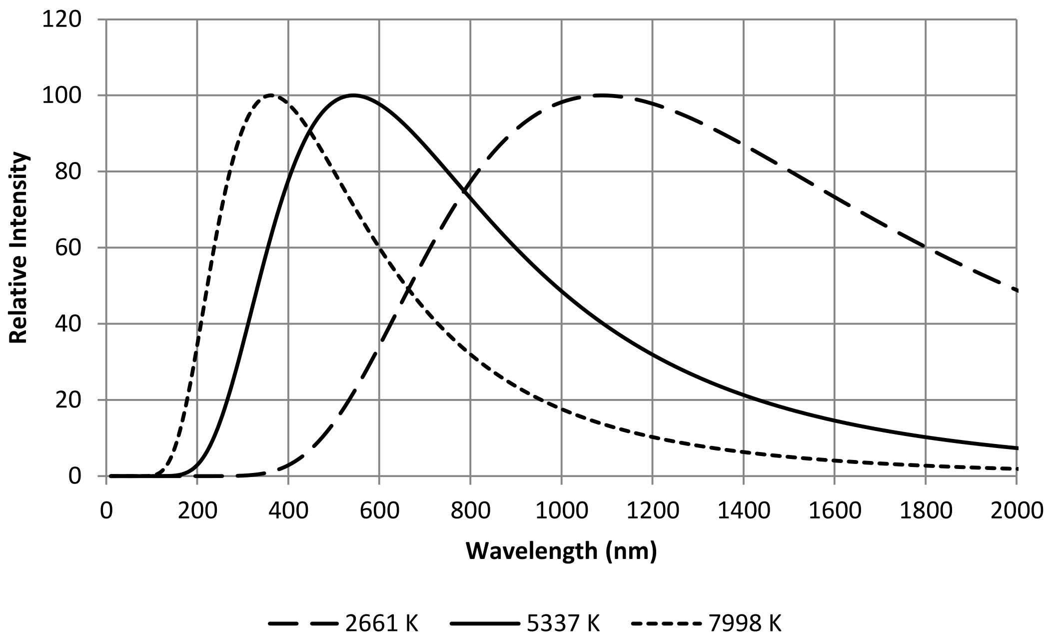

Figure 4.3 Blackbody radiation curves for the three different temperatures.

For illustrative purposes, the blackbody radiation curves in Figure 4.3 cover the spectral region from 0 to 2 000 nm. The visible spectrum only covers the region from 380 nm to 780 nm. The calculated blackbody radiation curves are now compared with the measured spectral curves.

Figure 4.4 shows the blackbody radiation curve at 7 998 K when superimposed on the curve as measured for "sky" radiation.

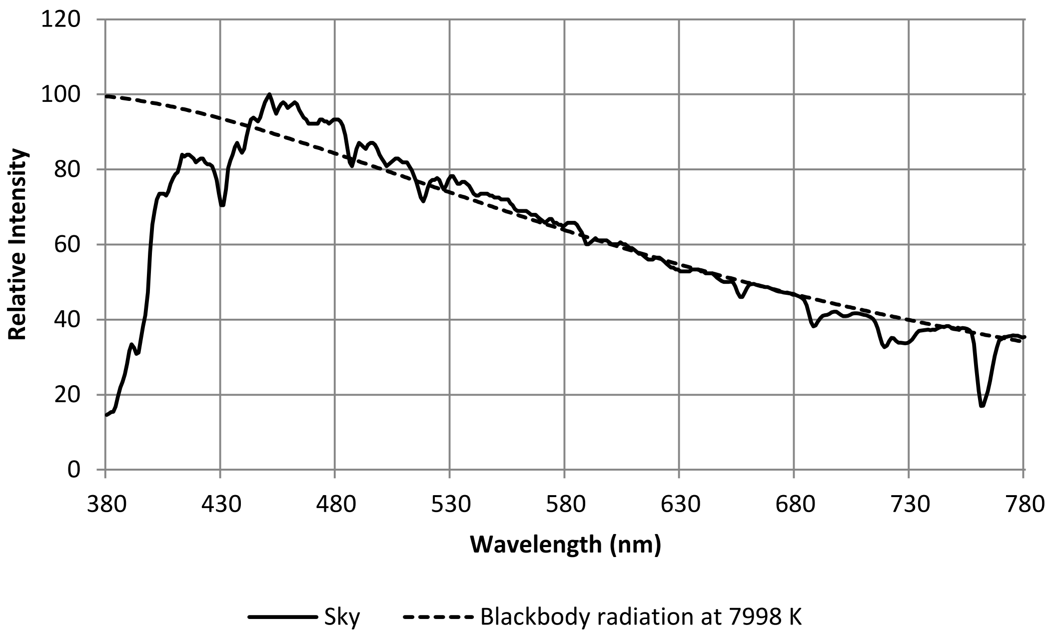

Figure 4.4 Calculated blackbody radiation at 7998 K superimposed on measured "sky" radiation.

Figure 4.5 shows the blackbody radiation curve at 5 337 K when superimposed on the curve as measured for "sun/sky" radiation. Figure 4.6 shows the blackbody radiation curve at 2 661 K when superimposed on the curve as calculated for "sun" radiation.

Although measured at substantially different locations on earth, results presented in Figure 4.5 are very similar to those published by Kerlin *et al*. (2016).

4.2.2 Reference source

The SPD of the halogen source is presented in Figure 4.7.

A voltage of 12.5 V was applied to the halogen lamp. The current through the lamp was adjusted with intervals of 200 mA from 2.4 A to 3.4 A. Parameters were measured at each set point and these are presented in Table 4.4. CIE (1931) chromaticity coordinates as measured for the halogen lamp is x = 0.4832 and y = 0.4144 with Duv = 0.0016. Coordinates as measured for the sun is x = 0.4631 and y = 0.4113 with Duv = 0.0020.

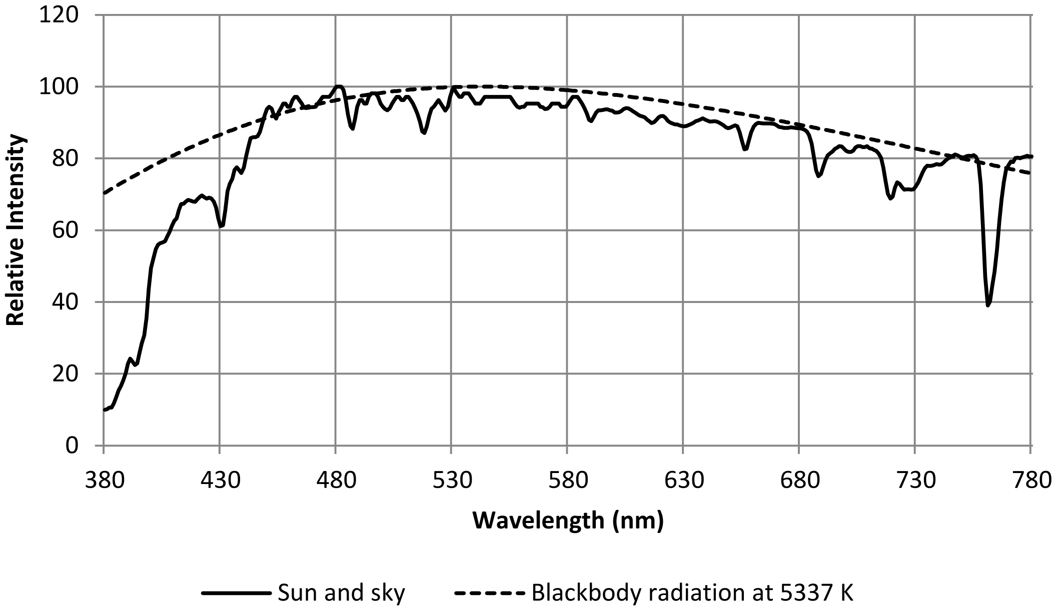

Figure 4.5 Calculated blackbody radiation at 5 337 K superimposed on measured “sun/sky” radiation.

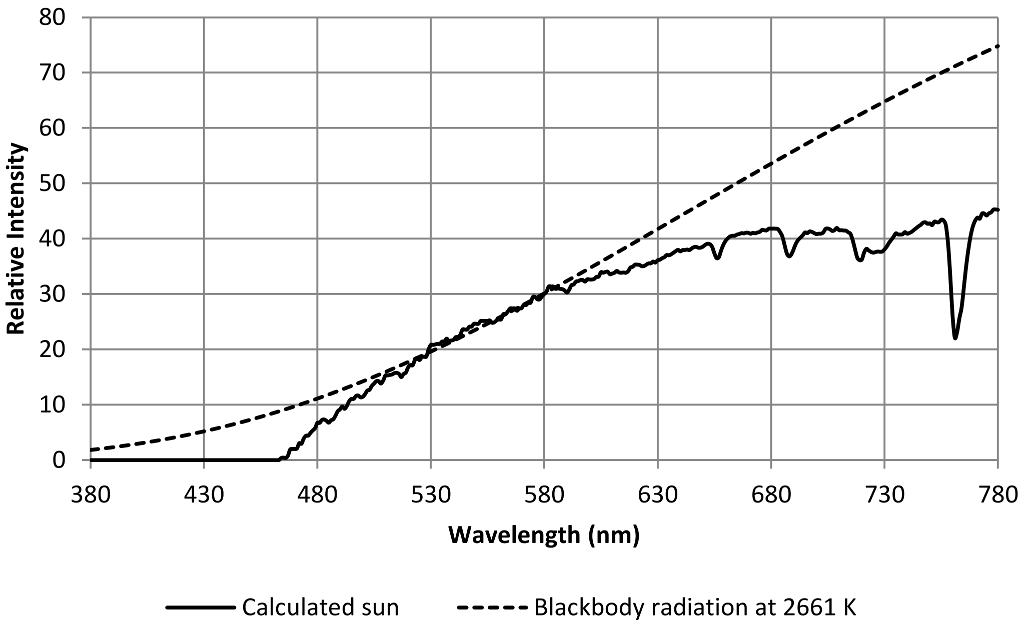

Figure 4.6 Calculated blackbody radiation at 2 661 K superimposed on calculated “sun” radiation.

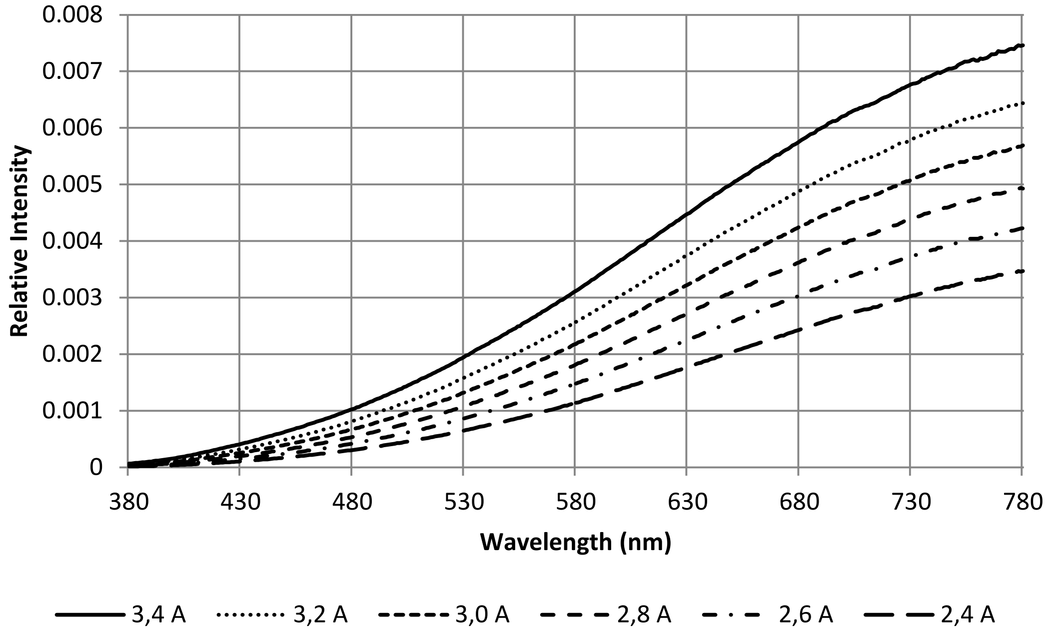

Figure 4.7 Reference source SPD for different lamp currents (halogen lamp).

Table 4.4 Reference source parameters with changing current. Both the average colour-rendering value R_a and the specific colour sample value R_9 remain at 99. These values are thus not influenced by a change in driving current.

Current	R_a	R_9	CCT	Peak Wavelength
3,4 A	99	99	2541 K	780 nm
3,2 A	99	99	2494 K	779 nm
3,0 A	99	99	2455 K	780 nm
2,8 A	99	99	2413 K	779 nm
2,6 A	99	99	2370 K	780 nm
2,4 A	99	99	2319 K	778 nm

For practical application of the test, it is necessary to adjust the reference source light levels. Light levels can be electronically adjusted by altering the supply current or they can be mechanically adjusted by using an iris or similar light-limiting device (as used by Fotios and Cheal (2007)). Implementing the mechanical method introduces restrictions on placement of the reference source. Using a mechanical device such as an iris limits the field of transmission of the source. (For improved light distribution, a source with a wide field of transmission is required.)

Adjusting the current is therefore a viable option to adjust lighting levels. The question is whether other source characteristics also change with intensity. For the purpose of this evaluation, average colour rendering (R_a) is a very important parameter. Current was adjusted through the source with R_a and peak being influenced. The results are shown in Figure 4.7 and Table 4.4. It can be seen that all of these parameters remain fairly stable from 2.4 A to 3.4 A.

4.2.3 Test source

The SPD of the composite LED source is presented in Figure 4.8. Figure 4.8 shows a typical SPD of the test source consisting of four LEDs. The SPD as adjusted by observers may be different.

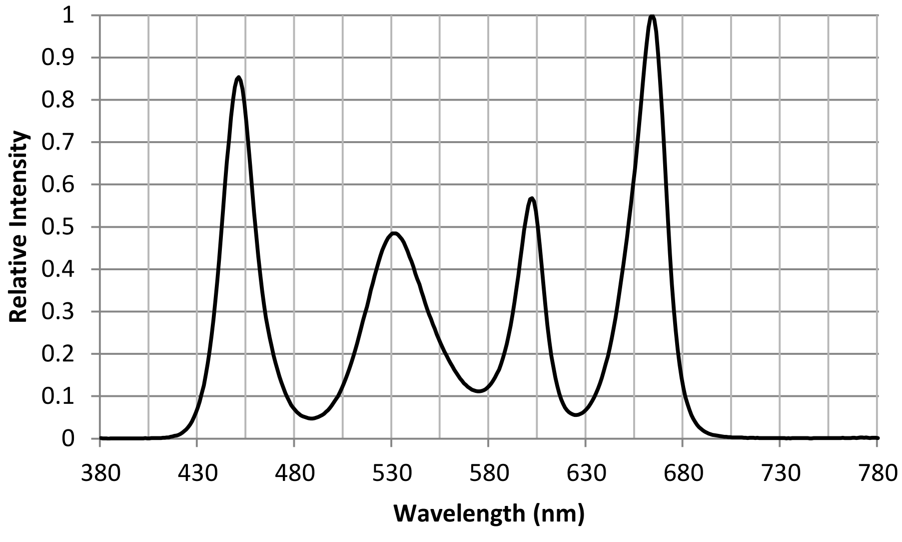

Figure 4.8 Test source SPD. (Composite tetrachromatic LED consisting of 455 nm, 528 nm, 590 nm and 657 nm)

4.3 CONCEPT EVALUATION

The results of practical evaluations are presented in this section. Results are graphically presented in the form of SPD graphs and sectional CIE chromaticity diagrams.

Tabulated results presented include CCT, R_a values, R_i values, x and y values and Duv values. The CIE (Method of Measuring and Specifying Colour Rendering Properties of Light Sources 1995) specified test colour samples, which were Munsell colour samples. These values are the approximate Munsell values for calculating the CRI values. The R_i values are the CRI values, which consist of values R_i ranging from R_1 to R_{15}. The spectrophotometer is capable of measuring the R_i values. The values may range from 0 to 100 although negative values are possible. The first eight R_i values are used for calculating the general CRI value R_a. Duv values are listed, as these are important to consider regarding light source quality (Ohno 2011).

4.3.1 Test groups

Four groups of evaluators were used. The first group consisted of people of 40 years old and younger (17 people, mean age 28.8, standard deviation 6.8). The second group consisted of people of 50 years and older (19 people, mean age 57.6, standard deviation 4.8). The first two groups were used in the white perception test as well as in the reference source matching test using the split booth test procedure.

The third group consisted of people of 40 years old and older, but was larger than the first group (22 people, mean age 30.3, standard deviation 5). The fourth group consisted of people of 50 years old and older and included more observers than the second group (20 people, mean age 57.2, standard deviation 4.6).

4.3.2 Ishihara colour screening

Although not specifically gathering information about colour blindness, it is interesting to note that 14.3% of males in the group younger than 40 failed the colour screening procedure, whereas 17.6% of males older than 50 failed the colour screening procedure. The established figure for male colour deficiency is 8% (Dalton 1798). The reason why the older group presented with higher colour deficiency is not known and should perhaps be investigated using a larger sample, although the difference is not significant.

4.3.3 White perception test

The results of the white perception test are presented in Table 4.5 and Table 4.6.

The result of the white perception test is graphically summarised in the SPD graph in Figure 4.9 and the sectional CIE 1931 chromaticity diagram in Figure 4.10.

Table 4.5 Source specification as measured for white perception for two age groups.

Parameter	Under 40	Over 50
R_a	74	89
CCT	6 592 K	5 150 K
x	0.3170	0.3393
y	0.2822	0.3258
duv	-0.0255	-0.0112
Dominant λ	565 nm	509 nm
Peak λ	658 nm	658 nm

4.3.3.1 Relative source intensity

The two age groups were tasked to select a light source that produces the "best white perceived light" when a standard MCC colour checker white patch was used for light reflection. It seems that the two age groups differed substantially in the design of a light source to produce "white perceived reflection".

As discussed in Section 2.4.3, transmission through the crystalline lens of the human eye decreases spectrally with age. The lens becomes more yellow, which means that transmission of shorter wavelengths (blue) is decreased.

Table 4.6 White perception results with CRI measured against approximate Munsell colour samples. A difference of more than 5 is considered significant (Houser 2015)

CRI values	**Appearance under daylight** (Chroma-Q Product Support 1997-2016)	**Under 40**	**Over 50**	**Difference**
R_1	Light greyish red	70	94	24
R_2	Dark greyish yellow	88	93	5
R_3	Strong yellow green	70	87	17
R_4	Moderate yellowish green	60	83	23
R_5	Light bluish green	75	98	23
R_6	Light blue	89	91	2
R_7	Light violet	83	86	3
R_8	Light reddish purple	58	78	20
Average		**74**	**89**	**15**
$\mathbf{R_a}$		**74**	**89**	**15**
Strong colours				
R_9	Strong red	-7	39	46
R_{10}	Strong yellow	85	86	1
R_{11}	Strong green	44	68	24
R_{12}	Strong blue	72	70	2
Additional colours				
R_{13}	Light yellowish pink (skin)	70	92	22
R_{14}	Moderate olive green (leaf)	80	92	12
R_{15}	Asian skin	66	85	21

It is thus to be expected that the older group of observers will select a higher component of blue to compensate for lens transmission loss in the blue region. This physiological measurement is not reflected in the evaluation of “white perception” of the two age groups. It is thus possible that older observers are able to compensate for lens transmission loss when evaluating colours and the loss of blue through the lens is therefore not really a problem.

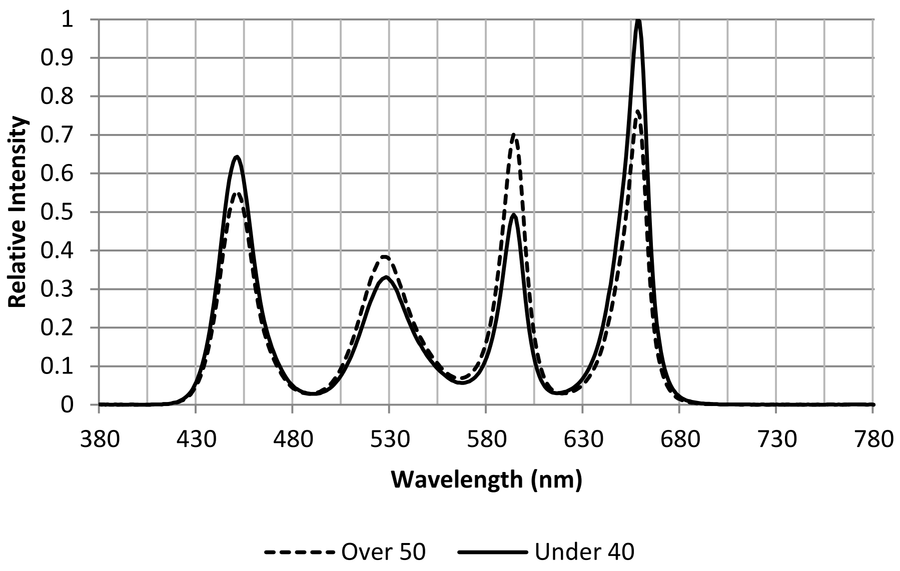

Figure 4.9 SPD graph for sources as selected by two age groups to achieve "white perception". Differences at tetra-chromatic wavelengths are 13.2% at 455 nm, 13.6% at 528 nm, 27.6% at 590 nm and 23.5% at 657 nm.

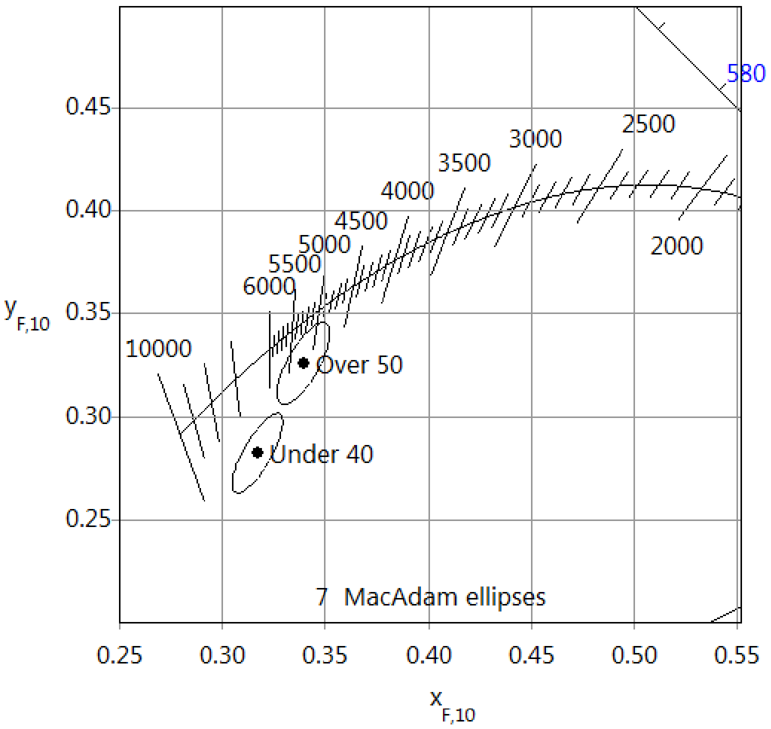

Figure 4.10 A sectional part of the CIE 1931 chromaticity diagram showing x and y coordinates of sources as selected by two age groups to achieve "white perception". Seven-step MacAdam ellipses are drawn around the x-y points.

Moving through the spectrum, the older group selected a higher intensity (+13.6 %) at 528 nm (green), a higher intensity (+27.6 %) at 590 nm (yellow) and a much lower intensity (-23.5 %) at 657 nm (red) than the younger group. The reasons for these differences cannot readily be explained. One possibility is that older observers may be more accustomed to sources that contain a high component of yellow. Older observers grew up using incandescent sources, while younger observers may be regular users of tablets, computer screens, LED TV screens and cell phones, which feature a high component of blue. Indeed, the younger observers selected a source with a higher (+13.2 %) component of blue.

The older observer may thus “perceive” reflected light to be “white” when a high component of yellow/red is included, but in practice only a higher yellow component is selected and not an increased red one as well.

4.3.3.2 Colour matching

When considering CRI colour measurement results, the two source specifications selected by the two different age groups are very different. Table 4.5 and Figure 4.9 provide more details. The younger group selected a source with CRI average colour rendering (R_a) of 74 (CCT = 6 592 K), while the R_a value for the older group is 89 (CCT = 5 150 K). A very important value is that of $R_{9,}$ which is measured at -7 for the younger group and 39 for the older group. A manufacturer of light sources states that a light source with an acceptable CRI features an R_a value of at least 80 and an R_9 value of higher than 0 (Bailey 2013). Using such a measure as a guide means that the source specified by the older group to achieve “white perception” is close to standard commercial sources. The source specified by the younger group closely matches the older group’s source at R_{10} (strong yellow), and R_{12} (strong blue) but not at R_{11} (strong green). The older group of observers thus prefers a light source with a higher value of R_a and a huge difference in R_9 value to achieve a “perception of white”.

Figure 4.10 shows seven-step MacAdam ellipses drawn around the gamut points. As the outlines of the ellipses do not overlap (or even touch), it can be deduced that the average observer's vision will perceive the two sources to be chromatically different. According to Ohno (2011), it is important to consider Duv values, as these are important for light source colour quality. The source selected by the older group features a Duv value of -0.0112 and the source selected by the younger group features a Duv value of -0.0255. Both values are below the Planckian locus. Padfield (2017) states that Duv values with a value larger than 0.006 are not preferential as "white light". The ideal value for "white light" should be less than 0.001. Both sources selected by the two observer groups can thus be classified as being "white". Ohno *et al*. (2013) completed a vision experiment on white light chromaticity for lighting to evaluate the Duv values perceived to be most natural by observers. They concluded that the chromaticity region below the Planckian locus is preferred by observers to represent natural light. (All CIE 1931 chromaticity diagrams were drawn using OSRAM ColorCalculator software, which is freely available.)

4.3.4 Reference source matching test (split booth test procedure)

The results of the reference source matching test, when using the split booth procedure, are presented in Table 4.7 and Table 4.8.

Table 4.7 Split booth reference matching tests using two age groups.

Parameter	**Under 40**	**Over 50**
R_a	88	89
CCT	2 323 K	2 372 K
x	0.4763	0.4726
Y	0.3903	0.3911
duv	-0.0056	-0.0057
Dominant λ	589 nm	589 nm
Peak λ	660 nm	660 nm

The result of the split booth reference matching test is graphically summarised in the SPD graph in Figure 4.11 and the sectional CIE 1931 chromaticity diagram in Figure 4.12.

Table 4.8: Split booth reference matching test with CRI measured against approximate Munsell colour samples. A difference of more than 5 is considered significant. (Houser 2015)

CRI values	**Appearance under daylight** (Chroma-Q Product Support 1997-2016)	**Under 40**	**Over 50**	**Difference**
R_1	Light greyish red	91	92	1
R_2	Dark greyish yellow	93	94	1
R_3	Strong yellow green	96	96	0
R_4	Moderate yellowish green	77	78	1
R_5	Light bluish green	83	85	2
R_6	Light blue	88	88	0
R_7	Light violet	94	94	0
R_8	Light reddish purple	89	85	4
Average		**88**	**89**	**1**
$\mathbf{R_a}$		**88**	**89**	**1**
Strong colours				
R_9	Strong red	67	74	7
R_{10}	Strong yellow	81	81	0
R_{11}	Strong green	53	53	0
R_{12}	Strong blue	80	81	1
Additional colours				
R_{13}	Light yellowish pink (skin)	86	87	1
R_{14}	Moderate olive green (leaf)	97	97	0
R_{15}	Asian skin	98	97	1

4.3.4.1 Relative source intensity

Reference source matching tests are not about intensity matching but rather colour perception matching. Differences were measured at 9.1% at 455 nm, 7.6% at 528 nm, 6.7% at 590 nm and 2.6% at 657 nm. Across the spectrum, the older group selected the higher intensity, which is to be expected because of a loss in transmission of the crystalline lens.

The biggest loss (9.1%) was measured at 455 nm, which is also expected because of yellowing of the lens with age.

4.3.4.2 Colour matching

The CRIs of the sources selected by the two different age groups for colour matching using the split booth test procedure are very similar. Figures 4.11 and 4.12 provide more details.

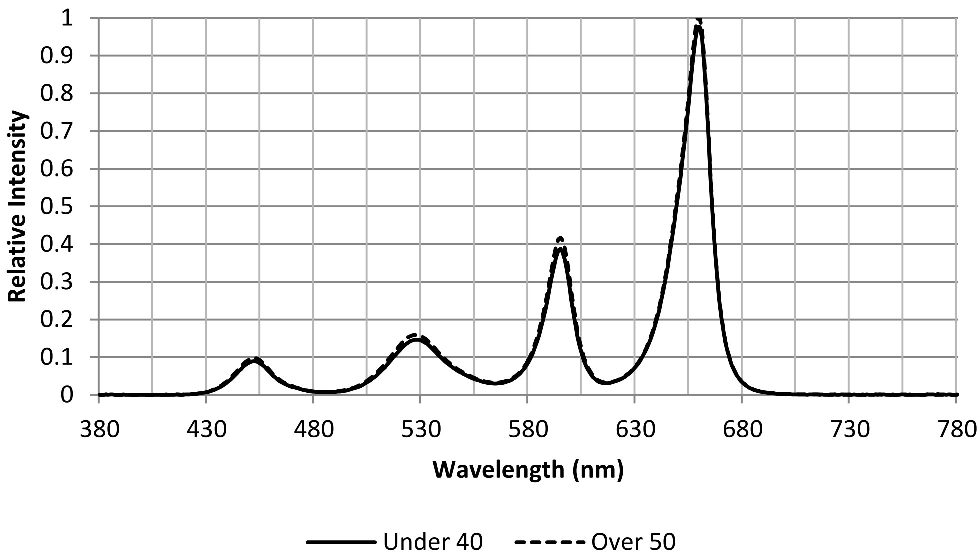

Figure 4.11 SPD graph for sources selected by two age groups to match colours using the split booth test procedure. Differences at tetra-chromatic wavelengths are 9.1% at 455 nm, 7.6% at 528 nm, 6.7% at 590 nm and 2.6% at 657 nm.

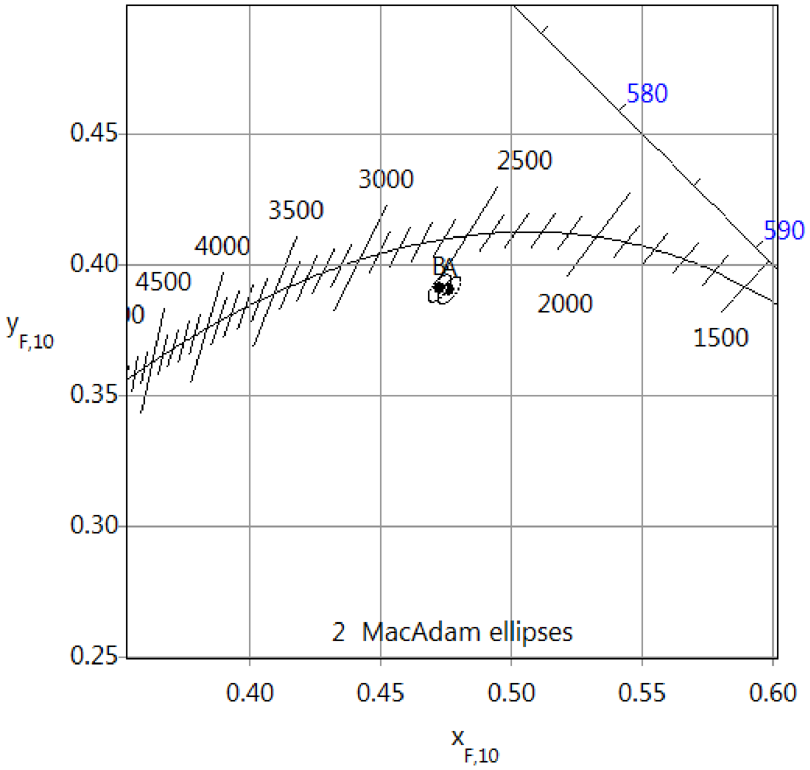

Figure 4.12 Sectional part of the CIE 1931 chromaticity diagram showing x and y coordinates of sources selected by two age groups (A = under 40 and B = over 50) to match colours. Two-step MacAdam ellipses are drawn around the x-y points.

The older group selected a source with an R_a value of 89 (CCT= 2 372 K), while the younger group selected a source with an R_a of 88 (CCT = 2 323 K). Houser *et al*. (2015) state that differences in CRI R_a values of less than 5 points are mostly not noticeable. Figure 4.12 shows two-step MacAdam ellipses drawn around the gamut points. The outlines of ellipses overlap and it can be deduced that the average observer will perceive the two sources to be chromatically similar. It can be deduced that the two age groups preferred almost identical sources for matching of colour samples. If matching of the colour rendering samples (R_1 – R_8) and the additional detail samples (R_9 – R_{15}) is considered, data are almost equal except for R_9 where the older group selected a value of 74 and the younger group selected a value of 67, thus producing a significant difference of 7.

It is interesting that using the split booth colour matching method, the colour perception of both age groups is the same. The older group thus seems to be able to compensate for a loss in crystalline lens transmission.

4.3.5 Reference source matching test (side-by-side test booth procedure)

The results of the reference source matching test, when using the side-by-side booth procedure, are presented in Table 4.9 and Table 4.10.

Table 4.9 Side-by-side booth reference matching tests using two age groups.

Parameter	**Under 40**	**Over 50**
R_a	91	89
CCT	2 310 K	2 529 K
x	0.4765	0.4853
y	0.3889	0.3904
duv	-0.006	-0.006
Dominant λ	589 nm	588 nm
Peak λ	660 nm	660 nm

Table 4.10 Side-by-side booth reference matching test with CRI measured against approximate Munsell colour samples. A difference of more than 5 is considered significant (Houser 2015).

CRI values	**Appearance under daylight** (Chroma-Q Product Support 1997-2016)	**Under 40**	**Over 50**	**Difference**
R_1	Light greyish red	96	91	5
R_2	Dark greyish yellow	94	94	0
R_3	Strong yellow green	94	96	2
R_4	Moderate yellowish green	83	76	7
R_5	Light bluish green	88	84	4
R_6	Light blue	87	88	1
R_7	Light violet	92	94	2

CRI values	**Appearance under daylight** (Chroma-Q Product Support 1997-2016)	**Under 40**	**Over 50**	**Difference**
R_8	Light reddish purple	94	91	3
Average		**91**	**89**	**2**
$\mathbf{R_a}$		**91**	**89**	**2**
Strong colours				
R_9	Strong red	96	80	16
R_{10}	Strong yellow	82	82	0
R_{11}	Strong green	59	53	6
R_{12}	Strong blue	80	85	5
Additional colours				
R_{13}	Light yellowish pink (skin)	90	86	4
R_{14}	Moderate olive green (leaf)	96	97	1
R_{15}	Asian skin	91	97	6

The result of the side-by-side booth reference matching test is graphically summarised in the SPD graph of Figure 4.13 and the sectional CIE 1931 chromaticity diagram of Figure 4.14.

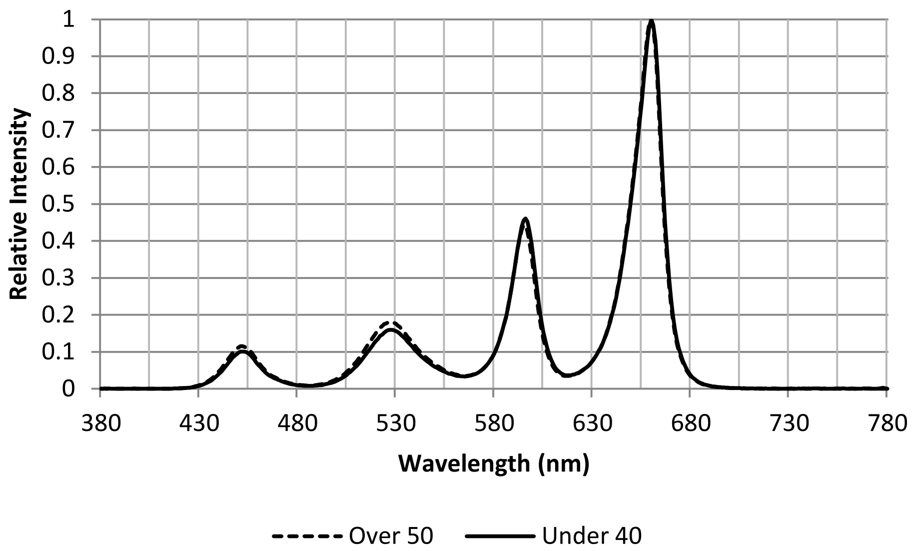

Figure 4.13 SPD graph for sources as selected by two age groups to match colours using the conventional side-by-side test procedure. Differences at tetra-chromatic wavelengths are 11.3% at 455 nm, 11.3% at 528 nm, 0.4% at 590 nm and 2.1% at 657 nm.

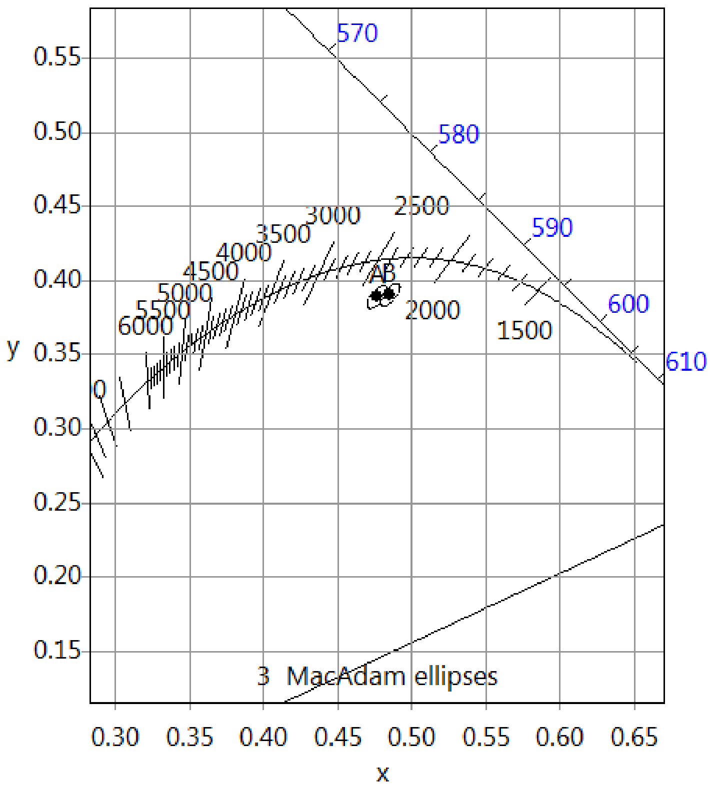

Figure 4.14 Sectional part of the CIE 1931 chromaticity diagram showing x and y coordinates of sources selected by two age groups (A = under 40 and B = over 50) to match colours. Three-step MacAdam ellipses are drawn around the x-y points.

4.3.5.1 Relative source intensity

Reference source matching tests are not about intensity matching but rather colour perception matching. Differences were measured at 11.3% at 455 nm, 11.3% at 528 nm, 0.4% at 590 nm and 2.1% at 657 nm. The biggest loss (11.3%) was measured at 455 nm and 528 nm, which are the shorter wavelengths. This is to be expected because of yellowing of the lens with age.

4.3.5.2 Colour matching

The CRI values of the sources selected by the two different age groups for colour matching using the side-by-side booth test procedure are very similar. Figure 4.13 and Figure 4.14 provide more details. The older group selected a source with an R_a value of 89 (CCT = 2 529 K), while the younger group selected a source with an Ra of 91 (CCT = 2 310 K). Houser *et al*. (2015) state that differences in CRI R_a values of less than 5 points are mostly not noticeable. Figure 4.14 shows three-step MacAdam ellipses drawn around the gamut points. The outlines of ellipses overlap and it can be deduced that the average observer will perceive the two sources to be chromatically similar. Using such a guideline, it can be deduced that the two age groups preferred almost identical sources for matching colour samples. If matching of the colour rendering samples (R_1 – R_8) and the additional detail samples (R_9 – R_{15}) is considered, data are almost equal except for R_9, where the older group selected a value of 80 and the younger group selected a value of 96, yielding a significant difference of 16.

4.3.6 Reference source matching test comparison (side-by-side booth test procedure compared with split booth test procedure)

Two groups of observers took part to perform an identical test using two different test setups. The one setup featured the traditional side-by-side test setup while the other featured the alternative split booth method using a rotating mirror. The results were examined to determine whether those achieved using the two test methods were comparable. Section 4.3.6.1 presents the results achieved for the under-40 group and Section 4.3.6.2 presents the results achieved for the over-50 group.

4.3.6.1 Test method comparison for the under-40 age group

Table 4.11 and Table 4.12 show the results achieved by the observer group younger than 40.

Table 4.11 Under-40 reference matching comparison for two different test methods.

Parameter	Under 40 (Split booth)	Under 40 (Side-by-side booth)
R_a	88	91
CCT	2 323 K	2 310 K
x	0.4763	0.4765
y	0.3903	0.3889
Duv	-0.0056	-0.006
Dominant λ	589 nm	589 nm
Peak λ	660 nm	660 nm

The result of the test method comparison for the under-40 group is graphically summarised in the SPD graph of Figure 4.15 and the sectional CIE 1931 chromaticity diagram of Figure 4.16.

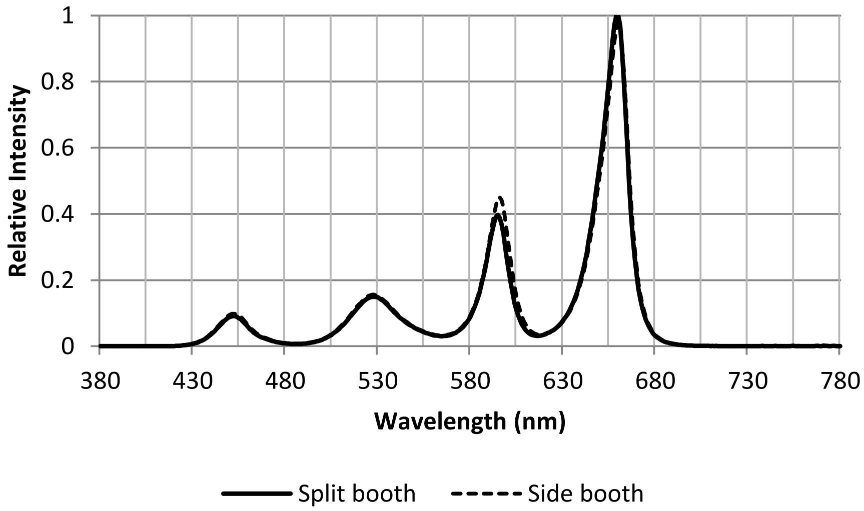

Figure 4.15 Test method comparison SPD for the under-40 age group. Differences at tetra-chromatic wavelengths are 9% at 455 nm, 4% at 528 nm, 3.7% at 590 nm and 5.9% at 657 nm.

Table 4.12 CRI detail values for the under 40 age group when comparing the split booth colour matching method and the side-by-side booth colour matching method. A difference of more than 5 is considered significant (2015).

CRI values	**Appearance under daylight** (Chroma-Q Product Support 1997-2016)	**Under 40 (Split booth)**	**Under 40 (Side-by-side booth)**	**Difference**
R_1	Light greyish red	91	96	5
R_2	Dark greyish yellow	93	94	1
R_3	Strong yellow green	96	94	2
R_4	Moderate yellowish green	77	83	6
R_5	Light bluish green	83	88	5
R_6	Light blue	88	87	1
R_7	Light violet	94	92	2
R_8	Light reddish purple	85	94	9
Average		**88**	**91**	**3**
$\mathbf{R_a}$		**88**	**91**	**3**
Strong colours				
R_9	Strong red	67	96	29
R_{10}	Strong yellow	81	82	1
R_{11}	Strong green	53	59	6
R_{12}	Strong blue	80	80	0
Additional colours				
R_{13}	Light yellowish pink (skin)	86	90	4
R_{14}	Moderate olive green (leaf)	97	96	1
R_{15}	Asian skin	98	91	3

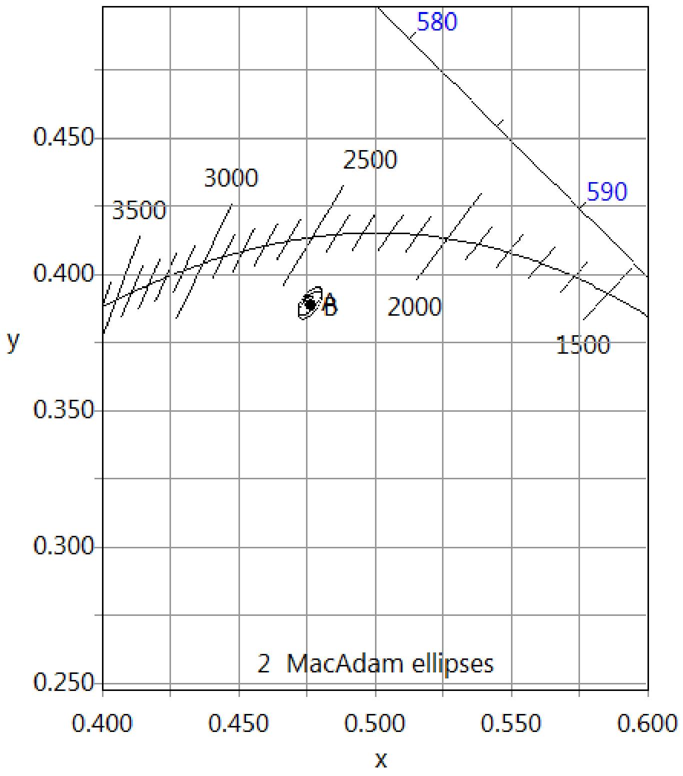

Figure 4.16 Sectional part of the CIE 1931 chromaticity diagram showing x and y coordinates of sources selected by the under-40 age group using two different methods of colour matching (A = split booth method and B = side-by-side booth method) to match colours. Two-step MacAdam ellipses are drawn around the x-y points.

4.3.6.1.1 Relative source intensity

The split booth test method uses a rotating mirror in the optical light path and it is thus expected that a constant transmission loss throughout the photonic spectrum will be measured. Differences were measured at 9% at 455 nm, 4% at 528 nm, 3.7% at 590 nm and 5.9% at 657 nm.

4.3.6.1.2 Colour matching

The CRI values selected by the same under-40 observer group when using two different test methods are closely matched. With the split booth method, the group selected a source with an R_a of 88 (CCT = 2 323 K) and an R_a of 91 (CCT = 2 310 K) for the side-by-side booth method. Houser *et al*. (2015) state that differences in CRI R_a values that are less than 5 points are mostly not noticeable. Figure 4.16 shows two-step MacAdam ellipses drawn around the gamut points. The outlines of ellipses overlap and it can be deduced that the average observer will perceive the two sources to be chromatically similar. Using such a guideline, it can be deduced that the two test methods yield almost identical results for matching of colour samples. If matching of the colour rendering samples (R_1 – R_8) and the additional detail samples (R_9 – R_{15}) is considered, data are almost equal except for R_9 where the split booth method yielded a value of 67 and the side-by-side method produced a value of 96, which is considered significant.

4.3.6.2 Test method comparison for the over-50 age group

Table 4.13 and Table 4.14 present the results as selected by the over-50 age group.

Table 4.13 Over-50 reference matching comparison for two different test methods

Parameter	Over 50 (Split booth)	Over 50 (Side-by-side)
R_a	89	89
CCT	2 372 K	2 529 K
x	0.4726	0.4599
y	0.3911	0.3904
duv	-0.0057	-0.0063
Dominant λ	589 nm	588 nm
Peak λ	660 nm	660 nm

The result of the test method comparison for the over-50 age group is graphically summarised in the SPD graph of Figure 4.17 and the sectional CIE 1931 chromaticity diagram of Figure 4.18.

Table 4.14 CRI detail values for the over-50 age group when comparing the split booth method and the side-by-side colour matching method. A difference of more than 5 is considered significant (Houser 2015)

CRI values	**Appearance under daylight** (Chroma-Q Product Support 1997-2016)	**Over 50 (Split booth)**	**Over 50 (Side-by-side booth)**	**Difference**
R_1	Light greyish red	92	91	2
R_2	Dark greyish yellow	94	94	0
R_3	Strong yellow green	96	96	0
R_4	Moderate yellowish green	78	76	2
R_5	Light bluish green	85	84	1
R_6	Light blue	88	88	0
R_7	Light violet	94	94	0
R_8	Light reddish purple	89	91	2
Average		**89**	**89**	**0**
R_a		**89**	**91**	**2**
Strong colours				
R_9	Strong red	74	80	6
R_{10}	Strong yellow	81	82	1
R_{11}	Strong green	53	53	0
R_{12}	Strong blue	81	85	4
Additional colours				
R_{13}	Light yellowish pink (skin)	87	86	1
R_{14}	Moderate olive green (leaf)	97	97	0
R_{15}	Asian skin	97	97	0

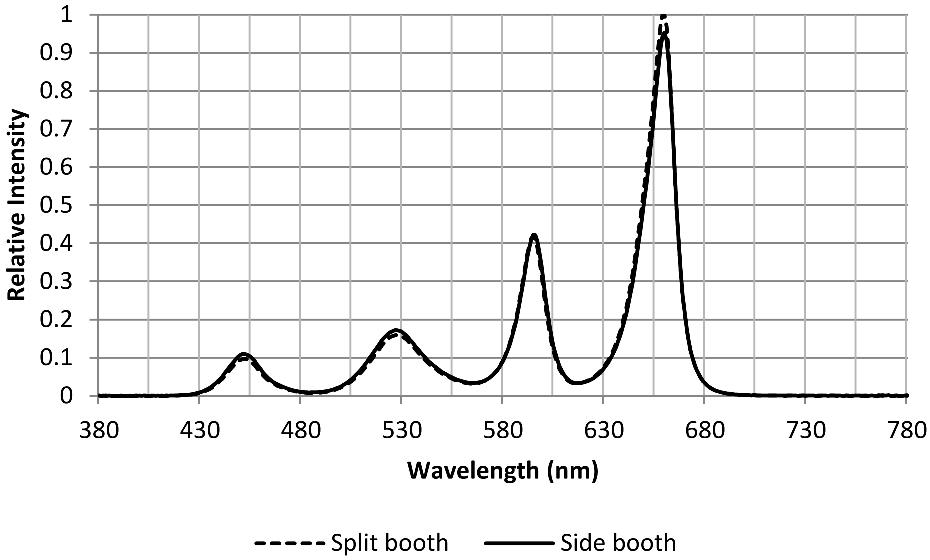

Figure 4.17 Test method comparison SPD for the over-50 age group. Differences at tetra-chromatic wavelengths are 11.2% at 455 nm, 7.7% at 528 nm, 2.8% at 590 nm and 6.4% at 657 nm.

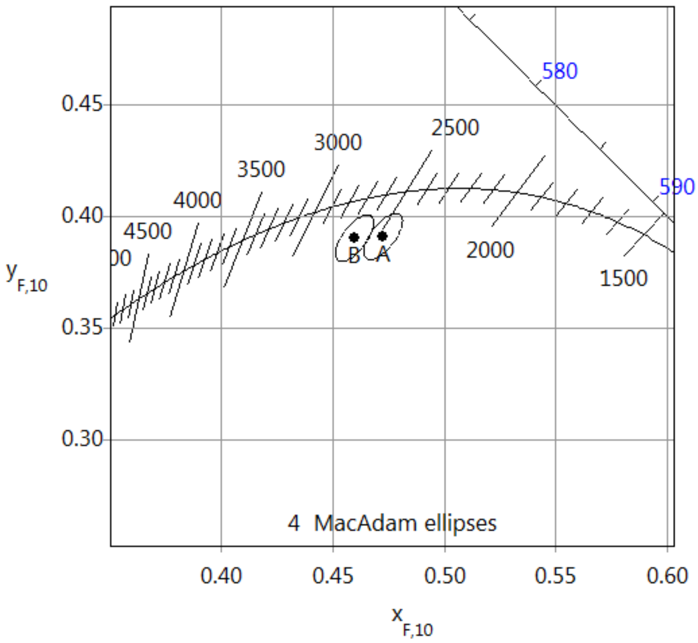

Figure 4.18 Sectional part of the CIE 1931 chromaticity diagram showing x and y coordinates of sources selected by the over-50 age group using two different methods of colour matching. (A = split booth method and B = side-by-side booth method) to match colours. Four-step MacAdam ellipses are drawn around the x-y points.

4.3.6.2.1 Relative source intensity

The split booth test method uses a rotating mirror in the optical light path and it is thus expected that a constant transmission loss throughout the photonic spectrum will be measured. Differences were measured at 11.2% at 455 nm, 7.7% at 528 nm, 2.8% at 590 nm and 6.4% at 657 nm.

4.3.6.2.2 Colour matching

The CRI values selected by the same over-50 observer group when using two different test methods are closely matched. With the split-booth method, the group selected a source with an R_a of 89 (CCT = 2 372 K) and for the side-by-side booth method an R_a of 91 (CCT = 2 529 K). Houser *et al.* (2015) state that differences of CRI R_a values of less than 5 points are mostly not noticeable. Figure 4.18 shows four-step MacAdam ellipses drawn around the gamut points. The outlines of ellipses overlap and it can be deduced that the average observer will perceive the two sources to be chromatically similar. Using such a guideline, it can be deduced that the two test methods yield almost identical results for matching of colour samples. If matching of the colour rendering samples (R_1 – R_8) and the additional detail samples (R_9 – R_{15}) is considered, data are almost equal except for $R_{9,}$ where the split booth method yielded a value of 74 and the side-by-side method produced a value of 80.

4.3.7 Reference source matching test comparison after one year (side-by-side booth test procedure)

Two groups of observers took part to perform an identical test using the same side-by-side test setup. The same test was repeated after one year with exactly the same observers. The purpose of this test was to investigate the repeatability of human colour perception. Section 4.3.7.1 presents the results achieved for the under-40 group and Section 4.3.7.2 presents the results achieved for the over-50 group.

4.3.7.1 Colour perception after one year for the under-40 age group

Table 4.15 and Table 4.16 show the results achieved by the under-40 age group when the same colour reference procedure was repeated after one year using the same group of observers.

Table 4.15 Results achieved by the under-40 age group at the beginning of a one-year test period and after one year passed using the side-by-side test method.

Parameter	**Year 1**	**Year 2**
R_a	92	90
CCT	2 331 K	2 300 K
x	0.477	0.4845
y	0.3922	0.3984
duv	-0.005	-0.0027
Dominant λ	589 nm	589 nm
Peak λ	660 nm	660 nm

Table 4.16 CRI detail values for the under-40 age group when comparing results after one year using identical observers and using the side-by-side booth colour matching method. A difference of more than 5 is considered significant (Houser 2015).

CRI values	**Appearance under daylight** (Chroma-Q Product Support 1997-2016)	**Year 1**	**Year 2**	**Difference**
R_1	Light greyish red	97	93	4
R_2	Dark greyish yellow	95	94	1
R_3	Strong yellow green	94	96	2
R_4	Moderate yellowish green	84	77	7
R_5	Light bluish green	90	84	6
R_6	Light blue	88	88	0
R_7	Light violet	92	95	3
R_8	Light reddish purple	94	90	6
Average		**92**	**90**	**2**
$\mathbf{R_a}$		**92**	**90**	**2**
Strong colours				
R_9	Strong red	96	79	17
R_{10}	Strong yellow	84	82	2
R_{11}	Strong green	59	52	7
R_{12}	Strong blue	83	81	2
Additional colours				
R_{13}	Light yellowish pink (skin)	91	87	4
R_{14}	Moderate olive green (leaf)	96	97	1
R_{15}	Asian skin	90	96	6

The result of the one-year lapse comparison of the under-40 group is graphically summarised in the SPD graph of Figure 4.19 and the sectional CIE 1931 chromaticity diagram of Figure 4.20.

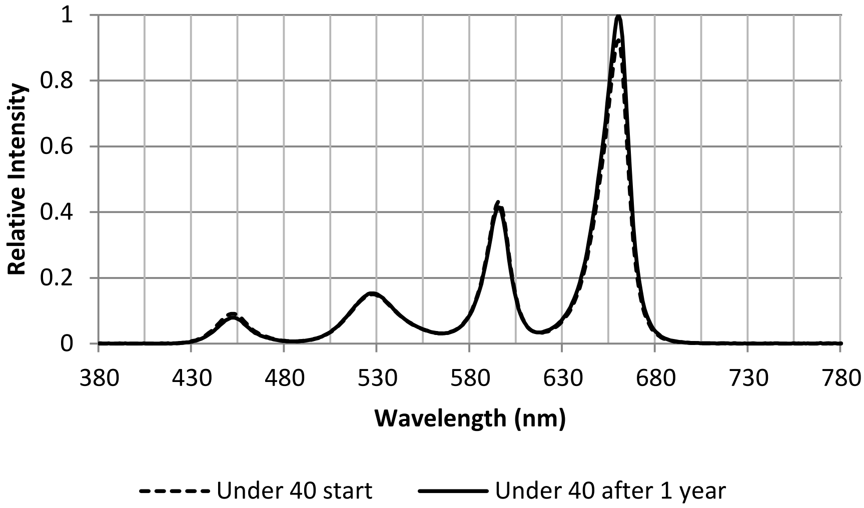

Figure 4.19 Results after one year SPD for the under-40 age group. Differences at tetra-chromatic wavelengths are 12.3% at 455 nm, 2.2% at 528 nm, 3.4% at 590 nm and 6.7% at 657 nm.

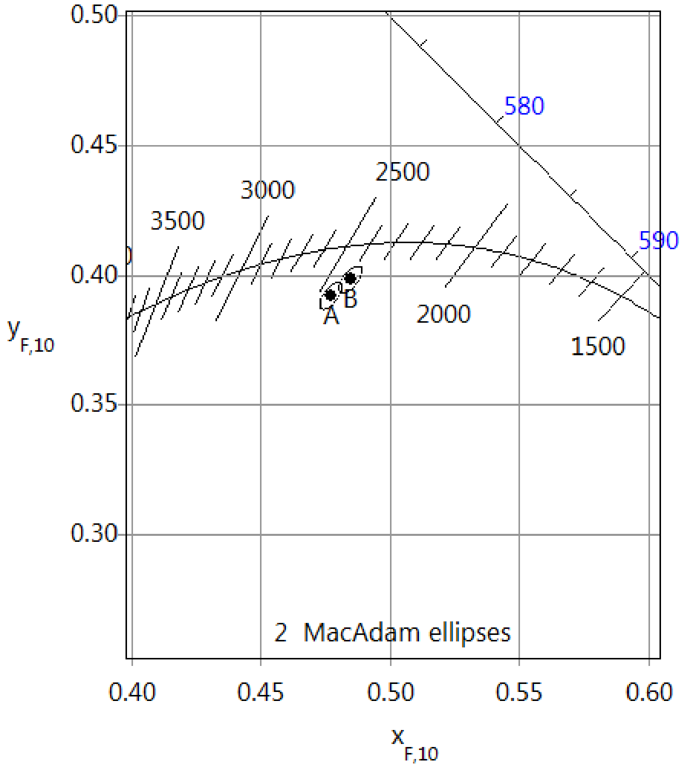

Figure 4.20 Sectional part of the CIE 1931 chromaticity diagram showing x and y coordinates of sources selected by the under-40 age group before and after one year (A = before the year and B = after one year) to match colours. Two-step MacAdam ellipses are drawn around the x-y points.

4.3.7.1.1 Relative source intensity

It is expected that a constant transmission difference throughout the photonic spectrum will be measured. Differences were measured at 12.3% at 455 nm, 2.2% at 528 nm, 3.4% at 590 nm and 6.7% at 657 nm.

4.3.7.1.2 Colour matching

The CRI values selected by the same under-40 observer group when using the side-by-side method before and after one year are fairly closely matched, with some important differences. At the beginning of the year, the group selected a source with an R_a of 92 (CCT = 2 331 K), but an R_a of 90 (CCT = 2 300 K) a year later. Houser *et al*. (2015) state that differences in CRI R_a values of less than 5 points are mostly not noticeable. Figure 4.20 shows two-step MacAdam ellipses drawn around the gamut points. The outlines of ellipses overlap and it can be deduced that the average observer will perceive the two sources to be chromatically similar before and after a year. If matching of the colour rendering samples (R_1 – R_8) and the additional detail samples (R_9 – R_{15}) is considered, data differ by more than 5 points at R_4 (yellowish-green), R_5 (bluish-green), R_8 (reddish-purple), R_9 (strong red) and R_{15} (Asian skin). The general CRI R_a measured for the under-40 group remained very close after one year but it is also true that some significant colour perception changes were recorded after one year.

4.3.7.2 Colour perception after one year for the over-50 age group

Table 4.17 and Table 4.18 show the results achieved by the over-50 age group when the same colour reference procedure was repeated after one year using the same group of observers.

The result of the one-year lapse comparison of the over-50 group is graphically summarised in the SPD graph of Figure 4.21 and the sectional CIE 1931 chromaticity diagram of Figure 4.22.

Table 4.17 Results achieved by the over-50 age group at the beginning of a one-year test period and after one year passed using the side-by-side test method.

Parameter	Year 1	Year 2
R_a	91	93
CCT	2 563 K	2 545 K
x	0.4563	0.467
y	0.3884	0.4032
Duv	-0.007	-0.002
Dominant λ	588 nm	586 nm
Peak λ	660 nm	660 nm

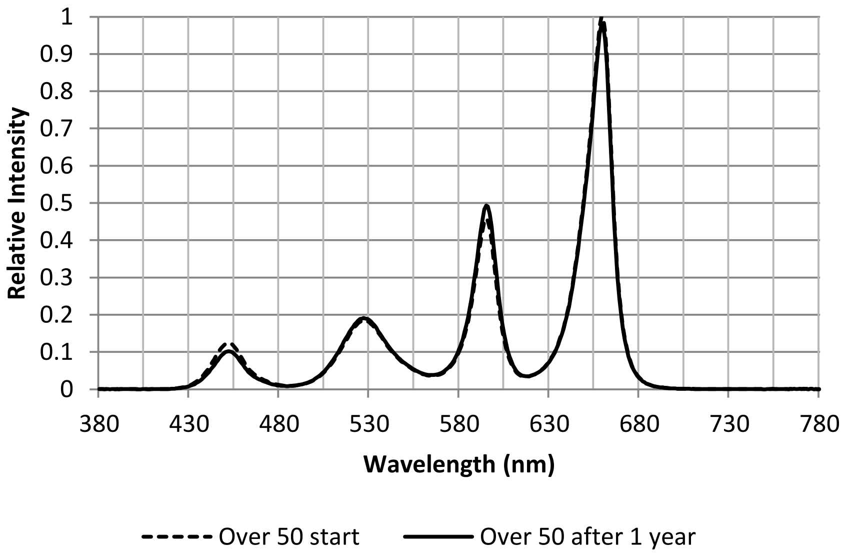

Figure 4.21 Results after one year SPD for the over-50 age group. Differences at tetra-chromatic wavelengths are 17.2% at 455 nm, 3.5% at 528 nm, 5.7% at 590 nm and 2% at 657 nm.

4.3.7.2.1 Relative source intensity

It is expected that a constant transmission difference throughout the photonic spectrum will be measured. Differences were measured at 17.2% at 455 nm, 3.5% at 528 nm, 5.7% at 590 nm and 2% at 657 nm.

Table 4.18 CRI detail values for the over-50 age group when comparing results after one year using identical observers and using the side-by-side booth colour matching method. A difference of more than 5 is considered significant (Houser 2015)

CRI values	**Appearance under daylight** (Chroma-Q Product Support 1997-2016)	**Year 1**	**Year 2**	**Difference**
R_1	Light greyish red	93	98	5
R_2	Dark greyish yellow	95	97	2
R_3	Strong yellow green	96	96	0
R_4	Moderate yellowish green	79	82	3
R_5	Light bluish green	86	91	5
R_6	Light blue	90	93	3
R_7	Light violet	94	94	0
R_8	Light reddish purple	93	94	1
Average		**91**	**93**	**2**
$\mathbf{R_a}$		**91**	**93**	**2**
Strong colours				
R_9	Strong red	85	91	6
R_{10}	Strong yellow	84	90	6
R_{11}	Strong green	56	60	4
R_{12}	Strong blue	86	93	7
Additional colours				
R_{13}	Light yellowish pink (skin)	87	92	5
R_{14}	Moderate olive green (leaf)	97	97	0
R_{15}	Asian skin	96	88	8

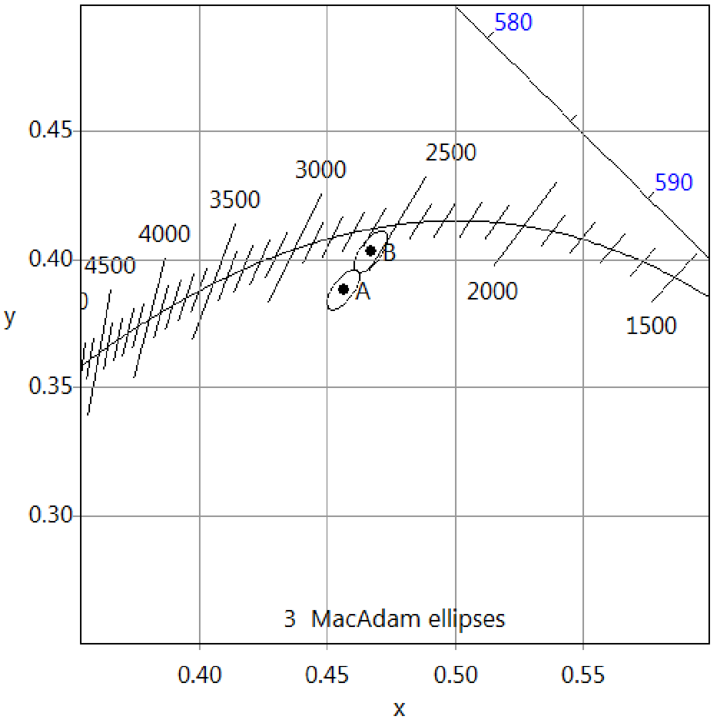

Figure 4.22 Sectional part of the CIE 1931 chromaticity diagram showing x and y coordinates of sources selected by the over-50 age group before and after one year (A = before the year and B = after one year) to match colours. Three-step MacAdam ellipses are drawn around the x-y points.

4.3.7.2.2 Colour matching

The CRI values selected by the same over-50 observer group when using the side-by-side method before and after one year are fairly closely matched, with some important differences. At the beginning of the year, the group selected a source with an R_a of 91 (CCT = 2 563 K), but selected an R_a of 93 (CCT = 2 545 K) a year later. Houser *et al.* (2015) state that differences in CRI R_a values of less than 5 points are mostly not noticeable. Figure 4.22 shows three-step MacAdam ellipses drawn around the gamut points. The outlines of ellipses overlap and it can be deduced that the average observer will perceive the two sources to be chromatically similar before and after one year. If matching of the colour rendering samples (R_1 – R_8) and the additional detail samples (R_9 – R_{15}) is considered, data differs by more than 5 points at R_4 (greyish-red), R_3 (yellow-green), R_5 (bluish-green), R_9 (strong red), R_{10} (strong yellow), R_{12} (strong blue) and R_{15} (Asian skin).

The general CRI R_a measured for the over-50 group remained very close after one year, but it is also true that some significant colour perception changes were recorded after one year.

4.4 PHOTOMETRIC CHARACTERISTICS

The human eye is able to differentiate between three different vision environments, which are classified according to ambient light levels (Human eye sensitivity and photometric quantities 2017). These are called photopic vision, scotopic vision and mesopic vision (OSRAM 2014). The eye operates in the photopic region when environmental illumination is bright and cones are sensing full colour. When environmental illumination is very dark, the eye operates in the scotopic region where rods are the main sensory elements, providing high sensitivity but poor colour-sensing ability. Between the photopic region and the scotopic region, an illumination area exists that is called the mesopic region. Both rod and cone sensory elements are operational in the mesopic region, but with depleted colour-sensing ability. SPIE classifies the three luminance conditions as more than 3 cd/m^2 for the photopic region and less than 0.03 cd/m^2 for the scotopic region. The mesopic region thus exists in a luminance condition from 0.03 cd/m^2 to 3 cd/m^2.(Schwiegerling 2004)

The visual sensitivity for the human eye under photopic and scotopic conditions is shown in Figure 4.23.

Evaluations and tests described in this report use light sources of more than 3 cd/m^2 and thus only photopic conditions are considered. This study investigates the colour perception of various groups of observers. As depleted colour sensitivity is found in scotopic and mesopic conditions, only photopic illumination conditions are considered for colour perception tests.

The SPDs of each of the results presented in Section 4.3 is multiplied by the photopic V(λ) curve. The photopic curve thus also shows that blue (about 455 nm) and red (657 nm) responses will be depressed as the peak eye response is at 555 nm.

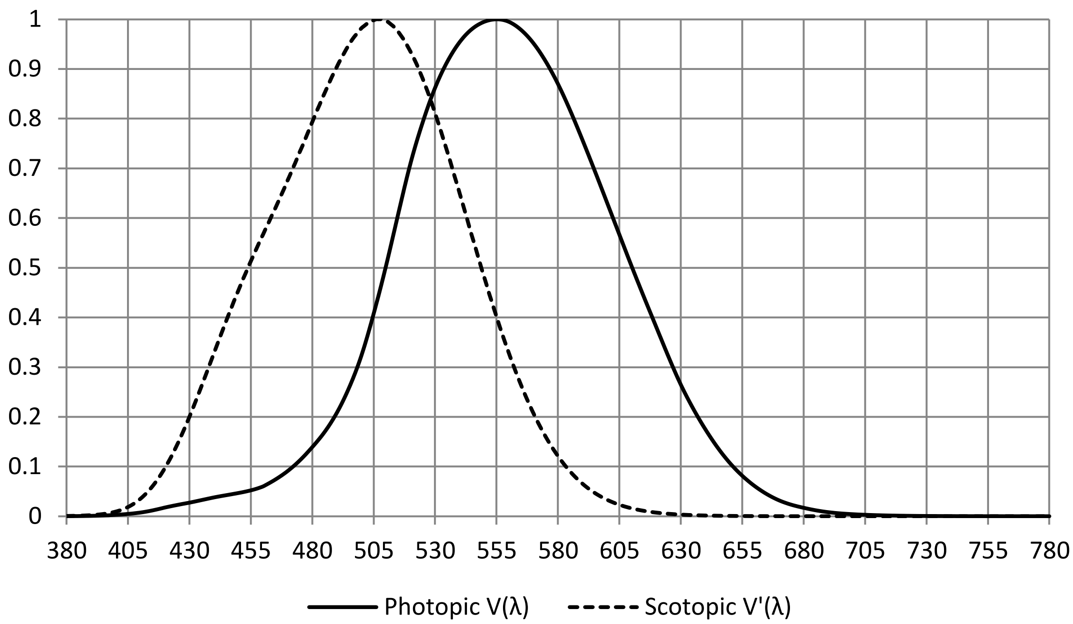

Figure 4.23 Photopic and scotopic luminosity curves for the human eye as measured with 2° cones. Curves were calculated from data freely available from Stockman (2008).

4.4.1 White perception test

Figure 4.24 shows the white perception test SPD measured with two age groups of observers and multiplied with the photopic V(λ) graph.

The result for the group older than 50 years shows that this group selects higher intensity illumination at 528 nm (green) and 590 nm (orange). This is expected, as it is probably to compensate for a loss in crystalline lens transmission as observers grow older. The under-40 group did select a higher intensity at 657 nm (red).

4.4.2 Reference source matching test (split booth test procedure)

Figure 4.25 shows the SPD for the split booth procedure when the reference source is matched with the test source and multiplied with the photopic V(λ) curve. Figure 4.25 shows the split booth test procedure results when the reference source and the test sources

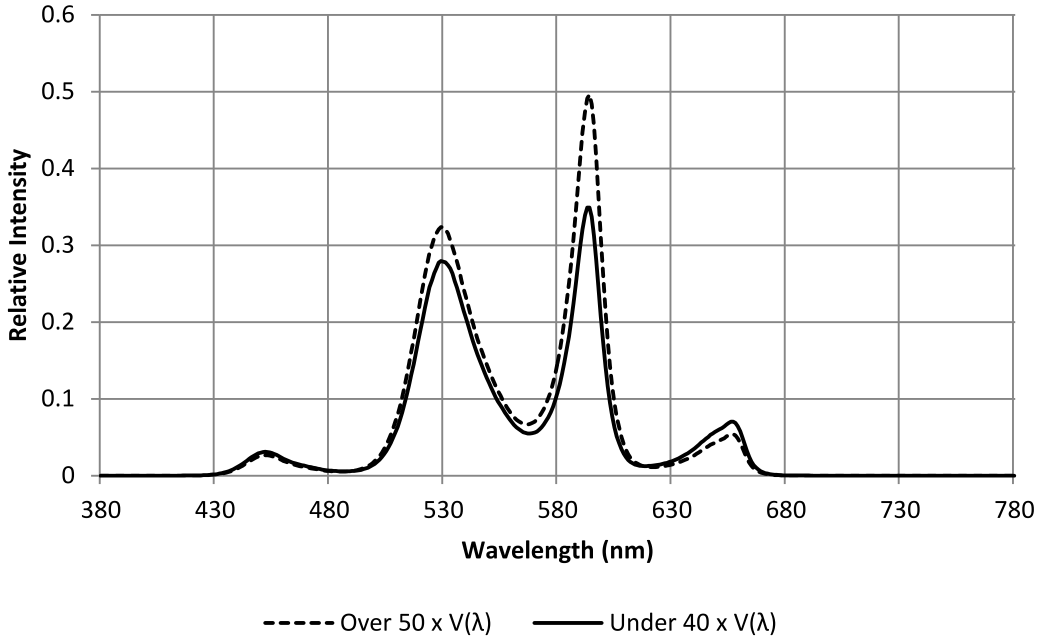

Figure 4.24 White perception SPD test result multiplied with photopic V(λ) curve. Differences at tetra-chromatic wavelengths are 13.2% at 455 nm, 13.6% at 528 nm, 27.6% at 590 nm and 23.5% at 657 nm.

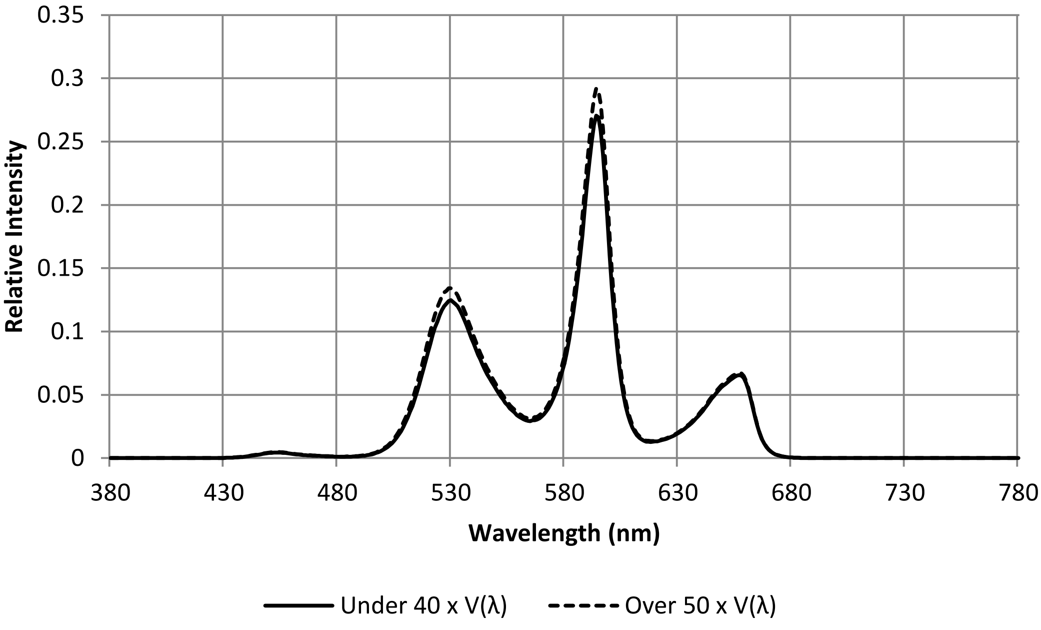

Figure 4.25 Split booth test procedure SPD source matching result multiplied with photopic V(λ) curve. Differences at tetra-chromatic wavelengths are 9.1% at 455 nm, 7.6% at 528 nm, 6.7% at 590 nm and 2.6% at 657 nm.

are matched by observers and the SPD curve is multiplied by the V(λ) curve. The over-50 group selected higher intensities at all wavelengths.

4.4.3 Reference source matching (side-by-side test booth procedure)

Figure 4.26 shows the SPD for the traditional side-by-side booth procedure when the reference source is matched with the test source and multiplied with the photopic V(λ) curve.

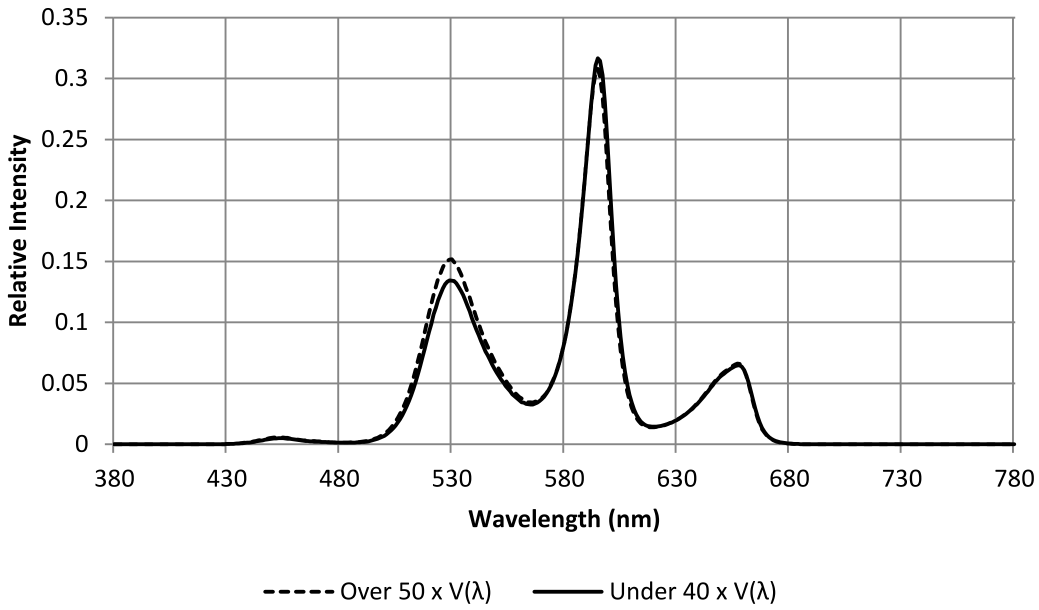

Figure 4.26 Side-by-side booth test procedure SPD source matching result multiplied with photopic V(λ) curve. Differences at tetra-chromatic wavelengths are 11.3% at 455 nm, 11.3% at 528 nm, 0.4% at 590 nm and 2.1% at 657 nm.

Figure 4.26 shows the side-by-side booth test procedure results when the reference source and the test sources are matched by observers and the SPD curve is multiplied by the V(λ) curve. The over-50 group selected higher intensities at all wavelengths except at 590 nm, where the under-40 group selected a higher intensity with a difference of 0.4%.

4.4.4 Reference source matching test comparison (side-by-side booth test procedure compared with split booth test procedure)

The side-by-side method is compared with the split booth test procedure when observers are carrying out a reference source matching test. These tests were completed for different age groups.

4.4.4.1 Test method comparison for the under-40 age group

Figure 4.27 shows the SPD for the two methods' comparison procedure when the reference source is matched with the test source and multiplied with the photopic V(λ) curve.

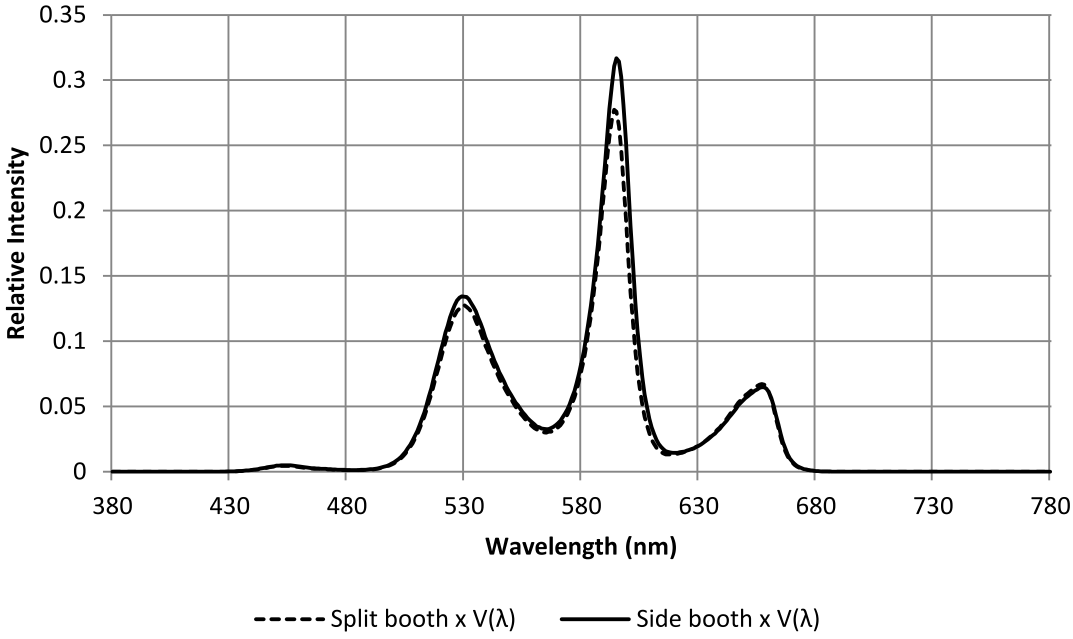

Figure 4.27 Comparison of different methods for reference source matching SPD results multiplied with the photopic V(λ) curve for the age group younger than 40. Differences at tetra-chromatic wavelengths are 9% at 455 nm, 4% at 528 nm, 3.7% at 590 nm and 5.9% at 657 nm.

Figure 4.27 shows the results when the reference source methods of measurement are compared using the under-40 age group. The SPD curve is multiplied by the V(λ) curve. The group younger than 40 selected a higher intensity when using the side booth at all wavelengths except at 657 nm, where the difference was 5.9%.

4.4.4.2 Test method comparison for the over-50 age group

Figure 4.28 shows the SPD for the two methods' comparison procedure when the reference source is matched with the test source and multiplied with the photopic V(λ) curve.

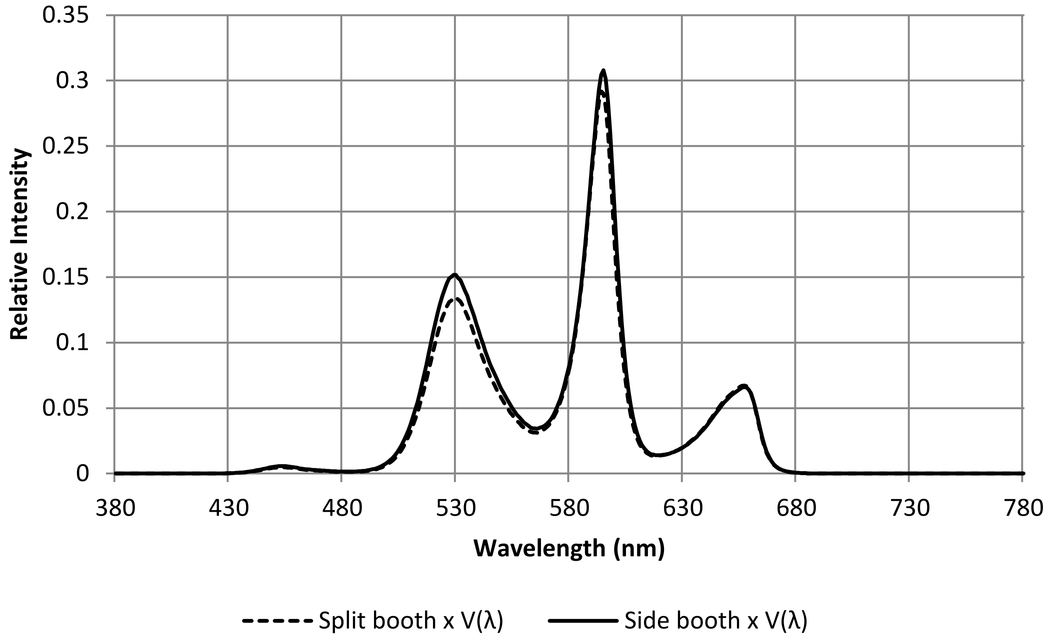

Figure 4.28 Comparison of different methods for reference source matching SPD results multiplied with the photopic V(λ) curve for the age group older than 50. Differences at tetra-chromatic wavelengths are 11.2% at 455 nm, 7.7% at 528 nm, 2.8% at 590 nm and 6.4% at 657 nm.

Figure 4.28 shows the results when the reference source methods of measurement are compared using the over-50 age group. The SPD curve is multiplied by the V(λ) curve. The age group older than 50 selected a higher intensity when using the side booth at all wavelengths except at 657 nm, where the difference was 6.4 %.

4.4.5 Reference source matching test comparison before and after one year

Two age groups of observers took part in an identical side-by-side colour matching test before and after one year. Exactly the same group of observers was used. The SPD curve of the result was multiplied by the V(λ) curve.

4.4.5.1 Colour perception after one year for the under-40 age group

Figure 4.29 shows the SPD for the time lapse procedure when the reference source was matched with the test source and multiplied with the photopic V(λ) curve.

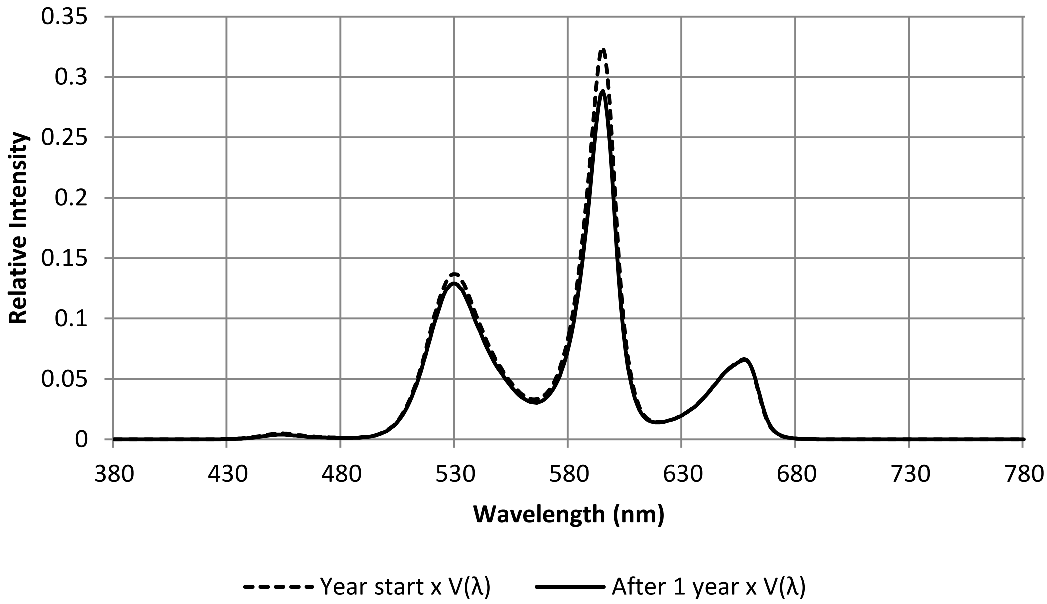

Figure 4.29 Comparison of colour perception matching before and after one year; SPD multiplied by the photopic V(λ) curve for the under-40 age group. Differences at tetra-chromatic wavelengths are 12.3% at 455 nm, 2.2% at 528 nm, 3.4% at 590 nm and 6.7% at 657 nm.

Figure 4.29 shows the results when the reference source measurement results are compared before and after one year using the under-40 age group. The SPD curve is multiplied by the V(λ) curve. After one year, the younger age group selected a lower intensity at all wavelengths except at 657 nm, where the difference was 6.7%.

4.4.5.2 Colour perception after one year for the over-50 age group

Figure 4.30 shows the SPD for the time lapse procedure when the reference source was matched with the test source and multiplied with the photopic V(λ) curve.

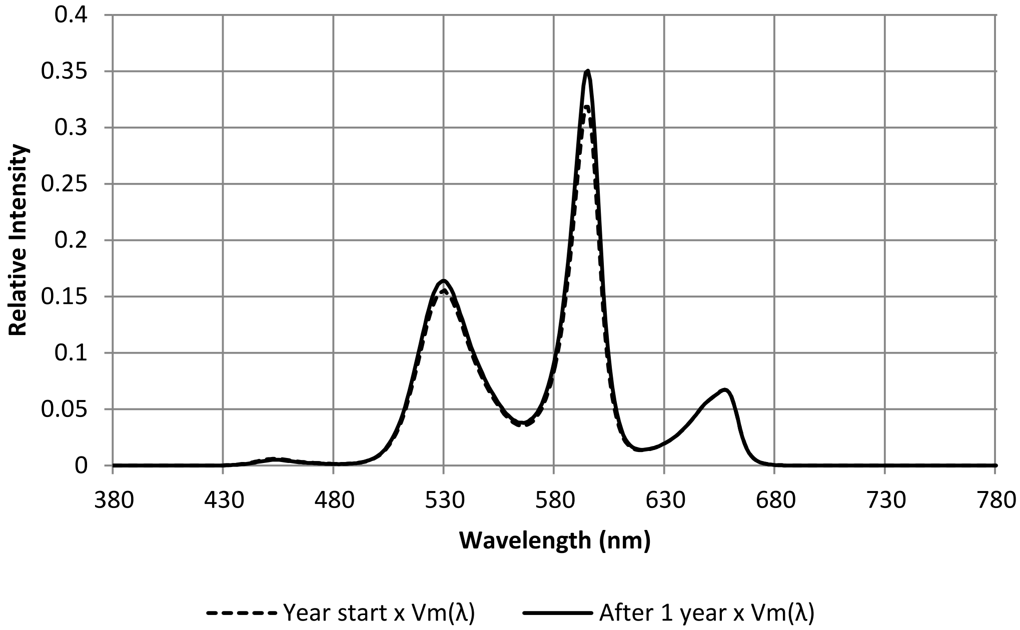

Figure 4.30 Comparison of colour perception matching before and after one year; SPD multiplied by the photopic V(λ) curve for the over-50 age group. Differences at tetra-chromatic wavelengths are 17.2% at 455 nm, 3.5% at 528 nm, 5.7% at 590 nm and 2% at 657 nm.

Figure 4.30 shows the results when the reference source measurement results are compared before and after one year using the over-50 age group. The SPD curve is multiplied by the V(λ) curve. After one year, the older age group selected a slightly higher intensity at all wavelengths except at 657 nm, where the difference was 2%.

4.5 RESULTS SUMMARY AND COMPARISON

Results measured in Sections 4.3 and 4.4 are compared in this section.

Table 4.19 The difference in intensity at four wavelengths between the two age groups when using the split-booth test procedure and the side-by-side booth test procedure.

Wavelength (nm)	**Test Procedure**	
	Split-booth procedure	**Side-by-side booth procedure**
455	9.1 %	11.3 %
528	7.6 %	11.3 %
590	6.7 %	0.4 %
657	2.6 %	2.1 %

Table 4.20 The difference in intensity at four wavelengths for the two age groups when comparing the split-booth test procedure with the side side-by-side test procedure.

Wavelength (nm)	**Age Group**	
	Younger than 40	**Older than 50**
455	9.0 %	11.2 %
528	4.0 %	7.7 %
590	3.7 %	2.8 %
657	5.9 %	6.4 %

Table 4.21 The difference in intensity at four wavelengths for the two age groups when measured before and after one year.

Wavelength (nm)	**Age Group**	
	Younger than 40	**Older than 50**
455	12.3 %	17.2 %
528	2.2 %	3.5 %
590	3.4 %	5.7 %
657	6.7 %	2.0 %

4.6 MIRROR CHARACTERISTICS

The test as described in Section 3.5.2 (split test booth test procedure) uses a rotating mirror in the optical path, as part of the experimental test setup. The effect of the mirror on colour perception is investigated in this section.

4.6.1 Evaluation procedure

The question investigated was whether the mirror introduced a wavelength shift in light of the visible spectrum. Also important was whether a possible wavelength shift was greater or less in certain areas of the visible spectrum. It was decided to use four LED sources at four different wavelengths, evenly spaced through the visible spectrum. An Ocean Optics HR2000 High-Resolution Spectrometer was used to measure the SPD of each LED with and without the mirror in the optical path. The LED sources used are listed in Table 4.22.

Table 4.22 LED source specifications as used in mirror test

Dominant Wavelength (nm)	Wavelength Range (nm)	Forward Voltage	Typical Current (Non-pulsed)	Transmission Angle	Part Number
455	449 - 461	3,2 V	100 mA - 1000 mA	120 °	OSRAM LDW5SM-4S4T-35
528	513 - 537	3.3 V	100 mA - 1000 mA	120 °	OSRAM LTW5SN-KYLY-25
617	612 - 624	2.3 V	100 mA - 1000 mA	170°	OSRAM LAW5SM-JYKY-24
657	646 - 666	2.2 V	100 mA - 1000 mA	170°	OSRAM LH W5AM-1T3T-1

4.6.2 Results

The results achieved with the four different LED sources are presented in Figure 4.31.

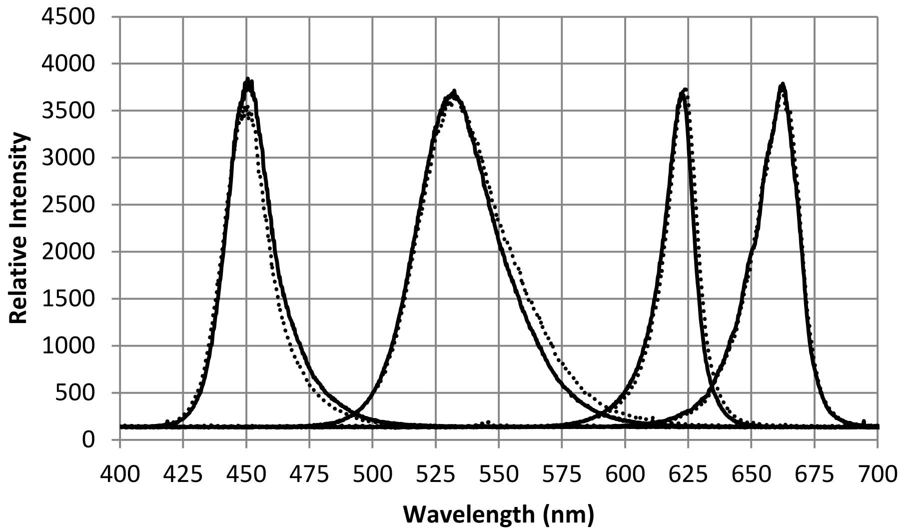

Figure 4.31 Combined LED source SPDs. Solid lines are SPDs without a mirror and dotted lines with a mirror inserted.

At 455 nm a wavelength shift is not evident but rather a spectral bandwidth narrowing of about 5 nm. At 528 nm a wavelength shift is not evident either, but rather a spectral bandwidth widening of about 5 nm. At 617 nm a wavelength shift towards the red of about 2 nm was measured. (In this case the spectral bandwidth seems to stay unchanged.) At 657 nm no wavelength shift is evident and no change in spectral wavelength bandwidth is measured. At each wavelength, the solid line is the SPD of the LED source measured without the mirror and the dotted line is SPDs measured after mirror insertion in the optical path. Figure 4.31 shows that any changes are small indeed.

4.7 CHAPTER SUMMARY

Results of measurements were presented in this chapter.

- Section 4.2.1 showed the measured SPD of the sun and sky in an effort to characterise the "perfect" source. These curves were compared with calculated blackbody curves.

- Section 4.3.2 showed that a larger percentage of older males (17.6%) failed the Ishihara colour screening test than younger males (14.3%).
- Section 4.3.3 showed that two different age groups selected two different light sources to achieve a "perception of white" when reflected light from an MCC is evaluated.
- Sections 4.3.4, 4.3.5 and 4.3.6 showed that the colour perception of both age groups is very similar. Results achieved with two alternative test-setups show that the alternative setups can be used as alternative test methods.
- Section 4.3.7 showed the result of colour perception testing, before and after one year. Whereas the results of the younger group are consistent, those of the older group show significant change in colour perception before and after one year. Optical loss measurements was presented in Section 4.5, where the older group of observers presents with a higher loss at 455 nm (blue), which is expected because of yellowing of the crystalline lens with age.
- Section 4.6 showed no significant wavelength shift due to the introduction of a mirror in the optical test path.

CHAPTER 5 DISCUSSION

5.1 CHAPTER OBJECTIVES

This chapter discusses results achieved.

- Section 5.3.1 discusses results achieved when completing the "white perception test". Table 5.1 is included to present crystalline lens transmission loss figures from similar studies.
- Sections 5.3.2, 5.3.3 and 5.3.4 discuss reference source matching results using two different test methods.
- Section 5.2.5 discusses the repeatability of psychophysical evaluation for colour perception testing.

5.2 OVERVIEW

The role of the reference source in improving CIE CRI for visual perception optimisation was investigated. In order to specify an improved reference source, human colour perception was investigated. The traditional side-by-side booth method was used for measurements and an alternative rotating mirror concept was designed and used for the same measurements. Observers were tasked to report on perceived "white perception" as well as perceived "colour perception". The same group of observers was evaluated one year apart in order to evaluate the repeatability of psychophysical testing methods when applied to colour matching measurements.

5.3 RESULTS

5.3.1 White perception test

Observers from two different age groups were requested to choose an illumination source which produced "white" when reflected light from an MCC test chart was evaluated.

The two observer groups selected two very different light sources. This made it necessary to determine whether the difference in source selection could be attributed to yellowing of the human crystalline lens or whether other factors should be considered.

Measurements of crystalline lens transmission loss were completed using a variety of methods. It was examined whether a relationship could be found between crystalline lens transmission loss and the measurement of white perception.

Table 5.1 is a compilation of lens transmission loss results as established by different researchers. Note 1: In this column, a negative figure indicates that the older age group selected a higher intensity and a positive figure indicates that the younger age group selected a higher intensity.

λ (nm)	**Loss Measured for Researcher and Age Group**			
	This study. Age 29 – 58 *(Note 1)*	**(Artigas *et al*. 2012) Age 40 - 59**	**(Boettner *et al*. 1962)**	**(Brøndsted *et al*. 2013)**
420		-40 %		
450			4-53y: -40 % 53-75y: -32 %	
455	+13 %			
460		-29 %		
500		-26 %		
528	-14 %			
540		-24 %		
580		-18 %		
590	-28 %			
657	+24 %			
Unknown				18 – 76y: -33 %

Table 5.1 presents lens transmission loss figures that contradict results achieved in the blue region (420 nm – 460 nm) when measuring "white perception" measurements. This phenomenon can thus not readily be explained by the yellowing of the crystalline lens of the older observers. It is possible that older observers are (without consciously doing so)

able to compensate for the spectral change in transmission of the crystalline lens when evaluating colours.

When considering detailed CRI, average CRI and special CRI values, the R_9 value features the largest difference for the two age groups (a value of 39 versus a value of -7). This is the value that may influence the design of an improved “reference source” most (Bailey 2013) The younger group of observers thus prefers a much lower value for “strong red”.

Another factor to be considered is that people from the younger group probably spend more time using tablets, smart phones, monitors, laptop computers and LED television screens. These devices all feature light sources with high components of blue. This may lead to a perception of white where yellow is less prominent.

5.3.2 Reference source matching test (split booth test procedure)

It was investigated whether the colour matching ability of people change as they grow older. Tables 4.5 to 4.6 and Figures 4.5 to 4.6 seem to prove that this is not the case. The colour selections chosen by both groups are very similar. Although thus far only a concept was investigated, the results are in agreement with those measured by Dorcus (1926) Dorcus used a number of colour samples and came to the conclusion that colour preference in age groups remains the same. The results, however, contrast with those achieved by Ou *et al.* (2012), who found that colour emotion may change as people grow older. They state that the reasons for this may include a number of factors such as different psychological environments and a change in social requirements applicable to different life stages.

When considering observer intensity selection at the four wavelengths, the biggest difference is recorded at 455 nm (11.3%). This test thus supports a loss of transmission at 455 nm.

5.3.3 Reference source matching test (side-by-side booth procedure)

With regard to colour matching, data presented in Tables 4.7 to 4.8 and Figures 4.7 to 4.8 agree with the conclusion reached in Section 5.2.2.

When considering observer intensity selection at the four wavelengths, the biggest difference is recorded at 455 nm (9.1%). This test thus also supports a loss of transmission at 455 nm.

5.3.4 Evaluation of split booth test procedure

The traditional method used in psychophysical evaluation has been the side-by-side booth method (as described in Sections 2.3 and 2.4.). This method has some practical application problems and a possible alternative method was designed, built and evaluated. Results achieved as measured for the group younger than 40 are presented in Tables 4.9 and 4.10 and Figures 4.9 and 4.10. Results measured for the group older than 50 are presented in Tables 4.11 to 4.12 and Figures 4.11 and 4.12. Colour perception differences between the two test methods are limited and it is therefore deduced that the split booth method is an acceptable alternative for the side-by-side method. The split booth is transportable (using a family wagon type vehicle), which offers the advantage that the test station can be used at schools or at any other observer group. A dark room is advisable but not necessary.

5.3.5 Repeatability of psychophysical evaluation for colour perception testing

Psychophysical testing methods are often used in the evaluation of colour perception and especially colour matching. The repeatability of results was measured using two different age groups of observers. Results achieved for the group younger than 40 are presented in Tables 4.13 and 4.14. Results measured for the group older than 50 are presented in Tables 4.15 and 4.16 and Figures 4.15 and 4.16. A summary is presented in Table 4.20. Colour matching of the younger group before and after one year yields similar results. X and y coordinates of matching sources on the CIE chromaticity diagram are close enough that two-step MacAdam ellipses overlap. Colour matching of the group older than 50 before and after one year shows greater variation. X and y coordinates of matching sources on the CIE chromaticity diagram are so far apart that three-step MacAdam ellipses just touch. The largest difference is the selection of intensity at 455 nm where the group older than 50 selected a result that differs significantly after a year. Blue (455 nm) perception of the older group is thus significantly different after one year. The difference of 7 of R_{12} (strong blue) points to a change in blue perception, since the older group selected a lower component of blue after one year.

5.4 CHAPTER SUMMARY

Results were discussed in this chapter.

- Section 5.3.1 showed that two different age groups selected two different light sources to achieve a “perception of white” when reflected light from an MCC is evaluated. The younger age group selected a source with a higher blue component than the older age group.
- Sections 5.3.2, 5.3.3 and 5.3.4 showed that the colour perception of both age groups is very similar. Results achieved with two alternative test-setups shows that the alternative setups can be used as alternative test methods, which may be of benefit when measurements have to be completed when a dark room is not available.
- Section 5.3.5 showed the result of colour perception testing, before and after one year. Whereas results of the younger group are consistent, those of the older group show significant change in colour perception before and after one year, which means that colour evaluation of the older group is not very repeatable.

CHAPTER 6 CONCLUSION

This study endeavoured to investigate the role of the reference source in improving the CRI for visual perception optimisation. As visual perception is a human trait, it also includes colour perception. Two psychophysical test methods were used for measurements. One method is an established way of measuring colour perception and an additional test method was developed for similar measurements but with practical advantages. Observers were divided into two age groups to investigate the effect of age on colour perception. A group of younger than 40 years, with an average age of 29, was used and an older group of older than 50 years, with an average age of 57.

Results can be summarised as follows:

- The two age groups were tasked to specify the most acceptable reference source to produce a perception of “white” when reflected light from an MCC test chart was considered. Specifications of the two sources differed substantially, with the older group selecting lower levels of blue (455 nm) and red (657 nm), while preferring more intense levels of green (528 nm) and orange (590 nm).
- It is a fact that human crystalline lens transmission decreases spectrally with age, especially in the blue (455 nm) region. This loss could not be verified in results obtained from colour perception and white perception changes, where the observer used the complete ocular optical system and not only the lens. It can thus be deduced that older observers cope well with the loss of lens transmission and are able to compensate for lens spectral transmission loss when evaluating colours.
- Colour perception of the younger group of observers is surprisingly similar to that of the older group of observers.
- Colour perception testing using the two different test methods yielded similar results, which means that the alternative design can be used in circumstances where portability is required or where it is difficult for specific observer groups to be transported to test facilities.

- When subjected to a colour matching procedure one year apart, the group younger than 40 selected two sources that were closely matched. The group older than 50 selected two sources with greater variation, especially in the blue (455 nm) spectral region. The group older than 50 selected a lower component of blue after one year.
- When specifying an alternative reference source in the measurement of the CRI the “white perception” test results dictated that two very different sources be specified. When considering the results of the “colour perception” tests, the role of the reference source seems to be similar for both age groups and a single source may be specified.

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ADDENDUM A: ORIGINAL DATA

Tables with raw data presenting concept evaluation as described in Section 4.2.

Table A1 Data for persons younger than 40 years of age used for white perception study.

Observer	Age	Sex	Race	White perception current (mA)			
				455 nm	528 nm	590 nm	657 nm
AS	23	F	W	40	85	100	122
BW	25	M	W	54	93	149	0
EVDB	28	M	W	34	85	92	91
HM	29	F	W	24	74	92	104
PS	31	F	B	126	74	0	360
NBJ	33	F	B	126	74	0	104
MS	33	F	W	109	104	149	122
JJN	35	M	W	34	74	100	0
CP	35	M	W	109	163	270	350
RF	36	F	W	34	74	112	104
TN	36	F	W	126	152	169	167
MBG	39	F	I	34	74	92	0
AVR	19	M	W	54	65	197	0
BP	19	F	B	34	74	270	0
JA	30	M	W	40	85	100	104
REN	20	M	B	24	74	149	0
NN	19	F	B	126	65	92	0
Average	**28.82353**			**66.35294**	**87.58824**	**125.4706**	**95.76471**

Table A2 Data for persons older than 50 years of age used for white perception study.

Observer	Age	Sex	Race	White perception current (mA)			
				455 nm	528 nm	590 nm	657 nm
HLG	50	M	W	54	74	270	91
CB	51	M	W	126	152	340	0
DB	53	M	W	109	163	169	104
MD	53	F	W	64	116	169	250
AJP	54	M	W	47	116	197	0
PAHG	54	M	W	34	65	350	0
DFV	55	M	W	40	93	112	104
HVDB	56	F	W	54	85	112	0
JW	58	M	W	109	152	340	250
PVS	59	M	W	0	65	92	0
CVDB	59	M	W	24	74	149	0
LK	60	M	W	24	65	92	91
PCM	60	M	W	72	152	112	191
DM	61	M	W	109	163	112	0
JBL	63	M	W	34	93	112	91
LPB	63	M	W	109	138	149	0
AC	53	M	W	40	85	100	104
EC	66	M	W	24	65	92	91
SW	66	M	W	40	116	270	0
Average	**57.57895**			**58.57895**	**106.9474**	**175.7368**	**71.94737**

Table A3 Data for persons younger than 40 years of age used for colour matching study using the split booth method.

Observer	Age	Sex	Race	Split booth current (mA)			
				455 nm	528 nm	590 nm	657 nm
AS	23	F	W	24	65	169	191
BW	25	M	W	24	138	350	360
EVDB	28	M	W	24	138	350	360
HM	29	F	W	24	152	350	360
PS	31	F	B	0	65	350	191
NBJ	33	F	B	24	116	350	360
MS	33	F	W	24	163	350	360
JJN	35	M	W	24	65	169	0
CP	35	M	W	24	74	112	122
RF	36	F	W	34	74	112	91
TN	36	F	W	24	65	340	360
MBG	39	F	I	24	116	350	280
AVR	19	M	W	24	116	350	280
BP	19	F	B	24	93	270	191
JA	30	M	W	24	116	340	250
REN	20	M	B	54	116	350	143
NN	19	F	B	24	104	112	360
Average	**28.82353**			**24.94118**	**104.4706**	**280.8235**	**250.5294**

Table A4 Data for persons older than 50 years of age used for colour matching study using the split booth method.

Observer	Age	Sex	Split booth current(mA)			
			455 nm	528 nm	590 nm	657 nm
HLG	50	M	24	152	350	360
CB	51	M	24	116	340	280
DB	53	M	0	65	169	143
MD	53	F	47	85	92	280
AJP	54	M	47	74	350	360
PAHG	54	M	47	65	340	91
DFV	55	M	24	138	350	360
HVDB	56	F	24	152	340	360
JW	58	M	24	74	340	191
PVS	59	M	0	163	169	360
CVDB	59	M	24	138	340	167
LK	60	M	34	74	149	122
PCM	60	M	24	116	340	250
DM	61	M	24	152	340	360
JBL	63	M	24	85	340	91
LPB	63	M	24	104	169	360
AC	53	M	24	116	340	250
EC	66	M	24	93	340	360
SW	66	M	34	138	350	250
Average			**26.15789**	**110.5263**	**292**	**262.8947**

Table A5 Data for persons younger than 40 years of age used for colour matching study using the side-by-side booth method.

Observer	Age	Sex	Race	Side-by-side booth. Test source right.			
				Test source current (mA)			
				455 nm	528 nm	590 nm	657 nm
NBJ	33	F	B	24	116	350	250
TN	36	F	W	24	93	350	250
JJN	35	M	W	24	85	340	122
CP	35	M	W	24	116	350	167
MS	33	F	W	24	116	340	280
BW	26	M	W	24	138	350	360
HM	29	F	W	24	138	340	360
CF	39	M	W	24	116	340	191
AS	23	F	W	24	85	270	250
RF	36	F	W	24	138	270	167
EVDB	28	M	W	24	116	350	250
MBG	39	F	I	24	152	340	360
AVR	19	M	W	24	138	350	0
JA	30	M	W	24	85	340	143
JJ	27	M	I	34	40	350	250
TH	24	M	I	24	104	350	280
JB	28	M	W	72	104	350	250
DLF	28	F	W	24	163	350	360
SB	17	M	W	24	116	350	280
MS	28	F	C	24	93	340	122
SN	28	F	W	24	138	340	360
LT	24	M	W	40	116	270	250
EC	35	M	W	24	138	350	280
Average	**29.56522**			**27.21739**	**114.9565**	**336.087**	**242.6957**

Table A6 Data for persons older than 50 years of age used for colour matching study using the side-by-side booth method.

Observer	Age	Sex	Race	Side-by-side booth. Test source right.			
				Test source current (mA)			
				455 nm	528 nm	590 nm	657 nm
JW	58	M	W	24	116	350	280
PVS	59	M	W	24	138	350	360
PCM	60	M	W	24	116	350	250
AJP	54	M	W	24	85	270	143
CVDB	59	M	W	24	93	340	167
DM	61	M	W	64	116	100	280
EM	66	M	W	24	85	340	280
SW	66	M	W	24	152	340	360
DB	53	M	W	34	138	350	360
MD	53	F	W	72	104	270	280
CB	51	M	W	24	138	350	360
JBL	63	M	W	24	85	197	191
LPB	63	M	W	24	93	340	167
DFV	55	M	W	24	65	149	122
HVDB	56	F	W	24	104	340	280
HLG	50	M	W	24	138	350	360
LK	60	M	W	34	74	149	91
PAHG	54	M	W	24	163	350	360
AC	53	M	W	24	138	350	0
DJVR	50	M	W	24	104	340	250
Average	**57.2**			**29.4**	**112.25**	**298.75**	**247.05**

Table A7 Data for persons younger than 40 years of age used for colour matching study using the side-by-side booth method with readings taken one year apart.

Observer	Age	Sex	Race	Year 1 current (mA)				Year 2 current (mA)			
				455 nm	528 nm	590 nm	657 nm	455 nm	528 nm	590 nm	657 nm
NBJ	33	F	B	24	116	350	250	24	74	350	104
TN	36	F	W	24	93	350	250	24	93	350	191
CP	35	M	W	24	116	350	167	24	138	350	280
MS	33	F	W	24	116	340	280	24	104	340	122
BW	26	M	W	24	138	350	360	24	138	350	280
HM	29	F	W	24	138	340	360	24	116	350	280
CF	39	M	W	24	116	340	191	24	93	350	250
AS	23	F	W	24	85	270	250	24	104	350	250
RF	36	F	W	24	138	270	167	24	138	270	280
EVDB	28	M	W	24	116	350	250	24	138	350	280
MBG	39	F	I	24	152	340	360	24	163	340	360
JA	30	M	W	24	85	340	143	34	138	270	360
TH	24	M	I	24	104	350	280	34	138	350	360
JB	28	M	W	72	104	350	250	24	138	340	360
DLF	28	F	W	24	163	350	360	24	152	340	360
MS	28	F	C	24	93	340	122	24	163	340	360
SN	28	F	W	24	138	340	360	24	138	340	360
LT	24	M	W	40	116	270	250	24	138	350	360
Average	**30.38889**			**27.55556**	**118.1667**	**332.7778**	**258.3333**	**25.11111**	**128**	**337.7778**	**288.7222**

Table A8 Data for persons older than 50 years of age used for colour matching study using the side-by-side booth method with readings taken one year apart.

Observer	Age	Sex	Race	Year 1 current (mA)				Year 2 current (mA)			
				455 nm	528 nm	590 nm	657 nm	455 nm	528 nm	590 nm	657 nm
JW	58	M	W	24	116	350	280	24	85	112	191
PVS	59	M	W	24	138	350	360	24	65	92	122
PCM	60	M	W	24	116	350	250	24	116	350	250
AJP	54	M	W	24	85	270	143	24	85	169	167
CVDB	59	M	W	24	93	340	167	24	138	350	167
DM	61	M	W	24	152	340	360	24	138	340	280
EM	66	M	W	24	85	163	74	24	163	350	360
SW	66	M	W	24	152	340	360	24	163	350	360
MD	53	F	W	72	104	270	280	24	74	112	143
CB	51	M	W	24	138	350	360	24	152	350	360
JBL	63	M	W	24	85	197	191	24	93	340	191
LPB	63	M	W	24	93	340	167	24	163	350	360
DFV	55	M	W	24	65	149	122	24	104	350	167
HVDB	56	F	W	24	104	340	280	24	152	350	360
HLG	50	M	W	24	138	350	360	24	138	340	280
LK	60	M	W	34	74	149	91	24	65	350	104
PAHG	54	M	W	24	163	350	360	24	152	340	360
AC	53	M	W	24	138	350	0	24	152	340	360
DJVR	50	M	W	24	104	340	250	24	116	350	191
JCB	58	M	W	34	93	270	250	24	138	350	250
FO	55	M	W	95	152	270	280	54	116	340	191
SDT	55	M	W	24	138	350	280	24	93	350	191
PS	58	M	W	24	65	169	167	24	138	340	280
Average	**57.26087**			**30.04348**	**112.6522**	**293.3478**	**236.1739**	**25.30435**	**121.6957**	**307.1739**	**247.1739**

ADDENDUM B: STATISTICAL ANALYSIS

This appendix shows student t probability mass functions for results presented in Section 4.2. The x-axis of each graph shows CRI R_i values. These values are the special colour-rendering index values, which consist of a set of values R_i ranging from R_1 to R_{15}. The sources selected by the two groups of observers were measured using a spectrophotometer. Some of the results measured by the spectrophotometer form a set of results that yields the CRI R_i values. The values can range from 0 to 100, although negative values may also be possible.

B1 WHITE PERCEPTION TEST

Figure B1 shows the student t probability mass function of sampled CRI R_i values for the two age groups when evaluating the perception of white. These values are drawn in Figure B1 for each group of observers. The solid line shows the results for the under-40 group, with a variation from 58 to 89. The dotted line shows the results for the over-50 group, but with a variation from 74 to 92. Each R_i value is plotted on the graph. When a specific R_i value is chosen repeatedly, the value on the y-axis increases. One can thus see that the under-40 group selected a source where most of the R_i values were at the peak, around 73. The over-50 group selected a source where most of the R_i values were at the peak, around 83. These are not R_a values, as only the first eight R_i values are used to calculate R_a. It is nevertheless interesting to note that the two R_a values were measured to be 74 and 89. From the graph shapes, one can also see that the variation of selected choice in the under-40 group is wider than in the over-50 group. As the peak graph grows wider, variance increases. This graph is known as the probability mass function (PMF). The t-distribution was used to deduce the level of confidence in any given range that would contain the true mean. The probability density function (PDF) is related but uses continuous instead of discrete values, The graph thus show the point values on the R_i scale where a specific group of observers is likely to select a source with values in that area. When considering the “over-50”graph, it can be established that the probability of the over-50 group to select an R_i value of 87 is 0.37 (or 37%).

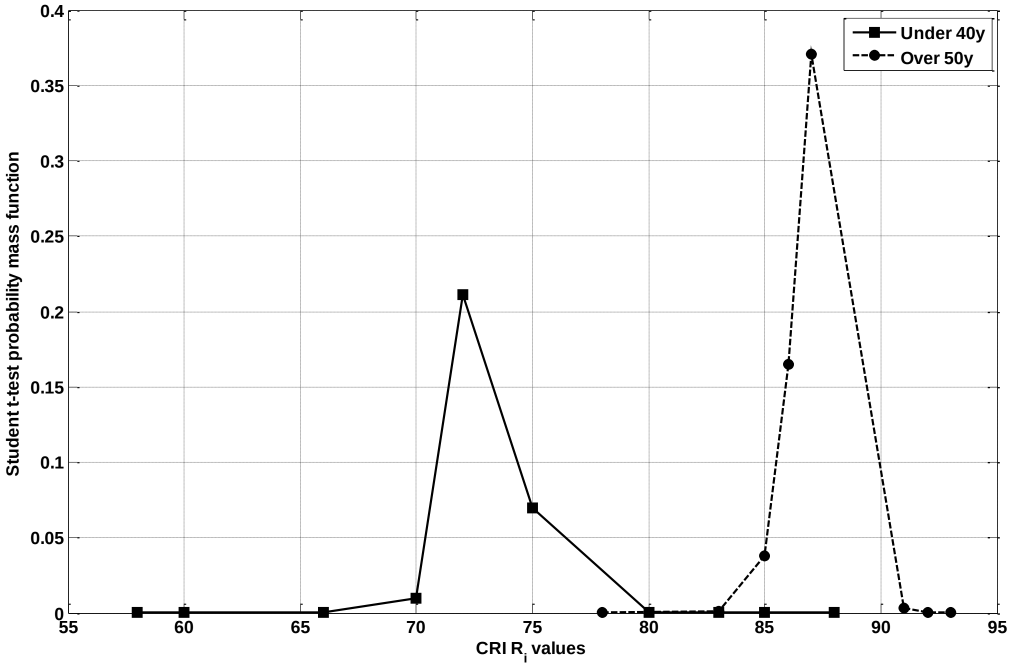

Figure B1. The student t probability mass function of sampled CRI R_i values for the two age groups when evaluating white perception

B2 REFERENCE SOURCE MATCHING TEST (SPLIT BOOTH TEST PROCEDURE)

Figure B2 shows the student t probability mass function of sampled CRI R_i values for the two age groups when a reference source matching test is completed using the split booth test procedure. These values are drawn in Figure B2 for each group of observers. The solid line shows the results for the under-40 group with a variation from 53 to 98. The dotted line shows the results for the over-50 group, but with a variation from 53 to 96. Each R_i value is plotted on the graph. When a specific R_i value is chosen repeatedly, the value on the y-axis increases. One can thus see that the under-40 group selected a source where most of the R_i values were at the peak, around 85. The over-50 group selected a source where most of the R_i values were at the peak, also around 85. These are not R_a values, as only the first eight R_i values are used to calculate R_a. The two R_a values were measured as 88 and 89 respectively. From the graph shapes, one can also see that the variation of selected choice in the under-40 group is similar to that in the over-50 group. As the peak graph grows wider, variance increases. This graph is known as the PMF. The t-distribution was used in order to deduce the level of confidence within any given range that would contain the true mean. The PDF is related but uses continuous instead of discrete values. The graph thus shows the point values on the R_i scale where a specific group of observers is likely to select a source with values in that area. When considering the "over-50"graph, it can be established that the probability of the over-50 group to select an R_i value of 85 is 0.29 (or 29%). The probability of the under-40 group to select an R_i value of 85 is 0.36 (or 36%).

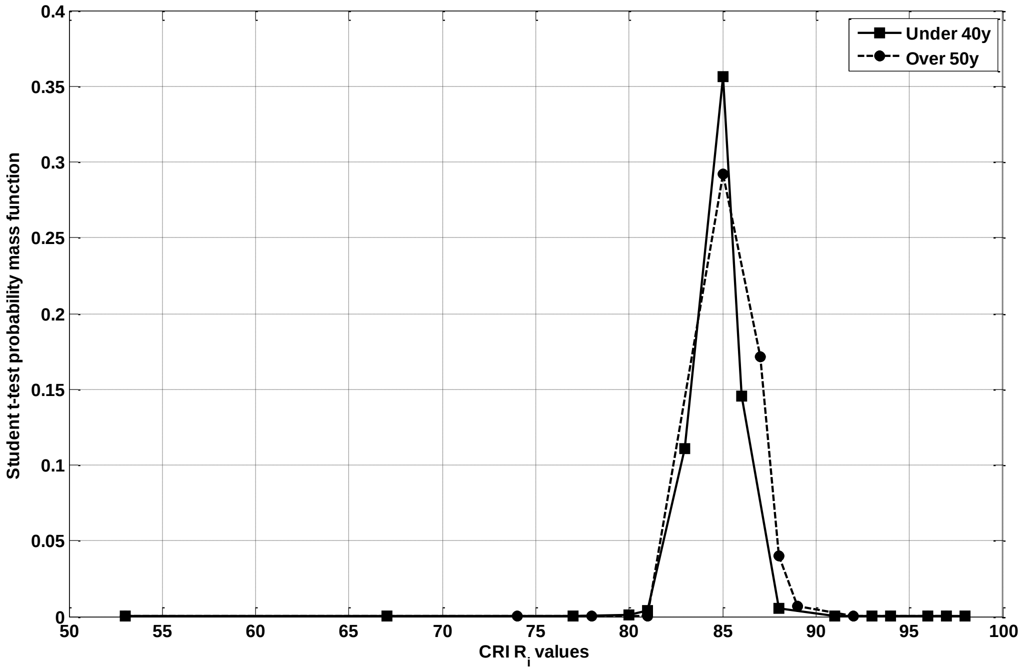

Figure B2. The student t probability mass function of sampled CRI Ri values for the two age groups when completing a reference source matching test using the split booth test procedure.

B3 REFERENCE SOURCE MATCHING TEST (SIDE-BY-SIDE TEST PROCEDURE)

Figure B3 shows the student t probability mass function of sampled CRI Ri values for the two age groups when a reference source matching test is completed using the side-by-side test procedure. These values are drawn in Figure B3 for each group of observers. The solid line shows the results for the under-40 group with a variation from 59 to 96. The dotted line shows the results for the over-50 group, but with a variation from 53 to 97. Each R_i value is plotted on the graph. When a specific R_i value is chosen repeatedly, the value on the y-axis increases. One can thus see that the under-40 group selected a source where most of the R_i values were at the peak, around 88. The over-50 group selected a source where most of the R_i values were at the peak, around 86. These are not R_a values, as only the first eight R_i values are used to calculate R_a. The two R_a values were measured to be 91 and 89 respectively. From the graph shapes, one can also see that the variation of selected choice in the under-40 group is similar to that in the over-50 group. As the peak graph grows wider, variance increases. This graph is known as the PMF. The t-distribution was used to deduce the level of confidence within any given range that would contain the true mean. The PDF is related but uses continuous instead of discrete values. The graph thus shows the point values on the R_i scale where a specific group of observers is likely to select a source with values in that area. When considering the “over-50”graph, it can be established that the probability of the over-50 group to select an R_i value of 86 is 0.37 (or 37%). The probability of the under-40 group to select an R_i value of 88 is 0.38 (or 38%).

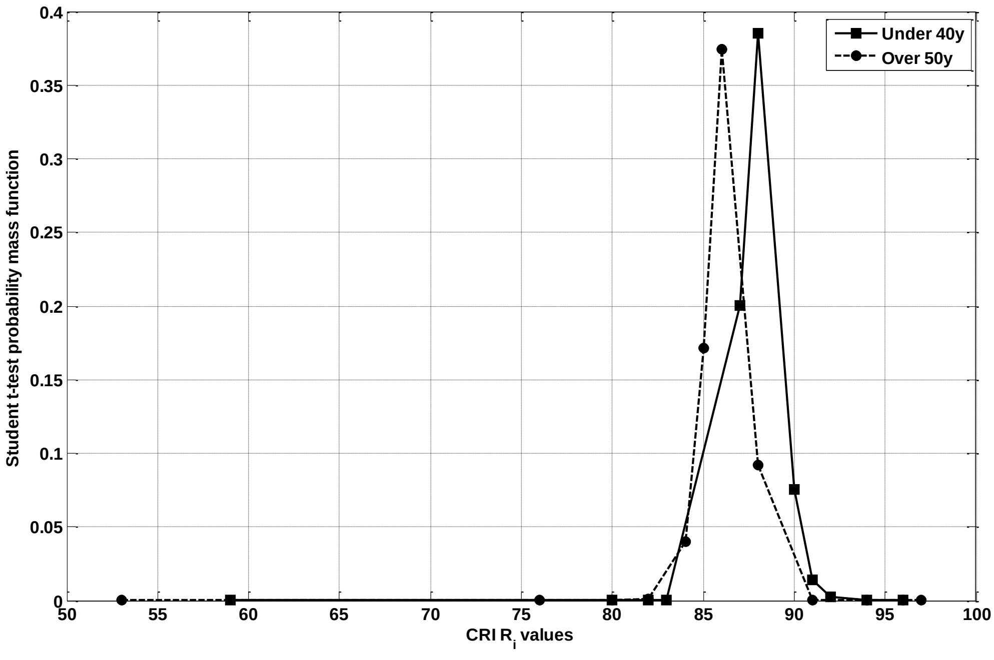

Figure B3. The student t probability mass function of sampled CRI R_i values for the two age groups when completing a reference source matching test using the side-by-side booth test procedure.

B4 REFERENCE SOURCE MATCHING TEST COMPARISON (SIDE-BY-SIDE TEST PROCEDURE COMPARED WITH SPLIT BOOTH TEST PROCEDURE)

Figures B4 and B5 display the student t PMF as a function of the sampled CRI R_i values for both age groups when completing a reference source matching test and using two different test methods. The values are drawn in Figures B4 and B5 for each group of observers.

Figure B4. The under-40 group. A variation of R_i value from 53 to 98 was measured for the split booth method, as shown by the solid line. The dotted line shows the results of the side-by-side booth method with a variation from 59 to 96. These are not R_a values, as only the first eight R_i values are used to calculate R_a. The two R_a values were measured to be 88 and 91 for the split booth and side-by-side booth. When a specific R_i value is chosen repeatedly, the value on the y-axis increases.

Figure B5. The over-50 group. A variation of Ri value from 53 to 97 was measured for the split booth method, as shown by the solid line. The dotted line shows the results of the side-by-side booth method with a variation from 53 to 97. These are not R_a values, as only the first eight R_i values are used to calculate R_a. The two R_a values were measured to be 89 and 89 for both methods. When a specific R_i value is chosen repeatedly, the value on the y-axis increases.

These graphs are known as the PMF. (The PDF is related but uses continuous instead of discrete values.) The graphs thus show the point values on the R_i scale where a specific group of observers is likely to select a source with values in that area. The probability of a specific observer group to select a source with specific R_i values can be read from Figures B4 and B5. When considering Figure B4 and reading on the “split booth” graph, it can be established that the probability of the group younger than 40 to select an R_i value of 85 is 0.36 (or 36%).

Although the change in R_a values of both age groups are not significant, the change variance of selected R_i values is relatively large. At the beginning of the year, the under-40 age group selected a source with an R_a value of 92 and after a year the value was 90. The variance in R_i values changed from 32 to 45. The group older than 50 selected a source with an R_a of 91 at the beginning of the year and a value of 93 after one year. The variance in R_i values changed from 18 to 38.

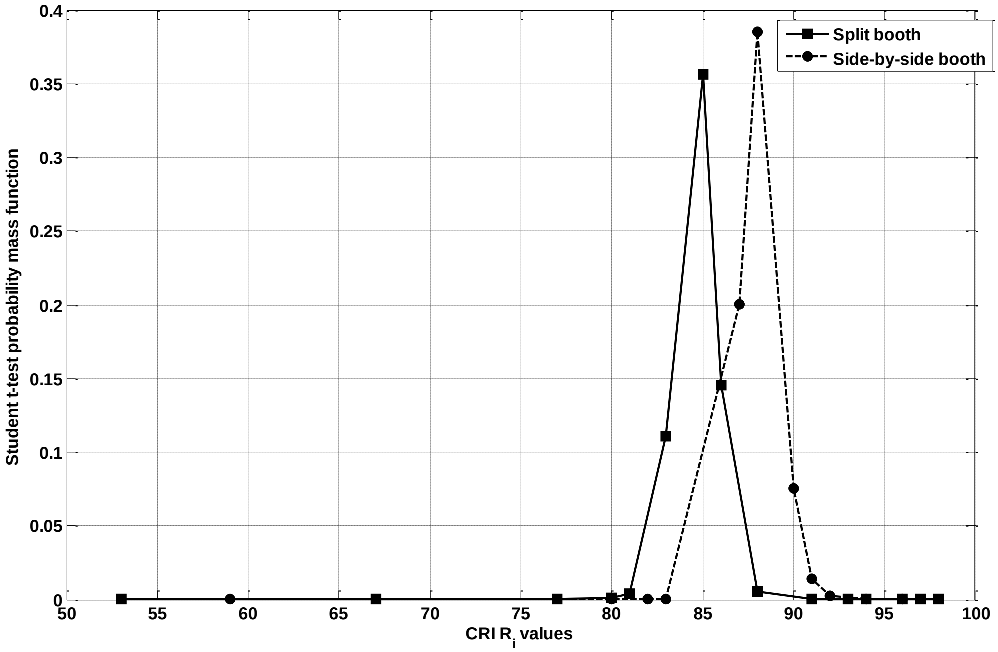

Figure B4. The student t probability mass function of sampled CRI Ri values for the age group younger than 40 when completing a reference source matching test and comparing the side-by-side booth test procedure with the split booth test procedure.

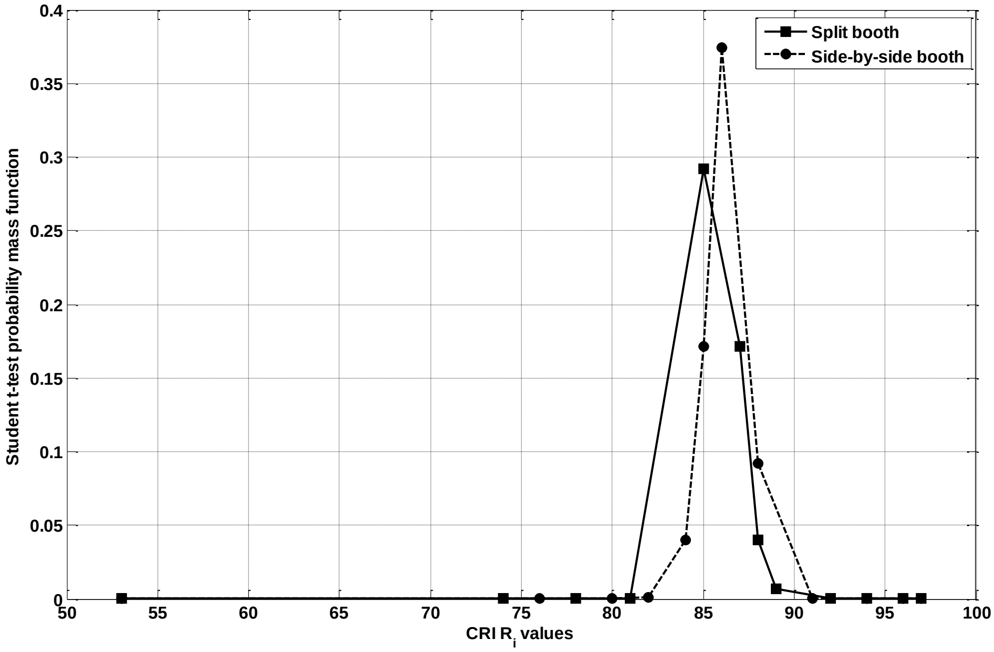

Figure B5. The student t probability mass function of sampled CRI R_i values for the age group older than 50 when completing a reference source matching test and comparing the side-by-side booth test procedure with the split booth test procedure.

B5 REFERENCE SOURCE MATCHING TEST PROCEDURE BEFORE AND AFTER ONE YEAR

Figures B6 and B7 display the student t PMF as function of the sampled CRI R_i values for both age groups and with observer group evaluations one year apart. The values are drawn in Figures B6 and B7 for each group of observers.

Figure B6. The solid line shows the results for the under-40 group at the beginning of the year. A variation of R_i value from 59 to 97 was measured. The dotted line shows the results after one year with a variation from 52 to 97. These are not R_a values, as only the first eight R_i values are used to calculate R_a. The two R_a values were measured to be 97 and 93 for the beginning and end of year measurements. When a specific R_i value is chosen repeatedly, the value on the y-axis increases.

Figure B7. The solid line shows the results for the over-50 group at the beginning of the year. A variation of R_i value from 56 to 97 was measured. The dotted line shows the results after one year with a variation from 60 to 98. These are not R_a values, as only the first eight R_i values are used to calculate R_a. The two R_a values were measured to be 91 and 93 for the beginning and end of year measurements. When a specific R_i value is chosen repeatedly, the value on the y-axis increases.

These graphs are known as the PMF. (The PDF is related but uses continuous instead of discrete values) The graphs thus show the point values on the R_i scale where a specific group of observers is likely to select a source with values in that area. The probability of a specific observer group to select a source with specific R_i values can be read from Figures B6 and B7. When considering Figure B6 and reading on the “Year 2” graph, it can be established that the probability of the group younger than 40 to select an R_i value of 90 is 0.36 (or 36%).

Although the change in R_a values of both age groups are not significant, the change variance of selected R_i values is relatively large. At the beginning of the year, the under-40 age group selected a source with an R_a value of 97 and after a year the value was 93. The variance in R_i values changed from 38 to 45. The group older than 50 selected a source with an R_a of 91 at the beginning of the year and a value of 93 after one year. The variance in R_i values changed from 41 to 38.

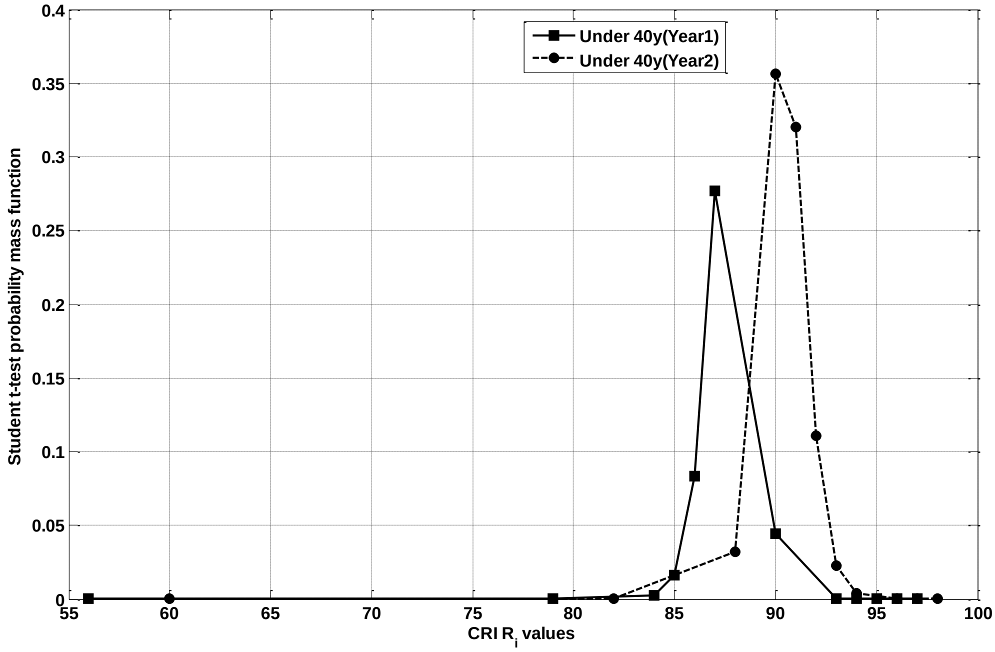

Figure B6. Student t probability mass function of sampled CRI R_i values for the age group younger than 40 and evaluated one year apart.

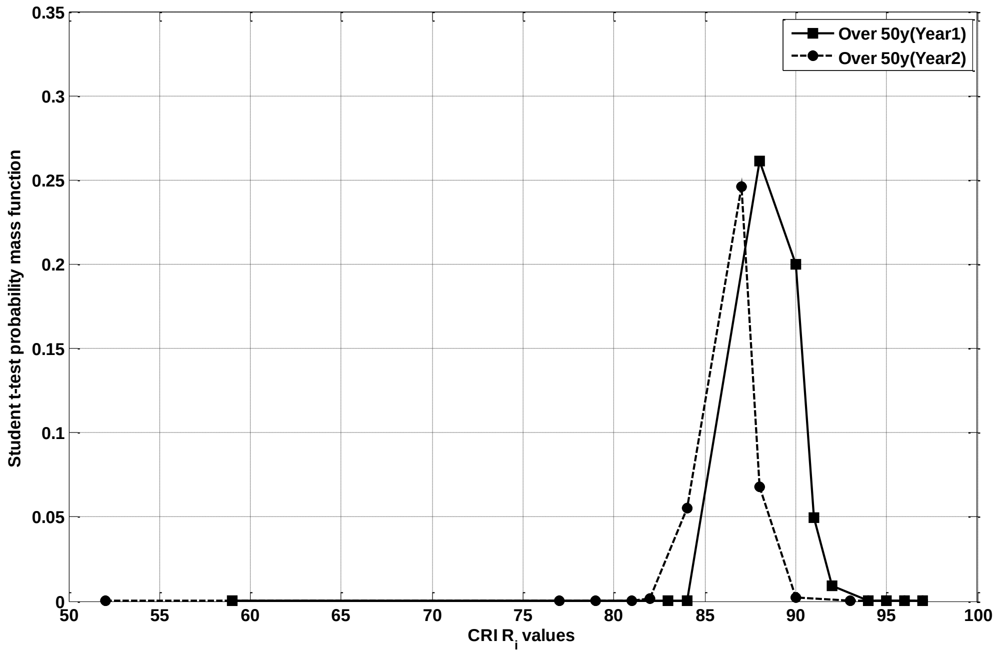

Figure B7. Student t probability mass function of sampled CRI R_i values for the age group older than 50, evaluated one year apart.

ADDENDUM C: TEST BOOTH SURFACE CHARACTERISTICS

The inside surface of the test booths are covered with white paint; which was measured to feature a reflectivity of better than 90% from 420 to 800 nm. It is necessary to ensure that reflectivity is spectrally constant and that surface characteristics remains unchanged for all measurements. The reflectivity graph is shown in Figure C1.

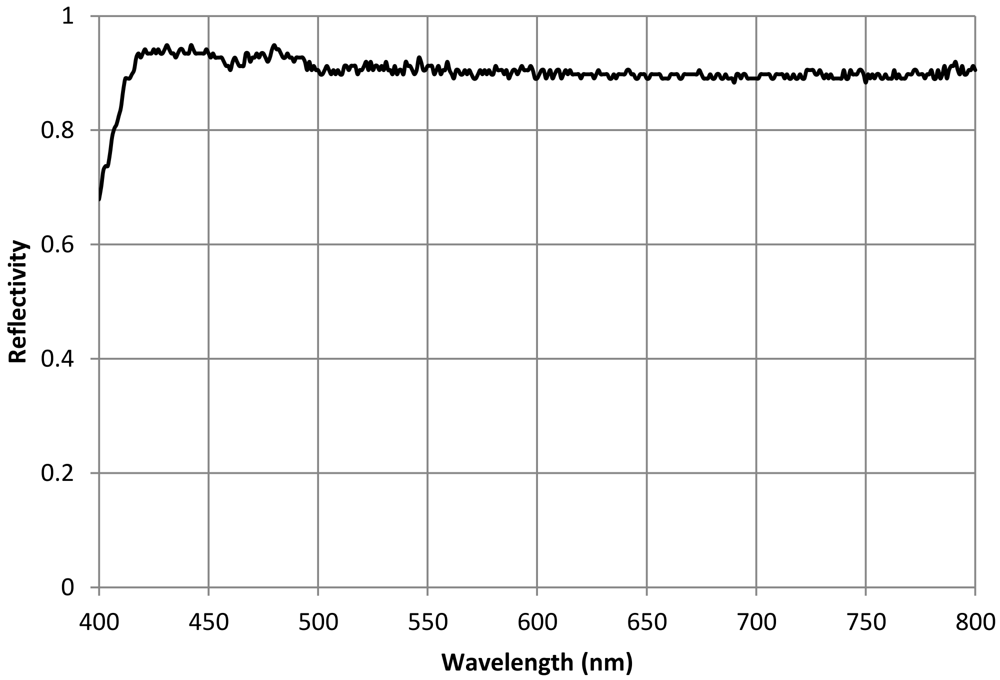

Figure C1. Inside test booth surface spectral reflectivity. (Reflectivity values are absolute.)

ADDENDUM D: PHOTOS

This section presents colour photos in an effort to practically illustrate the difference in white perception regarding age. (Bearing in mind that colour reproduction processes may not yield a true-colour experience to the reader) Figure D1 shows the inside of the test booth which is populated with various objects generally regarded as “white”. (Paper, polystyrene, carton, porcelain and foam.) The objects are illuminated by light sources selected by two age groups to yield a “perception of white”.

Figure D1. Test booth on the left is illuminated by a source selected by the under-40 group as yielding “white” light. It shows a higher component of blue. The test booth on the right is illuminated by a source selected by the over-50 group as yielding “white” light. It shows a smaller component of blue and a larger component of yellow.

Figure D2 shows results achieved when using the Macbeth Colour Checker (MCC) and illuminated by two different sources as selected by two different age groups.

Figure D2. MCC on the left is illuminated by a source selected by the under-40 group as yielding “white” light. It shows vivid blue and purple coloured blocks while red, yellow and orange seems to be less saturated.. The MCC on the right is illuminated by a source selected by the over-50 group as yielding “white” light. It shows saturated orange, red and yellow while blue and purple appears to be less saturated.

ADDENDUM E: FUTURE RESEARCH

E1 METHOD

One certainty in the engineering world is that all designs can be improved. This study presented an improved design of the traditional side-by-side test booth method. This design can also be improved and a basic layout is presented in Figure E1.

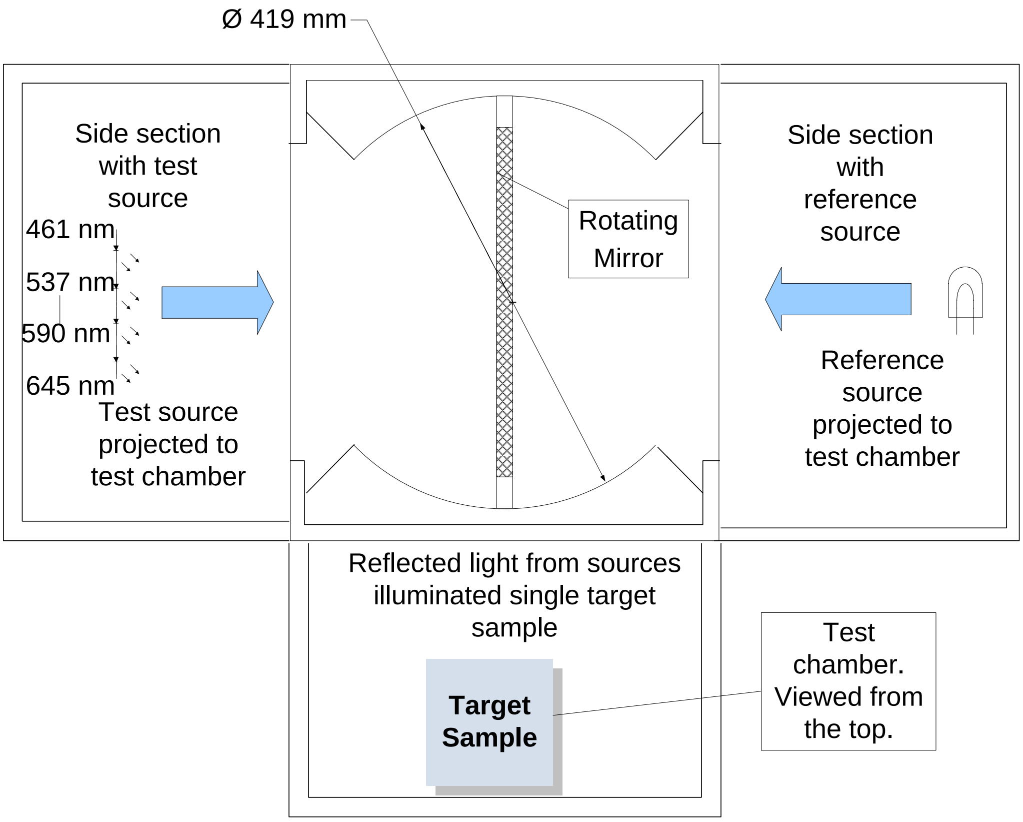

Figure E1. Test booth design with common illuminated test chamber.

The rotating mirror setup of Section 3.2.6 is retained. The method described in this section is expanded and a common "test chamber" is added to the design. Either the reference source or the test source can be used to illuminate the sample in the test chamber.
Only one target sample is used, to improve commonality. The observer simply looks into the test chamber and evaluates lighting as applied to the sample.

Both test and reference chambers are fitted with domed roofs in an effort to integrate light from test and reference sources. Construction is only moderately more complicated than the unit built and used in this study. In order to achieve minimum light levels, sources with increased emitted intensity should be used.

E2 OBSERVER SAMPLE SIZE

Section 3.5.1 of this document provides a calculation for determining the minimum observer sample size. A figure of 384 is calculated. This study used an observer sample size that is much smaller. Some reasons are provided in the section mentioned. As also shown in Table 3.2, a number of comparable studies actually used even larger sample sizes. It is suggested, however, that better understanding of colour perception of different ages can be gained by using a much larger sample size, at least as calculated in the region of 400 persons. It would be even better if an observer sample size of 400 per age group can be used.