2015

# On a New Method for Interior Lighting Design

James Duff
*Technological University Dublin*, james.duff@arup.com

# On a new method for interior lighting design


James Duff

*Doctor of Philosophy (Ph.D.)*

Dublin Institute of Technology

Dr Kevin Kelly

Mr Christopher Cuttle

Prof Gerald Farrell

School of Multidisciplinary Technologies


December 2015

I certify that this thesis which I now submit for examination for the award of Doctorate of Philosophy, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work. This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for another award in any other third level institution. The work reported on in this thesis conforms to the principles and requirements of the DIT's guidelines for ethics in research.

DIT has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

Signed:………………………………………………………………………

Date:…………………………………………………………………………

# Abstract

In 2009, Christopher Cuttle began to challenge the suitability of the metrics contained within current lighting design standards and guidance. In short, Cuttle proposed a move away from providing an amount of light that relates to the difficulty of a visual task and instead, providing an amount of light that relates to the brightness of a space. This sense of brightness would be estimated by a new lighting metric, Mean Room Surface Exitance. The research presented in this thesis strove to examine, critically evaluate, analyse and investigate the merit of changing indoor lighting standards to include Mean Room Surface Exitance. More specifically, the research examined the following:

- To address issues surrounding derivation and calculation of Mean Room Surface Exitance, Cuttle's proposed formula to calculate Mean Room Surface Exitance was critically examined and found to be erroneous under certain conditions, with an alternative formula being developed, proposed and validated as part of this research.
- To address the issue with computation, a script was developed and validated as part of this research and this script allows calculation and computation of Mean Room Surface Exitance through currently available freeware.
- To facilitate measurement of Mean Room Surface Exitance in the field, a script was written and validated and this script can be applied, in conjunction with High Dynamic Range imaging technology, to easily, quickly and accurately record measurements once an installation is complete.
- To examine the relationship between Mean Room Surface Exitance and brightness, three experiments were set up that exposed a group of participants to a range of levels of Mean Room Surface Exitance, with each level delivered across a number of variables that would be experienced in practice. Generally, a linear relationship was found to exist between the level of Mean Room Surface Exitance and the subjective response to brightness.
- To investigate the relationship between Mean Room Surface Exitance and perceived lighting quality, two experiments were conducted. These demonstrated a strong correlation between the reported perceived brightness and the reported satisfaction with lighting quality. However, this relationship changed when participants were exposed to light scenes that contained extreme non-uniform light distributions; suggesting that whilst the space was bright enough, there is more to good lighting quality than brightness.

Each of the above is a distinct contribution to existing knowledge, but also the first step in a number of different directions, with each moving towards the possible widespread application of MRSE in lighting practice at some stage in the near future.

# Acknowledgements

The candidate would like to acknowledge the following people, whom in their own way, enhanced the quality, rigour, accuracy and ultimately the impact of the research presented within this thesis.

- Dr Kevin Kelly
- Mr Christopher Cuttle
- Dr Santiago Torres
- Mr Giulio Antonutto
- Mr Eamonn Murphy
- Mr Anselm Griffin
- Ms Mona Holtkoetter
- Prof Aidan Duffy
- Prof Gerald Farrell
- Prof Jonathan Blackledge
- Prof Eugene Coyle

# List of Acronyms

| | |
|---|---|
| MRSE | Mean Room Surface Exitance |
| PAI | Perceived Adequacy of Illumination |
| DALI | Digital Addressable Lighting Interface |
| DSI | Digital Serial Interface |
| PWM | Pulse Width Modulation |
| $R_a$ | Colour Rendering Index |
| CCT | Correlated Colour Temperature |
| HDR | High Dynamic Range |
| TAIR | Target / Ambient Illumination Ratio |
| IH | Illumination Hierarchy |
| FRF | First Reflected Flux |
| ANOVA | Analysis of Variance |
| SPSS | Statistical Package for the Social Sciences |
| SPD | Spectral Power Distribution |

# Contents

## Tables

## Figures

Figure 21 The mean spatial brightness response rate plotted against the relative level of mean room surface exitance for each light scene presented.

Figure 22 The mean spatial brightness response rate plotted against the relative level of horizontal illuminance for each light scene presented.

# 1 Thesis introduction

## 1.1 Source acknowledgement

Whilst the work contained within the thesis is entirely that of the candidates', a number of passages have been quoted verbatim from the following sources:

Duff J and Kelly K. A new approach to interior lighting design: Early stage research in Ireland. *Journal of Sustainable Engineering Design*: 2014. Vol. 1: Iss. 4. pp. 13-19.

Duff J. Research Note: On the magnitude of error in a formula to calculate mean room surface exitance. *Lighting Research and Technology*. In Press.

Duff J, Antonutto G and Torres S. On the calculation of mean room surface exitance. *Lighting Research and Technology*. First published 1 July, 2015, doi:10.1177/1477153515593579.

Duff J, Cuttle C and Kelly K.  Spatial brightness, horizontal illuminance and mean room surface exitance in a lighting booth. *Lighting Research and Technology*. First published 31 July, 2015, doi:10.1177/1477153515597733.

Duff J, Cuttle C and Kelly K.  Perceived adequacy of illumination, spatial brightness, horizontal illuminance and mean room surface exitance in a small office. *Lighting Research and Technology*. First published 2 September, 2015, doi:10.1177/1477153515599189.

Duff J, Cuttle C and Kelly K.  Spatial brightness, perceived adequacy of illumination, horizontal illuminance and mean room surface exitance in non-uniform light scenes. *Lighting Research and Technology*. In press.

Duff J and Kelly K. 500 lux, or something else? *Journal of Sustainable Engineering Design*: 2015. Vol. 1: Iss. 5. In Press.

## 1.2 Context

Similar to most disciplines in construction, current lighting design practice is typically governed by a range of guidance documents and standards, with each of these recommending a number of criteria that should be applied to ensure the safety and satisfaction of building occupants. In 2009, the first in what would be a series of journal papers, trade articles and discussions emerged and this explicitly stated concerns with the methods, criteria and values that are contained within current indoor lighting design standards. These concerns were voiced by Christopher Cuttle and were centred on an argument that current standards do little to relate lighting to a human response and as such, are inappropriate for ensuring a given level of subjective lighting quality. In short, Cuttle proposed a move away from providing an amount of light that relates to the difficulty of a visual task and instead, providing an amount of light that relates to the brightness of a space, or providing an amount of light that makes a space feel bright enough. To relate lighting to the perceived brightness of a space, Cuttle proposed a new lighting metric which he called mean room surface exitance (MRSE).

## 1.3 Aims and Objectives

Cuttle's proposals detailed an alternative methodology for designing artificial lighting within interiors and the PhD research set out to scrutinise and evaluate these proposals. More specifically, the research strove to examine, critically evaluate, analyse and investigate the merit of changing indoor lighting standards from where they currently sit, to this newly suggested approach that might better relate to a human response and in turn, improve the perceived quality of general lighting installations. Chapter 2 outlines in more detail the topic background, surrounding literature, further defines the need for this research and presents the research questions and sets out the thesis structure, but the main items this research aims to address are briefly described in the paragraphs following.

The research was broadly split across two distinctly different aspects, but with both aspects seeking to determine if MRSE is appropriate for use within lighting design practice. The first focused on how MRSE is derived, calculated, computed and measured and the second investigated the human response to MRSE, with a focus on how people related levels of it to their estimation of brightness and the quality of lighting.

Derived from a thought experiment, Cuttle proposed a formula that can be used to calculate MRSE. This research set out to critically examine this formula and investigate if it is the most accurate and practical manner in which to compute MRSE in practice.

Currently available lighting analysis software packages do not facilitate the calculation or direct computation of MRSE. A further objective of this research was to develop a script that can be run within current lighting analysis software engines to calculate MRSE.

Measuring MRSE in the field requires hundreds of measurements to document even a small space and this was considered a severe limitation of the metric. This research set out to investigate, develop and test a new script and methodology to measure MRSE in the field using HDR camera technology that would mitigate this limitation.

Cuttle argued that as visual tasks have become easier in recent years (e.g. with self-luminous screens or the disappearance of a fifth carbon copy), the prime function of lighting should move away from providing an amount of light that equates to the difficulty of the visual task and focus instead on providing an amount of light that relates to the brightness of a space. This research set out three experiments that examined the influence of MRSE on assessments of brightness under a range of different conditions typically experienced in practice, such as surface reflectance and light distribution. These experiments also compared how this new metric performed against the most widely used lighting metric currently, being the quantity of light on a horizontal plane.

In addition to relating lighting to brightness, Cuttle also proposed that a given level of MRSE would relate the feeling of the lighting in a space being appropriate or inappropriate, or more generally, that MRSE could be a high level predictor of lighting quality. This research set up two studies that examined the relationship between MRSE and this feeling of the lighting in a space being appropriate or inappropriate.

Since Cuttle first suggested this new approach, and in parallel to this PhD research, public discussions surrounding the topic have become more common amongst lighting designers, lighting researchers and those involved in writing legislation. The research conducted has been generally well received, producing seven relevant journal publications, three conference papers and two trade journal articles, with further dissemination planned for the coming year.

# 2 Improved lighting quality, by designing for appearance?

## Preamble to Chapter 2

This Chapter reviews the existing literature surrounding the research, but more specifically, it discusses how to define lighting quality, it reviews proposals of how lighting quality may be improved, it introduces the proposals of Christopher Cuttle and finally, it lays out the research questions along with their associated hypotheses and finishes with a brief description of how the core chapters within this thesis are structured.

## 2.1 Defining lighting quality

Before considering how to improve the quality of general lighting installations, we must consider what it is that represents good quality lighting. However, defining lighting quality is not an easy task. A number of approaches have been previously suggested. These include single number photometric indices calibrated by subjective responses, [1] results of holistic design processes based on lighting patterns,[2] lighting conditions which have a desirable impact on task performance, health and behaviour[3] and lighting which enhances the ability to discriminate detail, colour, form, texture and surface finishes without discomfort.[4] Despite these attempts, the most widely accepted and commonly understood definition remains the extent to which a lighting installation meets the objectives and constraints of the client and designer.[5]

In the past, Boyce[6] has questioned the purpose of lighting recommendations and suggested that lighting quality can be broken into three classes: the good, the bad and the indifferent.

> *Bad quality lighting is lighting which does not allow you to see what you need to see, quickly and easily and/or causes visual discomfort. Indifferent quality lighting is lighting which does allow you to see what you need to see quickly and easily and does not cause visual discomfort but does nothing to lift the spirit. Good-quality lighting is lighting that allows you to see what you need to see quickly and easily and does not cause visual discomfort but does raise the human spirit.*

Boyce[5] later concludes that bad quality lighting is a function of ignoring authoritative guidance or giving undue attention to a single criterion; indifferent quality lighting is the product of following lighting recommendations but paying disproportionate attention to quantitative criteria and that good quality lighting is typically produced at the hands of a creative architect and a talented lighting designer. However, this team is not available to everyone, so that begs the question; what can be done to move from providing indifferent quality lighting, to providing good quality lighting for all?

## 2.2 Good quality lighting for all?

Research suggests a number of approaches to bridging the gap between indifferent quality lighting and good quality lighting. The first and most obvious approach is to continue along the path that lighting enthusiasts have taken in the past and develop more lighting criteria. The Illuminating Engineer Society (predecessor to the Society of Light and Lighting) published the first edition of the Code approximately 70 years ago.[7] At the time, this document was little more than a list of illuminances that corresponded with various visual tasks. Changes since then have been somewhat driven by technologies. With the introduction of the fluorescent lamp came the colour rendering index and the glare index. With computer monitors came luminaire luminance limits and now with the growth of light emitting diodes (LEDs), the colour rendering index is being revised and older metrics for flicker are being examined for suitability. The characteristics that each of these metrics have in common is that they seek to avoid visual discomfort; in other words, to prevent indifferent lighting becoming bad lighting. With a history like this, it would seem unreasonable to think that developing more lighting criteria could produce good quality lighting.

A second approach is to make more, and better, use of daylight. People love daylight, but not unconditionally. Spaces that make extensive use of daylight are generally considered attractive,[8,9] but like any other light source, daylight must be controlled for visual and thermal discomfort. Providing this is done correctly, daylight through windows can increase occupants sense of brightness and interest, these being two dimensions by which people rate the quality of a space.[10] In general, spaces where daylight is delivered without thermal or visual discomfort are considered better spaces.[11] With this, it is safe to assume that where daylighting is designed correctly, there is potential to produce good quality lighting.

Boyce[5] describes a third approach as "revolutionary". This approach is driven by technology and involves handing control of localised lighting over to building occupants. LED luminaires are already easily dimmable and can alter spectrum and distribution on demand. Moreover, developments in wireless communication and computing power make it now possible to adjust a regular array of luminaires to provide preferred illuminances for building occupants with minimal electricity consumption and without moving luminaires when workstations are moved.[12] There are large individual differences in preferred illuminance levels.[13,14,15,16] This means that for any chosen illuminance, only a small percentage of occupants will experience their own individual preference. In conjunction with this, having ones' own preferred luminous environment has been shown to improve mood and improve judgements of lighting and environmental quality.[14,17] Further to this, improvements in mood, lighting satisfaction, and discomfort achieved by offering individuals' controls has been shown to be proportional to the difference between the fixed illuminance and the preferred illuminance.[18]

A fourth approach to potentially producing good quality lighting might be to change the basis of design within current lighting recommendations to one that widens focus to the appearance of the entire space, rather than fixating focus on a horizontal plane. Although the notion of a task plane has been introduced to replace the working plane, along with other lighting quality criteria such as cylindrical illuminance and modelling index,[19] the most widely used lighting metric remains the horizontal workplane illuminance. Boyce[5] argues:

> *Despite the use of task plane rather than working plane in recent recommendations and the fulminating of various eminent personages, the fact is the horizontal working plane is still the plane of choice for simple lighting calculations.*

A design method that considers the appearance of a space has potential to improve lighting quality as it would direct attention away from the working plane and consider the entire space, a consideration that often lies behind what is assessed as good lighting. In recent years, Cuttle has proposed such a method.[20,21,22,23,24]

## 2.3 Shortcomings of illuminance based schedules

Over the years, specifying bodies have added various lighting quality criteria to their pronouncements,[25,26,27,28] but to those working in the lighting industry, it can be seen that the central factor remains the task, or most commonly, horizontal workplane illuminance. It is claimed that the quantity of illuminance specified in schedules is determined primarily by the category of the visual task.[25,28] Cuttle identifies a procedure[29] that can determine the precise quantity of illuminance necessary for varying visual tasks, due to changes in task size, contrast, background reflectance and observer age. This procedure has been applied[22] to examine how the illuminance required for a high standard of visual performance relates to typical office reading tasks, for a normal sighted 25 year old. Figure 1 shows that, for a reading task of 12-point type on white paper, it requires just 20 lux to provide for a high level of visual performance.[22] It can be seen that the font size would have to be reduced to 6-point for the illuminance required to exceed 100 lux, or alternatively, reduced to 10-point but printed onto dark-coloured paper. However, this value of 100 lux falls far short of the levels currently provided for applications where reading tasks are prevalent. It is clear that the levels of illuminance specified by our standards, which typically fall within the range 300 to 500 lux,[25,28] are far in excess of that necessary for visual performance by occupants with healthy vision.[22]

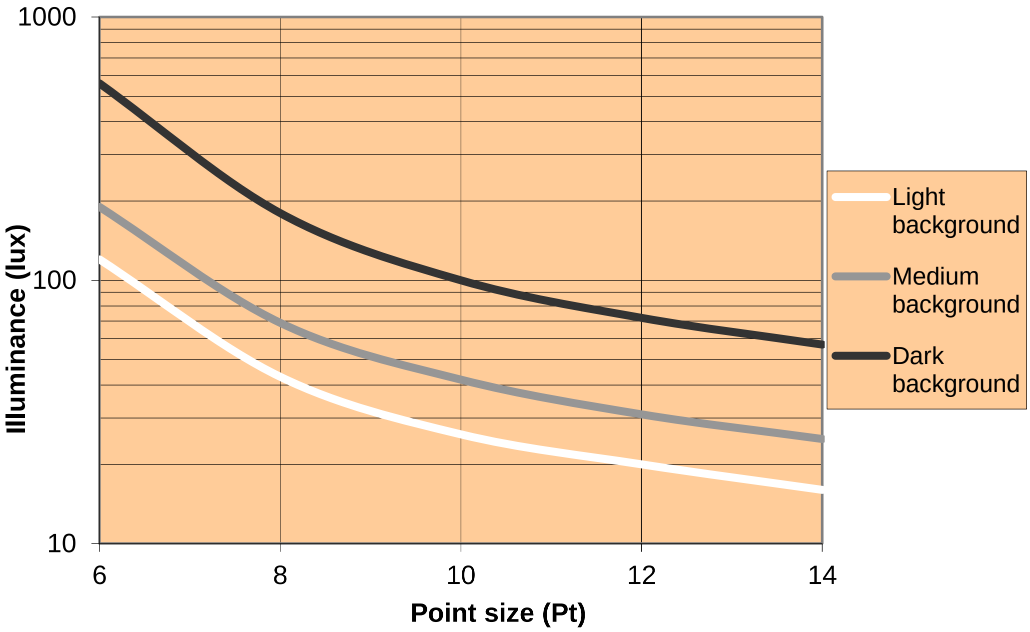


Figure 1 As applied by Cuttle, the task illuminance required to provide for relative visual performance for a range of reading tasks. The reader is a normal-sighted 25-year-old with a viewing distance of 350mm. The reading matter is black print, ranging from 6 - to 14-point size, on three types of paper: light (reflectance ρ = 0.9); medium (ρ = 0.6); and dark (ρ = 0.3). [Reproduced from Cuttle[22]]

In addition, there are a multitude of spaces that humans' pass through in which strenuous visual tasks are non-pertinent - areas where the most arduous visual task may be effortlessly navigating through the space? How much light do we need for this? In a study of emergency egress from buildings,[30] Boyce monitored subjects' departure from a building under varying illuminance levels and concluded that subjects were able to exit the space with very little difference between 1 lux and 500 lux. This would seem to suggest that we need 1 lux in these spaces for optimum visual performance, but again, our standards specify far in excess of this, typically a minimum of 100 lux.[25,28] This begs the question of why? The answer is obvious. If buildings were illuminated to these very low levels, they would appear dark, dim, murky and depressing. People would choose to avoid spaces illuminated in this manner. Cuttle stresses that this is the reason illumination schedules are outdated and need to change.[22] Lighting bears less relevance to the speed and accuracy in which people can complete a task, but has become more about meeting the expectations of building occupants.[22] In the 21st century when everything that needs to be seen has been designed to be seen, buildings should be lit to meet occupant expectations, or in other words, appear adequately illuminated. Cuttle believes that what is needed is a fundamental re-think of whether or not users of a space will rate the lighting as adequate, or inadequate,[22] or by way of explanation, what is the photometric correlate to perceived adequacy of illumination (PAI)?

## 2.4 Designing for appearance

Two lighting design criteria for internal general lighting have been proposed[23] and both of these relate to the visual experience of lit surroundings. The first of these criteria is PAI,[22] which relates to the level of illumination that is likely to be judged sufficiently bright for the activity that the space is used for. Mean room surface exitance (MRSE), being the measure of overall density of reflected flux within a space, has been proposed[21] as a metric that may correlate to PAI. The second criterion is illumination hierarchy (IH). It involves devising distributions of illumination to express the visual significance of the contents of the space.[23] It is specified in terms of target / ambient illuminance ratio (TAIR), being the ratio of local illuminance on a target to the ambient illumination, indicated by the MRSE.

## 2.5 Mean room surface exitance

Within an enclosed space, the MRSE expresses the average value of indirect illuminance incident on any given surface. This surface may include the cornea of an observers' eye and for this reason, Cuttle believes it may provide a simple measure that correlates with how adequately illuminated a space will appear to be.[21,22]

$$MRSE = \frac{FRF}{A_{\propto}} \tag{1}$$

Where $FRF$ is the first reflected flux, being the sum of the direct flux reflected from each surface:

$$FRF = \sum F_{S(d)} \rho_S \tag{2}$$

And $A\alpha$ is the room absorptance, being the sum of the surface areas times their absorptance values, where absorptance is given by one minus reflectance:

$$A\alpha = \sum A_S(1 - \rho_S) \tag{3}$$

Cuttle believes that the objective of lighting standards should be to provide for illumination adequacy, or ensure that the PAI criterion is satisfied, irrespective of luminous distribution. It is on this basis that MRSE has been proposed.[22]

## 2.6 Target / ambient illumination ratio

Whilst the PAI criterion is concerned with providing adequate quantities of reflected flux, the IH criterion focuses on how direct flux from luminaires is distributed to create a pattern of illumination brightness.[23] This may direct attention to functional activities or create artistic effects. The designer will select target surfaces and designate values of TAIR based on the desired level of illumination difference required. MRSE provides a useful measure of indirect illumination within a space, and except where there are obvious reasons to believe otherwise, it is reasonable to assume that the incident illuminance on a surface will be the sum of the direct illuminance and MRSE:[23]

$$E_{tgt} = E_{tgt(d)} + MRSE \tag{4}$$

And the TAIR:

$$TAIR = \frac{E_{tgt}}{MRSE} \tag{5}$$

This provides a concept for planning how the direct illuminance from luminaires should be distributed within a space. For any chosen target, the direct illuminance is:

$$E_{tgt} = MRSE\ (TAIR - 1) \tag{6}$$

Cuttle has proposed ratios of illuminance (Table 1) that indicate degrees of perceived differences in levels of subjective brightness.[21] The quantity of direct illuminance to be applied to each surface or object can be determined from equation (6), and using this data, the distribution of direct luminous flux from the luminaires can be established. The concept of perceived difference is based upon an idea proposed by Lynes and Bedocs.[31]

Table 1 Approximate guide to perceived difference of illumination brightness related to MRSE difference or TAIR.[23]

| Perceived Difference | Illumination Ratio |
|---|---|
| Noticeable | 1.5:1 |
| Distinct | 3:1 |
| Strong | 10:1 |
| Emphatic | 40:1 |

## 2.7 The design procedure and a worked example

The design procedure for using MRSE / TAIR is explained in great detail elsewhere,[20,23,32] but a short summary and example are detailed below. In essence, the designer needs to consider an appropriate level of ambient illumination for the space. This will be the designers view on PAI and may be specified in terms of MRSE. Once the MRSE has been chosen, the designer must digest the properties of the space and shape direct illuminance within the space to achieve the envisaged illumination hierarchy, whilst maintaining adequate levels of MRSE. As an example, consider an office space and make reference to the spreadsheet shown in Table 2, which can be easily set-up and very much aids calculations. Select 200 $lm/m^2$ as an appropriate MRSE that may relate to PAI. Input this value and also those listed in columns one – three. Column four indicates the respective room surface absorption value and at the bottom of this column, we see that 23,141 lm of FRF are required to produce the desired MRSE. The chosen TAIR values are then input accordingly and the remaining information is calculated automatically. It is evident from Table 2 that 9269 lumens of the required FRF will come from the target surfaces, leaving the remaining 13,872 to be provided through reflection from other room surfaces.

Table 2 Spreadsheet indicating an applied example of MRSE / TAIR concepts for lighting an office space described in the text. The user inputs the MRSE value, followed by the surface information and the spreadsheet completes the Surface Absorption. The user then inputs desired level of TAIR and the remaining data is computed automatically.

| Office Space | | Desired MRSE (lm/m$^2$) | | 200 | | |
|---|---|---|---|---|---|---|
| Room Surface | Surface Area $A_s$(m$^2$) | Surface Reflectance $\rho_s$ | Surface Absorption $A_\alpha$(m$^2$) | TAIR | Direct Target Surface Illuminance $E_{ts(d)}$ (lx) | Target Surface First Reflected Flux $FRF_{ts}$ (lm) |
| Ceiling | 60 | 0.78 | 13.2 | 1 | 0 | 0 |
| Wall 1 | 21.75 | 0.59 | 8.9 | 1 | 0 | 0 |
| Artwork, wall 1 | 2.25 | 0.35 | 1.5 | 3 | 400 | 315 |
| Wall 2 | 40 | 0.59 | 16.4 | 1 | 0 | 0 |
| Wall 3 | 24 | 0.59 | 9.8 | 1 | 0 | 0 |
| Wall 4 | 52 | 0.59 | 21.3 | 1 | 0 | 0 |
| Whiteboard | 8 | 0.89 | 0.9 | 3 | 400 | 2848 |
| Door | 2 | 0.19 | 1.6 | 1 | 0 | 0 |
| Desk Area | 8.8 | 0.7 | 2.6 | 5 | 800 | 4928 |
| Floor Area | 51.2 | 0.23 | 39.4 | 1.5 | 100 | 1177.6 |
| Total Room Surface Absorption | | | 115.7 | Target Surface First Reflected Flux | | 9269 |
| Total Surface First Reflected Flux | | | 23141 | FRF Difference, $FRF_{rs} - FRF_{ts}$ | | 13872 |

When considering a distribution to achieve the remaining FRF, uplighting the ceiling would be a clever choice, given the high reflectance of the ceiling, and thus low absorption value. The necessary direct ceiling illuminance would be given by:

$$E_{clg(d)} = \frac{FRF_{clg}}{A_{clg} \times \rho_{clg}} \tag{7}$$

$$E_{clg(d)} = \frac{13{,}872}{60 \times 0.78} = 298\ lux \tag{8}$$

This value, added to the MRSE would give a total $E_{clg}$ of 498 lux and a TAIR value of approximately 2.5, meaning it would appear brighter than surrounding surfaces and not in-line with the desired IH. To reduce this, luminous distributions could be selected to split lumens between the ceiling and walls, or dedicated wallwashers could be used in conjunction. When considering target surfaces, column six lists the direct illuminance required. Freely available and familiar design software can be utilised to determine this. Reflectances are set to zero, thus the quantity of illuminance on a target surface is the quantity of direct illuminance. This works well for large target surfaces, but for smaller targets, such as sculptures, software will need to evolve or hand calculations[33] would be better suited. So, to provide for the FRF difference, an array of suspended pendants with uplights would work, spotlights could accurately highlight the artwork, the whiteboard could have a linear fitting wall mounted above, the desk spaces could have localised task luminaires and the floor and walls could be highlighted through a lesser distribution of flux from a downlight portion within the suspended pendants. Once the designer has finalised this, it is simply a matter of finding luminaires that match the intensity and distribution required.

## 2.8 Barriers to implementation

Since its introduction, the approach described has received both positive and negative feedback from the lighting community. Some believe that this proposition is doomed to failure due to lack of information available at design stage.[34,35] Whilst this may hold true, Boyce points out that in the face of such a situation, it is unreasonable to expect that good quality lighting will be the outcome of any design method.[6] Many agree that current codes and standards are long overdue a transformation[5,36,37] and indeed some currently choose to ignore them.[38] Brandston criticises current codes and building regulations for demanding an excessive quantity of illuminance on the task, leaving little remaining power density to light the space.[38] Others have noted that senior directors within notable Building Services firms refuse to deviate from standards and codes for the fear that their professional indemnity insurance will be affected.[39] This demonstrates that current lighting standards are placing substantial restrictions on designing for appearance, thus limiting creative design and potentially impeding good quality lighting. Loe comments[40] that subjects he has studied[41] prefer environments that are visually light and visually interesting. Whilst MRSE may never provide this, it is a fair assumption to state that the IH criterion might produce a visually bright and interesting space. Macrae believes the procedure to be “fundamentally flawed”, as to apply the methodology correctly requires a good understanding of light and lighting,[35] but should this not be mandatory for those involved in lighting? If good quality lighting is the desired outcome, then the answer must be yes.

Critics of Cuttle's earlier paper based solely on MRSE, voiced concerns that there may be enough light arriving at the observer's eye, but insufficient illuminance upon a task.[34,42,43] If applied correctly and with due thought, the IH criterion would designate strenuous visual tasks with a TAIR of above three and this should, combined with a sensible MRSE, quite comfortably provide adequate illuminance levels for optimum visual performance. Boyce agrees[44] that visual tasks have become easier over time, but questions if what people really care about is the perceived brightness of a space. Boyce points out that MRSE is a crude measure of brightness and the range of luminances in the field of view, combined with the source spectrum will also be important.[44] This raises an important point; producing a simple metric that incorporates all of these variables is a daunting task and would almost certainly go beyond the scope of what lighting standards are expected to do. Raynham states[42] that MRSE cannot become the "be-all and end-all of lighting design", but this was given before the introduction of the IH criterion, which adds an additional dimension to MRSE based design.

Despite the initial scepticism, there was a substantial amount of positive support. In two more recent publications,[5,45] Boyce promotes MRSE / TAIR together as a methodology that shows potential to improve the quality of lighting, so it would appear that as Cuttle's design theories have progressed to include illumination hierarchies, Boyce has become convinced that this method shows considerable potential. Boyce states about adopting MRSE based designs that "light distributions that illuminate the walls and ceiling then become much more energy efficient than those that concentrate their output onto the horizontal working plane".[5] Loe agrees with designing for ambience.[40] Shaw states that "this is one of those blindingly obvious ideas that we have all missed".[37] Poulton points out that codes and standards are "archaic and should be revised" and that Cuttle's way of thinking is "long overdue".[36] Hogget believes that the proposition is what talented lighting designers have intuitively been doing for years; a mathematical technique to quantify the task / ambient ratio.[46] Mansfield states that Cuttle's suggestion to use MRSE as an exploratory tool to define illumination adequacy is a good one and welcomes further dissemination of it as a tool for teaching and as a device to realign lighting design practice.[47] Brandston states that Cuttle's approach is in-line with his own. Brandston initially lights the space and then pays attention to the tasks.[38] Wilde agrees that dumping lumens on a working plane is fraught with problems.[39] Wilde believes that it is time to change from visibility to appearance and goes on to state that "it must be welcomed by the discerning designer".[39] Boyce describes the MRSE / TAIR procedure as "all-encompassing"[5] and highlights that the first step towards implementation would be the modification of current software, or development of new software, that easily facilitates its calculation.[5] This sentiment is backed up by Wilde.[39] Macrae[35] and others have also questioned how MRSE would be measured once an installation is complete, with no dedicated meters or procedures available.

Whilst the importance of appropriate software and instruments to measure MRSE in the field are indisputable, there are other concerns that need to be addressed before Cuttle's ideas can ever be given full consideration. This is succinctly summarised in a paper on emerging lighting metrics by Boyce and Smet:[45]

> *At the moment, the worth of mean room surface exitance and target/ambient illumination ratio as metrics for determining desirable light distributions are matters of belief rather than proof. What is required is some experimental evidence that mean room surface exitance is related to peoples' perception of the amount of light in a space and that that, in turn, is more closely linked to their satisfaction with the lighting than illuminance on the horizontal working plane.*

If this could be demonstrated, in conjunction with the development of appropriate software and measurement techniques, it can be argued that Cuttle's methodology shows much potential to improve the quality of lighting within general installations when compared with current practice of applying horizontal illuminance. It directs attention away from the working plane, it places emphasis upon the appearance of a space, it pays due attention to levels of brightness and it forces the designer to imagine the space and devise illumination hierarchies; all of these being traits and habits of good lighting designers.

## 2.9 The research

### 2.9.1 Research questions

The research questions that this project has aimed to answer are extracted from issues raised in the literature. The work strove to address the major concerns associated with potentially applying MRSE in lighting design. The major research questions were generally built around the major issues discussed above and six were chosen based on priority and feasibility. These are listed below:

1. Is the MRSE formula proposed by Cuttle robust and accurate under all conditions?
2. Is it possible to easily and accurately compute MRSE using currently available lighting analysis software?
3. Is it possible to simplistically, and accurately, measure MRSE within complex, real-world environments?
4. Is MRSE more closely related to subjective perceptions of spatial brightness than mean horizontal workplane illuminance?
5. Is MRSE more closely linked with PAI than mean horizontal workplane illuminance?
6. Do light scenes with non-uniform luminous distributions affect subjective assessments of both spatial brightness and PAI?

### 2.9.2 Defined hypotheses

To address each of these research questions, six hypothesis were defined and tested:

1. The formula derived by Cuttle is accurate under all conditions.
2. Calculation of MRSE is possible by adapting currently available software engines.
3. Measurement of MRSE in the field is possible by adapting High Dynamic Range (HDR) imaging.
4. MRSE is more closely related to subjective impressions of spatial brightness than mean horizontal workplane illuminance.
5. MRSE is more closely related to PAI than mean horizontal workplane illuminance.
6. Extreme non-uniform light distributions will affect perceptions of spatial brightness and PAI.

There are three reasons why these might constitute good hypotheses and justify the choice of research questions.

- First, each is a relevant statement whose validity cannot be determined from existing knowledge.
- Second, if any are demonstrated to be true, they have the potential to influence current practice.
- Finally, if any are demonstrated to be untrue, the work conducted will likely lead to a better understanding of the issue and how it may be properly addressed.

### 2.9.3 Thesis structure

To examine each of the hypotheses, a number of exploratory processes and experiments were undertaken. These will be discussed in detail within the thesis core chapters, which are generally structured as laid out in Table 3.

Table 3 An outline of how the core chapters in the thesis are structured, along with a brief description of the contents of each.

| **Core chapter number and title** | **High-level description** |
|---|---|
| Chapter 3<br>On the calculation and measurement of mean room surface exitance | Chapter 3 presents three main points:<br>1. It evaluates formula currently available to calculate MRSE and demonstrates that one is erroneous under certain conditions<br>2. It introduces a script that has been developed to calculate MRSE using the Radiance software engine as a platform<br>3. It presents a second script that is applied to HDR imaging techniques and this enables the measurement of MRSE in the field |
| Chapter 4<br>Spatial brightness, horizontal illuminance and mean room surface exitance in a lighting booth | Chapter 4 details an experiment that used a small, scaled, model lighting booth and a number of participants to investigate the relationship between MRSE and spatial brightness. |
| Chapter 5<br>Perceived adequacy of illumination, spatial brightness, horizontal illuminance and mean room surface exitance in a small office | Chapter 5 outlines a further experiment conducted that used a specifically designed small office space to investigate the relationships between:<br>• MRSE and spatial brightness<br>• MRSE and PAI |
| Chapter 6<br>Perceived adequacy of illumination, spatial brightness, horizontal illuminance and mean room surface exitance in non-uniform light scenes | Chapter 6 details an experiment that used the same small office space to investigate how non-uniform light distributions would impact on assessment of both spatial brightness and PAI. |

# Summary of Chapter 2

Chapter 2 has introduced the concepts behind this research. It has discussed lighting quality and presented opinions from the literature that suggest the proposals of Cuttle show potential to improve lighting quality, in addition to laying out the research questions and associated hypotheses that this work has investigated. It concluded by presenting an outline of how the core chapters of this thesis are structured.

# 3 On the calculation and measurement of mean room surface exitance

## Preamble to Chapter 3

Chapter 3 describes the work undertaken to address Research Question's 1, 2 and 3:

1. Is the MRSE formula proposed by Cuttle robust and accurate under all conditions?
2. Is it possible to easily and accurately compute MRSE using currently available lighting analysis software?
3. Is it possible to simplistically, and accurately, measure MRSE within complex, real-world environments?

The work that addressed these questions produced three distinct contributions to knowledge:

- First, it investigates and critically examines the MRSE formula proposed by Cuttle and demonstrates why it can be erroneous under certain conditions. In addition, an alternative formula is explored, developed, investigated and proposed to calculate MRSE and this formula is demonstrated to be accurate under any given conditions.
- Second, a script was developed to facilitate the calculation of MRSE using the Radiance lighting analysis engine as a platform.
- Third, another script was produced that allows MRSE to be accurately and quickly measured in the field using High Dynamic Range imaging and Radiance.

## 3.1 On an error in the formula proposed to calculate mean room surface exitance

MRSE is defined as "the measure of average illuminance at all points within the space due to reflected light from the room surfaces, with direct light from either the luminaires or windows excluded".[21] In that same paper, Cuttle introduces the concept of MRSE through a thought exercise and from this, mathematically defines MRSE as given in equation (1). This equation provides a simplistic and insightful way for lighting designers to relate the distribution of direct luminous flux to the total quantity of luminous flux within a space, but it is not without problems.

In the thought exercise previously mentioned, Cuttle used an imaginary space and this space always had uniform surface reflectances, i.e. the floor, walls and ceiling had the same reflectance value. When each surface has the same reflectance, how the FRF is distributed is irrelevant, but when the reflectance of surfaces differ, then the directional distribution of the FRF becomes problematic and the validity of the expression lapses. This happens because the luminous flux emitted from any given surface cannot be incident on that surface, and furthermore, its incidence on any other surface will depend on the geometric relationship between the two items, in addition to their reflectances. In other words, a precise solution needs to encompass, not only the spatial distribution of the first reflection, but also every subsequent inter-reflection, as the outcome is dependent upon the geometric and reflectance relationships of the room surfaces.

Raynham[48] has used a combination of transfer factors[49] and utilisation factors to estimate MRSE with hand calculations, but more complex spaces, and even general calculations, are easier dealt with using lighting analysis software that can readily account for a high number of inter-reflections, such as Radiance. Considering calculation of an almost infinite number of inter-reflections to be possible, and using a reasonable assumption that all surfaces within a space are Lambertian diffusers, MRSE can alternatively be defined by the sum of the area-weighted exitance values within a space, divided by the total room surface area:

$$MRSE = \frac{\sum M_S A_S}{\sum A_S} \qquad (9)$$

Where $M_S$ is the mean exitance of each surface within the space and is given by the product of the mean surface luminance, $L_S$, and pi, $\pi$:

$$M_S = L_S \pi \qquad (10)$$

### 3.1.1 The magnitude of error

From the above, it can be observed that there are two formulae which can be used to determine MRSE; the first, equation (1), is straightforward to calculate, but relies on all room surface reflectances being identical to maintain accuracy and the second, equation (9), is complex to calculate but will produce more reliable results. To investigate the magnitude of error in equation (1), calculations have been carried out with Radiance and using an imaginary space.[50] The space was 5 m in width and breath and 3 m in height, with a single pendant suspended at the centre of the space (1.5 m from the ceiling) that emitted 5000 lumens through a lambertian distribution, either entirely as uplight or downlight. Equation (1) was applied by setting surface reflectances to zero, thus simulating the direct luminous flux on each surface, recording this, then post processing the numbers using equations (2) and (3). To compute MRSE using equation (9), a script[51] previously written as part of this research was ran (note that this script is explained in detail later in the chapter). This script applies equation (10), whilst ignoring direct flux from luminaires, then post processes to calculate MRSE. Table 4 shows the percentage level of error in equation (1), calculated over a selection of room surface reflectance values that all have an average of 50%.

It can be observed that the error experienced using equation (1) is reasonable when similar room surface reflectances were used, but nonetheless, this error is enough to highlight the shortcomings of the expression. The error also has the potential to increase when geometry is varied beyond the simple cube tested here. Whilst equation (1) will most likely continue to serve as a teaching aid, and perhaps for lighting designers who understand its limitations and find benefit in using it to devise hierarchies; the calculation and measurement of MRSE for use in research, lighting standards or general illumination engineering should endeavour to apply equation (9) and this should be computed using appropriate methods and software programs.

Table 4 The percentage error between calculations using both MRSE formulae and a selection of room surface reflectance values.

| **Equation Used** | **Surface Reflectances (ceiling/walls/floor)** | **Light Distribution** | **Mean Room Surface Exitance ($lm/m^2$)** | **Percentage Error (%)** |
|---|---|---|---|---|
| (1) | 50% / 50% / 50% | Downlight | 45.45 | 0 |
| (9) | | Downlight | 45.45 | |
| (1) | 50% / 50% / 50% | Uplight | 45.45 | 0 |
| (9) | | Uplight | 45.45 | |
| (1) | 60% / 50% / 40% | Downlight | 38.8 | 0.8 |
| (9) | | Downlight | 39.1 | |
| (1) | 60% / 50% / 40% | Uplight | 52.55 | 1.15 |
| (9) | | Uplight | 51.95 | |
| (1) | 70% / 50% / 30% | Downlight | 31.9 | 2.45 |
| (9) | | Downlight | 32.7 | |
| (1) | 70% / 50% / 30% | Uplight | 59.4 | 7.6 |
| (9) | | Uplight | 55.2 | |
| (1) | 80% / 50% / 20% | Downlight | 25.1 | 3.8 |
| (9) | | Downlight | 26.1 | |
| (1) | 80% / 50% / 20% | Uplight | 66.3 | 11.0 |
| (9) | | Uplight | 59.7 | |
| (1) | 90% / 50% / 10% | Downlight | 18.2 | 4.9 |
| (9) | | Downlight | 17.35 | |
| (1) | 90% / 50% / 10% | Uplight | 73.1 | 17.7 |
| (9) | | Uplight | 62.1 | |

## 3.2 On the calculation of mean room surface exitance

As discussed in Chapter 2, a key question relating to MRSE is that it cannot be calculated with currently available software and this is generally how all lighting design is completed today. This section introduces a newly developed method that utilises Radiance[52] software as a platform to calculate MRSE.

Radiance is a suite of programs for the analysis and visualisation of lighting design. It lacks a graphical user interface, but as such, offers the user greater flexibility than typical lighting simulation programs. This research[i] has developed a script[51] to calculate MRSE for electric lighting designs and this is available to download from a web address given within Appendix 1.

### 3.2.1 Calculation: Procedure

To run the script, users will require an OS X interface with a full suite of Radiance commands installed, along with the ability to run a range of commands in the *Perl* language.

In general, the script works in two parts. The first applies calculation grids to each surface in the space and calculates a mean exitance value for it, as given in equation (10). The second processes the results to produce the MRSE, as given in equation (9). The individual steps to run the script are:

1. Create the 3d geometry as normal with any electric lighting Radiance calculation.
2. Create a *rad_X* folder which houses surfaces that are to have exitance calculations applied, i.e. excluding all *light*, *glass*, etc. types. *X* is a model reference number which is called within the command line.
3. To run the script, type *./run_mrse.pl X Y* within the command line, where *X* is the integer model reference number and *Y* is an optional float that sets the

[i] The Candidate acknowledges and is thankful for the time, discussions and input of Santiago Torres in the development of this script.

distance apart for which calculation points will be applied. The default float is 200 mm.

4. To produce the MRSE, within the command line type *total –m tmp_X/all.res.* This will spit out the MRSE for the space.

### 3.2.2 Calculation: Validation

To examine the accuracy of the script, a trial was conducted where results computed with it were compared with real-world measurements and also triangulated with calculations conducted using a radiosity based software. The space was 5000 mm long, 2900 mm wide and 2850 mm high, contained two ceiling mounted linear fluorescent luminaires and no furniture. The luminaires were dimmed to a level such that the real-world measurements produced an MRSE of approx. 100 lm/m$^2$. The value of flux emitted from each luminaire at the dimmed state was then calculated using the manufacturer dimming curve and cross-referenced with in-situ illuminance measurements. The total output flux used in the software calculations was then based on this figure.

- Calculation using the script was as described previously and using the default float and five ambient bounces (-*ab 5*).
- Calculation within the radiosity software was completed using the default indirect calculation settings to derive luminance values on each room surface, then post processing these to obtain the MRSE using equations (9) and (10).
- The real-world calculation was carried out using a luminance meter and equations (9) and (10). A gird point spacing of 300 mm was used.

The results of each calculation are given in Table 5:

Table 5 Calculation results showing levels of mean room surface exitance derived using the three methods described previously.

| **Calculation Method** | **Mean Room Surface Exitance (lm/m$^2$)** |
|---|---|
| Radiance script | 101 |
| Radiosity software | 107 |
| Luminance meter measurements | 103 |

### 3.2.3 Calculation: Limitations

Recommended settings for a typical Radiance calculation are suggested within a number of publications,[53,54] but when applying this calculation script, the quantity of ambient bounces (-*ab*) applied is of particular importance. Within Radiance, the number of ambient bounces applied governs the number of inter-reflections calculated. As a metric, MRSE theoretically requires an infinite number of flux inter-reflections, which is not practical given the computing power available to a typical lighting consultant. It is recommended[51] that four to five ambient bounces is a good trade-off between accuracy and calculation time, but this may need to change when extreme levels of surface reflectance are encountered.

## 3.3 On the measurement of mean room surface exitance

As discussed in Chapter 2, another common criticism relating to MRSE is that it cannot be easily measured or recorded once an installation has been completed. This section introduces methodology developed as part of this research that utilises High Dynamic Range imaging (HDRi) to record MRSE in the field.

HDRi is a set of techniques used in photography to produce a wider dynamic range of luminosity than is typically possible using standard digital imaging or photographing techniques. Essentially, HDRi uses multiple exposures of the same scene to produce images that better represent the perceived luminous environment.

At present, this can be applied to produce luminance-calibrated images of the lit environment.[55,56] This procedure has been adapted in this work[ii] to calculate the indirect flux incident on a camera lens. The intention is that multiple views of a space from various angles are captured, with the mean of the values of indirect flux being equivalent to the MRSE.

### 3.3.1 Measurement: Procedure

HDR images can be recorded using a digital single-lens reflex camera and calibrated using available software's such as Photosphere or using *hdrgen* and Radiance.[52,57] This research has developed a script to estimate the indirect flux incident on a camera lens and this is available to download from a web address given in Appendix 1. In general, it works with the user manually defining the value of direct luminance incident at the camera lens and removing all pixels in excess of this value from the HDR image, with a calculation of indirect illuminance at the camera lens conducted once this is complete. The necessary steps to apply this method are given below.

1. Capture a HDR image using an appropriate camera.
2. Calibrate the image using either Photosphere or *hdrgen* and Radiance.
3. Open the image using *X11* or a similar program that allows individual pixel luminance values to be viewed. While doing so, note the lowest quantity of direct luminance; this is used as the threshold above which pixels containing higher luminance levels are excluded.
4. In the command line, type *./run –t X –p Y*, where *X* is the threshold luminance value above which pixels will be excluded and *Y* is the filename

[ii] The Candidate acknowledges and is thankful for the time, discussions and input of Giulio Antonutto in the development of this script.

of the HDR image to which the script will be applied. The value of indirect flux is then spat out in the command line and should be noted.

5. As a cross-check, *.tif* images indicating both the direct and diffuse calculated components are generated. These can be viewed to ensure that the appropriate pixels have been excluded from the calculation.
6. The above process is repeated for a number of views within a space and the mean value of each indirect illuminance is representative of the MRSE. The mean must be manually calculated.

### 3.3.2 Measurement: Validation

To examine the accuracy of this method, a trial was conducted where results computed with it were compared with in-field measurements and also triangulated with calculations carried out in Radiance. The room and set-up described in section 3.2.2 were used.

- With the lens available at the time of validation, to fully capture the entire space and make the calculation appropriately accurate, a total of eight HDR images were recorded. Two from each corner of the space directly facing the opposing corner but at plus and minus 45° to the horizontal respectively. Using *X11*, direct luminance values were derived for each image based on the range of luminances presented in the camera view. The mean of the indirect flux within all eight images was taken as the MRSE. It should be noted that if a lens with an appropriate view angle (such as a wide angle or fish-eye) was available, the number of HDR images could be reduced to two, with similar levels of accuracy maintained.
- Calculation in Radiance was carried out using a script and the procedure described previously in this chapter.
- The in-field calculation was carried out using a luminance meter and equations (9) and (10). A gird point spacing of 300 mm was used.

The results of each calculation are given in Table 6:

Table 6 Calculation results showing levels of mean room surface exitance derived using the three methods described previously.

| **Calculation Method** | **Mean Room Surface Exitance (lm/m$^2$)** |
|---|---|
| HDR images | 111 |
| Radiance script | 101 |
| Luminance meter measurements | 103 |

### 3.3.3 Measurement: Limitations

When applying the measurement method described, the user must define a direct luminance threshold value. This could be considered a limitation, such that the absolute precise value above which direct luminance is incident on the camera lens is not so easy to determine and can be more difficult under certain circumstances. For example, consider an oddly shaped prismatic diffuser with very high output lamps hidden behind; here it is difficult to distinguish between the direct and indirect luminance incident on the camera lens as a result of this luminaire. Consequently, the variability in choosing the value of threshold luminance has an impact on the returned value of indirect illuminance. In addition, on occasion, lighting designers will encounter situations where the value of indirect luminance within a space is actually greater than the value of direct luminance in the same field of view. As an extreme example, consider a high output wallwash luminaire placed far too close to a wall and in the same field of view, a decorative, dimmed, low-output incandescent lamp. The method developed cannot exclude the direct flux from the dim incandescent lamp whilst including the high indirect luminance levels as a results of the wallwash. Whilst this is an extreme example, less severe versions of this situation are encountered more regularly than might be expected; a typical example being a direct/indirect type luminaire suspended close to a ceiling. Here, the value of indirect luminance on a white ceiling above can often be very similar, if not in excess, of the direct luminance at a given angle to the horizontal below.

# Summary of Chapter 3

Chapter 3 demonstrated three meaningful, but different, contributions to knowledge.

1. The first of these came about through critical examination of the MRSE formula derived by Cuttle. This formula was shown to be erroneous and an alternative formula was demonstrated to be accurate under all conditions.

2. The second contribution was the development and validation of a Radiance script that is capable of calculating MRSE through currently available software.

3. The third was the production of a different script that facilitates the measurement of MRSE in the field using readily accessible software and camera technology.

# 4 Spatial brightness, horizontal illuminance and mean room surface exitance in a lighting booth

## Preamble to Chapter 4

Chapter 4 presents work that set out to address Research Question 4:

4. Is MRSE more closely related to subjective perceptions of spatial brightness than mean horizontal workplane illuminance?

More specifically, it presents methods, results, analysis and discussion from an experiment that used a lighting booth and a group of participants to investigate the relationship between MRSE and spatial brightness and also between horizontal illuminance and spatial brightness.

It ultimately highlights one main original contribution to knowledge; the results presented within this chapter shows the level of MRSE to better correlate to perceived spatial brightness than the quantity of illuminance on a horizontal working plane.

## 4.1 Experiment 1: Introduction

In recent years, indoor lighting standards and guidance documents have changed to allow designers the option to select the orientation of the working plane within a space, which may, or may not be, the horizontal plane. In addition, new metrics such as mean cylindrical illuminance, a modelling index and minimum quantities of illuminance on major room surfaces have been added.[58,59,60] Whilst these have been formally introduced into standards and guidance, for those working within the lighting industry, it can be observed that the most prominent lighting metric in practice remains the quantity of illuminance on the horizontal working plane.

As discussed in Chapter 2, over the past decade, Cuttle has been the prime advocate for reforming indoor lighting standards from their current state, to consider an alternative approach that he believes better relates to what we see. Cuttle has suggested that MRSE may correlate with the perceived brightness of a space, or in other words, the spatial brightness.

The term spatial brightness has been used to relate to subjective assessments of the perceived brightness of a space. Fotios and Atli[61] have referred to a draft definition of spatial brightness being prepared by the Illuminating Engineering Society of North America Visual Effects of Lamp Spectral Distribution committee. Fotios and Atli state it is not an official definition, but it does offer some insight into what the term is intended to describe.

> *Spatial brightness describes a visual sensation to the magnitude of the ambient lighting within an environment, such as a room or lighted street. Generally the ambient lighting creates atmosphere and*

> *facilitates larger visual tasks such as safe circulation and visual communication. This brightness percept encompasses the overall sensation based on the response of a large part of the visual field extending beyond the fovea. It may be sensed or perceived while immersed within a space or when a space is observed remotely but fills a large part of the visual field. Spatial brightness does not necessarily relate to the brightness of any individual objects or surfaces in the environment, but may be influenced by the brightness of these individual items.*

Spatial brightness has also previously been referred to as building lighting,[62] room brightness[63] and scene brightness.[64,65] Numerous past studies have investigated the influence of spectral power distribution on spatial brightness.[66,67,68,69,70,71,72,73,74,75,76] Fotios et al provide a useful review of this.[77]

Other studies have investigated the relationship between spatial brightness and light on a vertical plane[78] and also luminance within a defined field of view.[79,80] Cuttle proposes MRSE with the intention that it would be a proxy for the quantity of light arriving at the eye, which could also be represented by the indirect illuminance on a vertical plane at eye level. Rea et al[78] found illuminance on a vertical plane to correlate better with assessments of brightness than that of light on a horizontal plane. In two separate studies, Loe et al found strong correlations between assessments of brightness and the illumination of a horizontal band 40° wide.[79,80]

This chapter presents results from an experiment that used a lighting booth to investigate the relationship between MRSE and spatial brightness and also between mean horizontal illuminance and spatial brightness.

## 4.2 Experiment 1: Methodology

A lighting booth was constructed from MDF and sealed for light tightness using silicone caulk (Figure 2 and Figure 3). The booth was 860 mm high, 1500 mm long and 850 mm deep and contained multiple hatches spaced out in a regular grid on all sides of the booth. The smaller hatches were used solely for measurement. Two large hatches, one on each long elevation of the booth, facilitated viewing points, with volunteer participants pressing their faces against this to view the booth interior. The booth sat 750 mm above finish floor level on in-built legs. Luminance values were recorded through each of the measuring hatches and converted to MRSE using equations (9) and (10). Luminance values were recorded using an independently calibrated Konica Minolta LS-110. Reflectance values were calculated using luminance and illuminance measurements. Prior to beginning each experiment, all lamps were run at full output for a sufficient length of time so that their output stabilised. This was verified with spot measurements taken at the start and end of each light scene.

Lighting in the booth was provided by pulse width modulation (PWM) dimmable 300 mm T5 fluorescent lamps, with two of each located inside custom aluminium housings. The lamps had a correlated colour temperature of 4000K and a colour rendering index of 80. Lamps were circuited, grouped (SC-1, SC-2, SC-3 in Figure 3) and dimmed together to produce uplight and downlight components. Light scenes were programmed using a DSI interface and a scene set panel.

The study examined the subjective response to the spatial brightness perception of 26 participants. Participants were between the ages of 18 and 25 years (mean=20.8 years, standard deviation=2.3 years) with no participant using corrective eyewear.

In each experiment, participants viewed a range of light scenes. The experiment used groups of two participants and each participant completed three separate sittings. During each sitting, participants were exposed to nine different light scenes at varying levels of MRSE, with the corresponding level of horizontal illuminance at booth floor level also recorded. Three levels of MRSE were set up; 25, 50 and 100 lm/m$^2$, along with three methods to achieve the distributions of each, these being indirect, direct and mixed. Indirect scenes were a combination of SC-1 and SC-2, direct scenes were solely SC-3 and the mixed scenes were a combination of all three switching circuits. The reflectance on the internal surfaces of the booth and within the interior of the experimental space were also varied to broadly represent light, medium and dark surface properties. Together, these combinations produced a total of 27 light scenes. A graphical breakdown of the light scenes are given in Figure 4 and further details about surface reflectances and luminance distributions are given in Table 7.

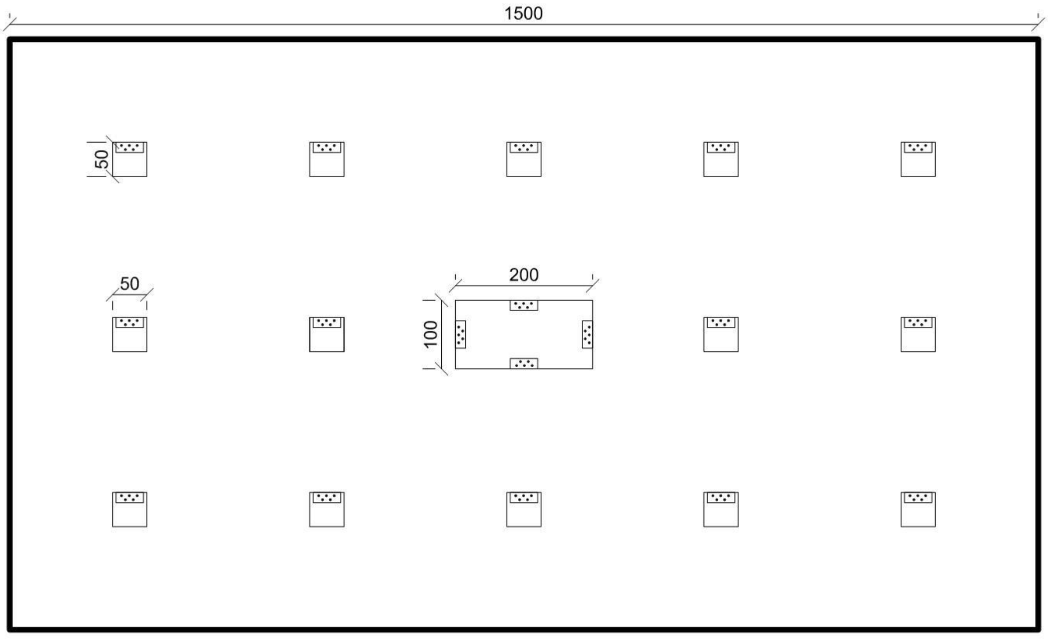


Figure 2 Front elevation of the lighting booth. Note the smaller measuring hatches and the larger central hatch for viewing. Measuring hatches, at similar

spacing, were used on all sides of the booth, including the top and bottom surfaces.

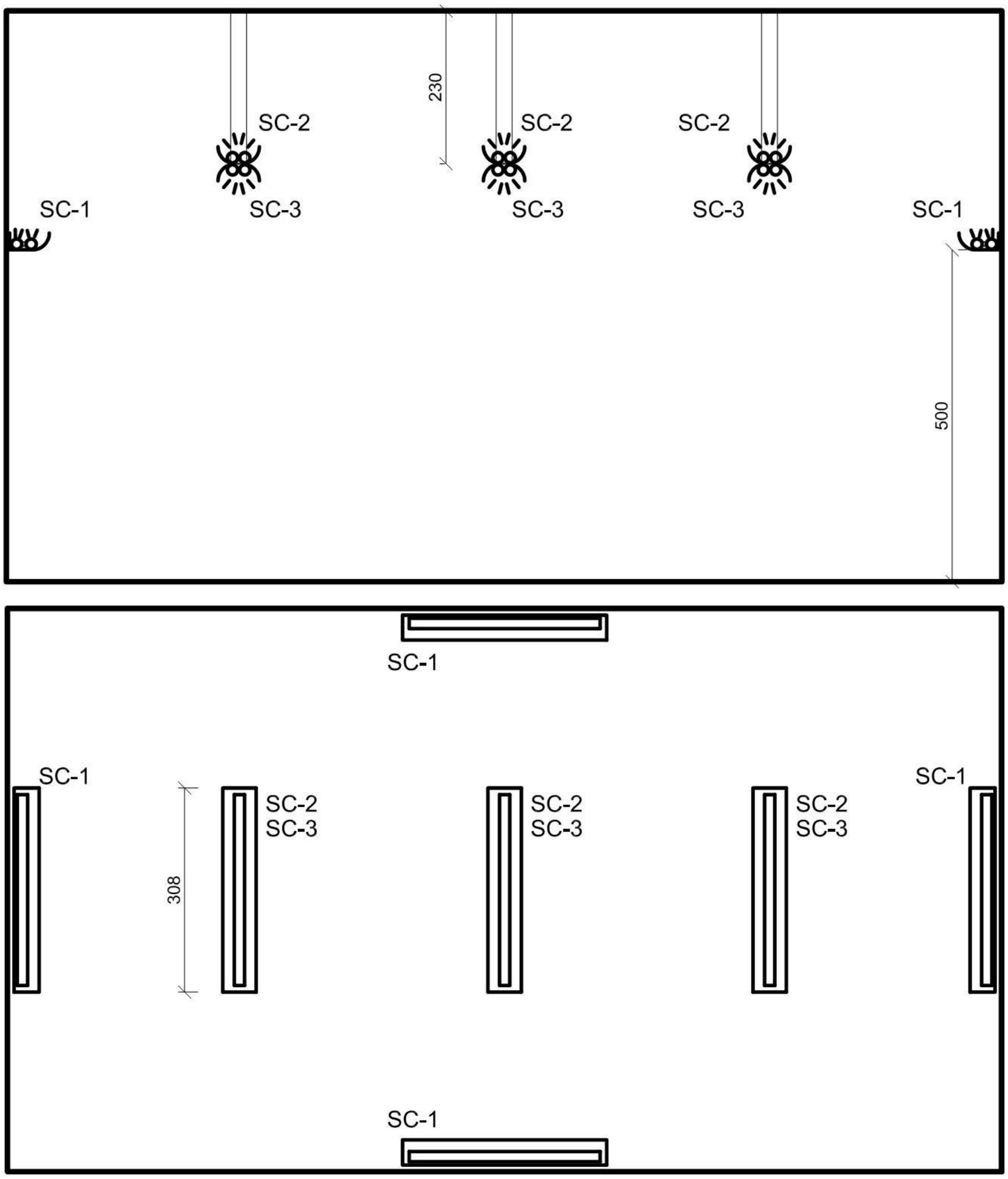


Figure 3 Elevation and plan sections of the lighting booth.

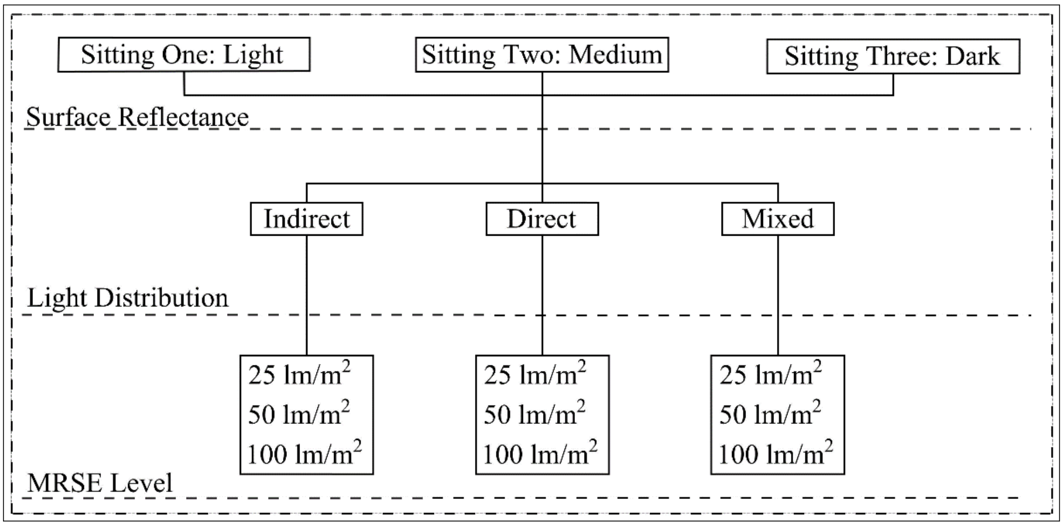


Figure 4 Graphical representation of each light scene programmed. Note that each sitting contained static surface reflectances, but varied levels of MRSE and light distribution.

The order of exposure to light scenes was randomised and three scenes were repeated to compare participant responses. The numbering of each light scene is given in Table 7. The repeated scenes were scene 7, scene 14 and scene 21 and were chosen to best include each of the variables; being one scene from each level of MRSE, one scene from each light distribution and one scene from each surface reflectance. Participants were exposed to each scene for two minutes and during each scene, answered one question that examined subjective spatial brightness levels on a seven point semantic differential scale. Question response polarity was varied at random to prevent directional bias.

*Q1. On the scale below, please rate the brightness of the entire booth.*

| | | | | | | |
|---|---|---|---|---|---|---|
| *very dim* | *dim* | *slightly dim* | *neither dim nor bright* | *slightly bright* | *bright* | *very bright* |

Brightness scales were defined using the definition coined by Vrabel et al;[81] “very bright is represented by the light in an outdoor sports area (when all the floodlights are on) and very dim is the level of an outdoor parking lot at night”. In addition to this, participants were reminded prior to each scene change that they should relate brightness to the entire booth, and not solely to their immediate field of view.

## 4.3 Experiment 1: Results and analysis

Values of one to seven were assigned for responses from very dim to very bright, respectively. A full list of the mean spatial brightness response ratings, coupled with the associated standard deviations, for all light scenes is given in Table 7.

Using parametric statistical tests requires the data to be drawn from a normally distributed sample. Distribution of data was investigated using statistical and graphical methods available through SPSS, namely; measures of central tendency, skewness, frequency histogram, kurtosis, box and whisker plots and probability plots. These tests indicated that the data were not normally distributed and as such, non-parametric statistical tests have been applied.

Table 7 Properties of the 27 lights scenes programmed. Also indicated is the mean subjective spatial brightness rating for each light scene.

| **Light Scene Number** | **Target MRSE (lm/m$^2$)** | **Surface Reflectance (Ceiling/ Wall/ Floor)** | **Light Distribution** | **Recorded MRSE (lm/m$^2$)** | **Recorded Horizontal Illuminance (lm/m$^2$)** | **Mean Recorded Luminance (cd/m$^2$)** | | | | **Mean Spatial Brightness Rating (SD)** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **Floor** | **Ceiling** | **Long Wall** | **Short Wall** | |
| 1 | 25 | Sitting 1 88/83/27 | Indirect | 29 | 98 | 3 | 16 | 10 | 8 | 2.08 (0.92) |
| 2 | 25 | | Direct | 26 | 67 | 6 | 7 | 10 | 9 | 1.54 (0.57) |
| 3 | 25 | | Mixed | 28 | 50 | 4 | 12 | 10 | 9 | 2.19 (0.68) |
| 4 | 50 | | Indirect | 51 | 68 | 5 | 28 | 17 | 15 | 2.96 (1.32) |
| 5 | 50 | | Direct | 46 | 126 | 11 | 13 | 16 | 16 | 2.38 (0.74) |
| 6 | 50 | | Mixed | 53 | 92 | 8 | 23 | 19 | 16 | 3.19 (0.83) |
| 7 | 100 | | Indirect | 101 | 137 | 9 | 56 | 34 | 30 | 4.96 (1.16) |
| 8 | 100 | | Direct | 104 | 260 | 22 | 28 | 40 | 34 | 4.31 (1.29) |
| 9 | 100 | | Mixed | 101 | 184 | 16 | 42 | 36 | 31 | 4.92 (0.92) |
| 10 | 25 | Sitting 2 73/64/27 | Indirect | 27 | 42 | 3 | 19 | 9 | 7 | 1.85 (0.77) |
| 11 | 25 | | Direct | 26 | 98 | 8 | 7 | 10 | 8 | 1.38 (0.56) |
| 12 | 25 | | Mixed | 24 | 82 | 4 | 13 | 9 | 7 | 2.27 (0.65) |
| 13 | 50 | | Indirect | 51 | 77 | 5 | 36 | 16 | 13 | 2.58 (0.84) |
| 14 | 50 | | Direct | 44 | 179 | 15 | 12 | 15 | 15 | 2.65 (0.68) |
| 15 | 50 | | Mixed | 55 | 128 | 10 | 28 | 19 | 15 | 2.62 (0.62) |
| 16 | 100 | | Indirect | 100 | 148 | 9 | 70 | 32 | 24 | 4.81 (1.14) |
| 17 | 100 | | Direct | 101 | 379 | 29 | 25 | 39 | 33 | 3.73(1.16) |
| 18 | 100 | | Mixed | 98 | 241 | 19 | 46 | 33 | 27 | 4.65 (1.04) |
| 19 | 25 | Sitting 3 48/44/13 | Indirect | 24 | 43 | 2 | 21 | 7 | 5 | 1.58 (0.78) |
| 20 | 25 | | Direct | 25 | 175 | 9 | 5 | 9 | 8 | 1.27 (0.52) |
| 21 | 25 | | Mixed | 24 | 82 | 4 | 13 | 9 | 7 | 2.15 (0.57) |

| Light Scene Number | Target MRSE (lm/m$^2$) | Surface Reflectance (Ceiling/ Wall/ Floor) | Light Distribution | Recorded MRSE (lm/m$^2$) | Recorded Horizontal Illuminance (lm/m$^2$) | Mean Recorded Luminance (cd/m$^2$) | | | | Mean Spatial Brightness Rating (SD) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Floor | Ceiling | Long Wall | Short Wall | |
| 22 | 50 | | Indirect | 48 | 84 | 3 | 43 | 14 | 9 | 2.42 (0.99) |
| 23 | 50 | | Direct | 43 | 374 | 17 | 10 | 14 | 15 | 1.96 (0.72) |
| 24 | 50 | | Mixed | 55 | 128 | 10 | 28 | 19 | 15 | 2.54 (0.96) |
| 25 | 100 | | Indirect | 97 | 169 | 7 | 86 | 28 | 18 | 5.08 (1.00) |
| 26 | 100 | | Direct | 99 | 945 | 50 | 29 | 45 | 45 | 4.08 (0.94) |
| 27 | 100 | | Mixed | 98 | 241 | 19 | 46 | 33 | 27 | 4.38 (1.09) |

### 4.3.1 Experiment 1: Repeated scenes

Repeated scenes were introduced to ensure that the order of light scene exposure had no impact on subjective assessments. As stated previous, three scenes were repeated without participants knowledge; scene 7, scene 14 and scene 21, with the repeated scene being excluded from the final results. Scores produced from each of these scenes were examined using the Wilcoxon signed-rank test. All three repeated scenes produced no statistically significant differences between participants' first response and their second (scene 7, $Z = -0.933$, $p = 0.351$; scene 14, $Z = -1.155$, $p = 0.248$ and scene 21, $Z = -1.265$, $p = 0.206$). It can thus be concluded that the order of exposure had no significant impact on participants' assessments.

### 4.3.2 Experiment 1: Mean room surface exitance and spatial brightness

Repeated measures analysis of variance (ANOVA) was used to investigate the influence of the different independent variables on spatial brightness assessments. To change the reflectance of the internal surfaces of the booth, they were repainted and as such, it could not be avoided that participants saw each surface reflectance in the same order, producing an associated order effect. For this reason, three separate two by three repeated measures ANOVA were carried out, with level of MRSE (3) and light distribution (3) as the independent variables.

In sitting one, participants viewed scenes with light surface reflectances as given in Table 7. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 5.49$, $p = 0.064$, level of MRSE, $X^2(2) = 0.0256$, $p = 0.987$, and the interaction between level of MRSE and light distribution, $X^2(9) = 2.682$, $p = 0.976$. Within subjects effects then showed that the subjective assessment of spatial brightness was influenced by the level of MRSE, $F(2, 50) = 190.112$, $p < 0.001$, and also by light distribution, $F(2, 50) = 15.605$, $p < 0.001$. There was no significant interaction between level of MRSE and light distribution, $F(4, 100) = 0.182$, $p = 0.947$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was a significant difference between direct and indirect scenes ($p < 0.001$) and also between direct and mixed ($p < 0.001$). No statistically significant difference could be found between the mixed and indirect scenes. For level of MRSE, there was a statistically significant difference between each of the pairs of means ($p < 0.001$).

In sitting two, participants viewed scenes with medium surface reflectances as given in Table 7. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 2.314$, $p = 0.314$, and for the interaction between light distribution and level of MRSE, $X^2(9) = 13.629$, $p = 0.137$, but not for level of MRSE, $X^2(2) = 12.954$, $p = 0.002$. For level of MRSE, F values are reported using degrees of freedom corrected with the Greenhouse-Geisser factor ($\varepsilon = 0.706$). Within subjects effects showed that subjective assessment of spatial brightness was influenced by level of MRSE, $F(1.41, 35.3) = 145.958$, $p < 0.001$, and also by light distribution, $F(2, 50) = 13.474$, $p < 0.001$. There was also a significant interaction between level of MRSE and light distribution, $F(4,100) = 4.698$, $p = 0.002$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was again a significant difference between direct and indirect scenes ($p < 0.001$) and also between direct and mixed ($p < 0.001$), but with no statistically significant difference being concluded between the mixed and indirect scenes. For level of MRSE, there was again a statistically significant difference between each of the pairs of means ($p < 0.001$).

In sitting three, participants viewed scenes with dark surface reflectances as given in Table 7. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 1.38$, $p = 0.502$, level of MRSE, $X^2(2) = 3.353$, $p = 0.187$, and the interaction between level of MRSE and light distribution, $X^2(9) = 10.598$, $p = 0.305$. Within subjects effects then showed that subjective assessment of brightness was influenced by level of MRSE, $F(2, 50) = 223.244$, $p < 0.001$, and also by light distribution, $F(2, 50) = 11.520$, $p < 0.001$. There was also a significant interaction between level of MRSE and light distribution, $F(4, 100) = 2.722$, $p = 0.002$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was again a significant difference between direct and indirect scenes ($p = 0.001$) and also between direct and mixed ($p < 0.001$). No statistically significant difference could be concluded between the mixed and indirect scenes. For level of MRSE, there was a statistically significant difference between each of the pairs of means ($p < 0.001$).

### 4.3.3 Experiment 1: Mean room surface exitance and mean horizontal illuminance

Graphing the mean spatial brightness response of each light scene visually indicates the difference in relationship between MRSE and spatial brightness, compared with horizontal illuminance and spatial brightness (Figure 5 and Figure 6). Applying a linear regression to MRSE and spatial brightness produces a strong relationship between the two items ($R^2 = 0.89$). Within this experiment, horizontal illuminance was not explicitly controlled as an independent variable and in addition, participants viewed values of it within a small range, generally between 50 lux and 250 lux. However, applying a linear regression model to horizontal illuminance and spatial brightness serves as a pragmatic backward inference as to the relationship experienced between the two items. Considering the entire dataset as a whole, no predictable relationship could be found. Visually examining Figure 6 shows that three outlying points strongly influence the regression line. Applying a linear regression that excludes these points improves the relationship experienced ($R^2$=0.46), but not to the level where it could be considered strong.

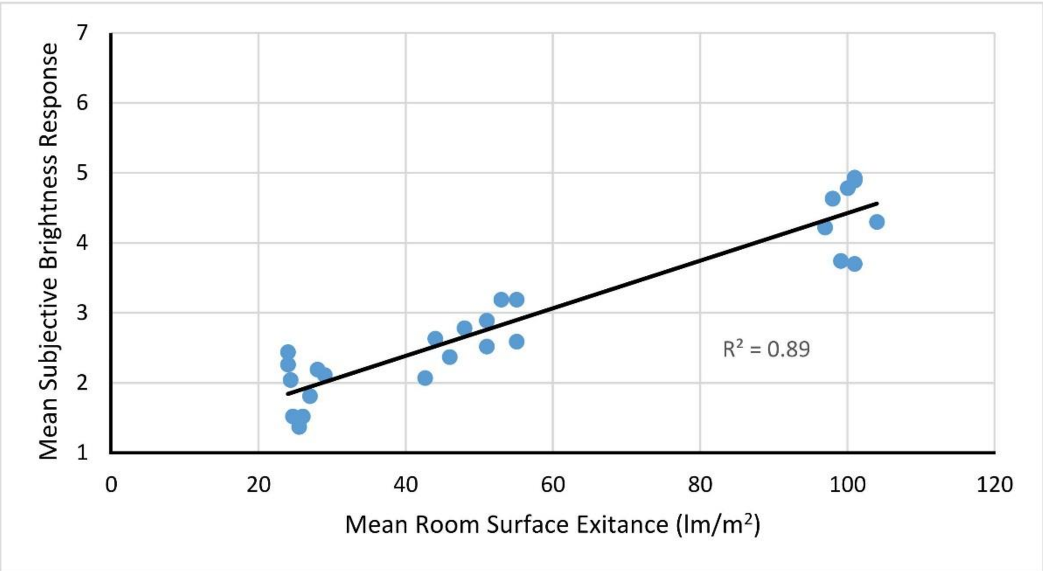


Figure 5 The mean spatial brightness rating plotted against the mean room surface exitance for each light scene presented.

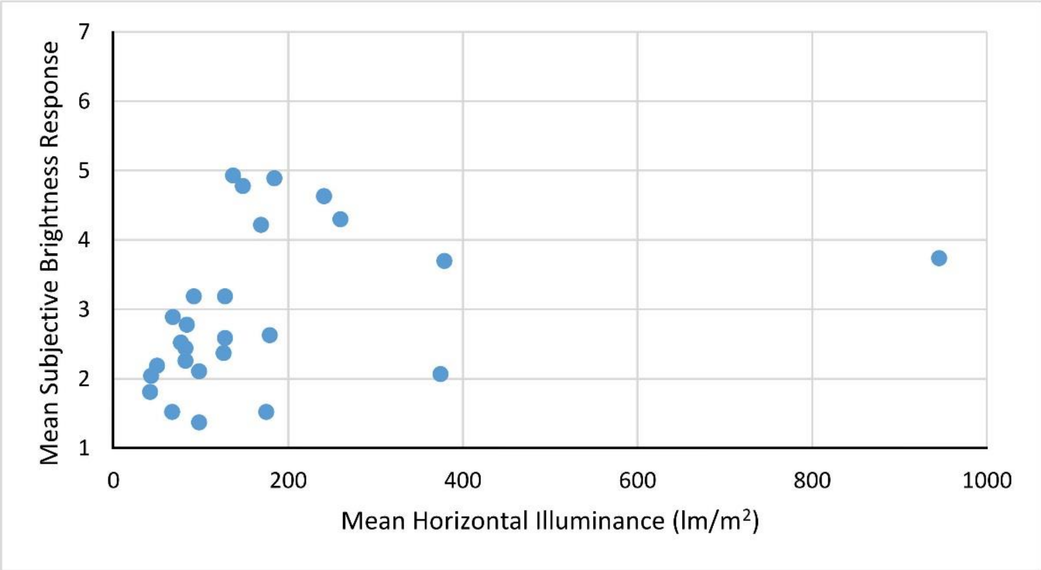


Figure 6  The mean spatial brightness rating plotted against the horizontal illuminance for each light scene presented.

### 4.3.4 Experiment 1: Discussion

Analysis of the results has shown that regardless of light distribution or surface reflectance, in the light scenes presented, the level of MRSE had a significant impact on subjective assessment of spatial brightness.  In addition, whilst participants were exposed to two independent variables during each sitting, MRSE and light distribution, analysis demonstrated that level of MRSE had a stronger impact on assessment of spatial brightness than light distribution.

The relationship between luminance and brightness has previously been shown to be logarithmic,[82,83,84,85,86] but the upper levels of luminance used in these studies reached values far in excess of what the participants were exposed to in this experiment.  Participants viewed scenes between 25 lm/m$^2$ and 100 lm/m$^2$, with the maximum recorded luminance being 86 cd/m$^2$.  The results in this study demonstrated a strong linear relationship between MRSE and spatial brightness. Remembering that values one to seven were assigned to each response category from very dim to very bright, the relationship between spatial brightness (B) and MRSE experienced in this study can be approximately given by:

$$B = 1 + \frac{MRSE}{30} \tag{11}$$

Again, it should be noted that the maximum value of MRSE used in this study was 100 lm/m$^2$. It is envisaged that as levels of MRSE increase above this value, ratings of brightness may plateau. Verifying and further understanding this relationship will be a focus for future work.

From the linear regression analysis, and visually from Figure 5 and Figure 6, it can be seen that for the light scenes used in this study, MRSE was a superior predictor of spatial brightness when compared with horizontal illuminance. Logically, increasing or decreasing the luminance of the surfaces within a space will have an impact on how dim or bright it appears, but the illumination engineering metrics used to control this phenomena are not yet widely understood. Loe et al investigated subjective response to brightness using the average luminance and the luminance distribution standard deviation within a horizontal band 40° wide.[79] Experiment 1 did not record luminance values within the horizontal band 40° wide, but did record luminance values on all booth surfaces. Using the premise that the mean luminance of the booth walls is approximately equivalent to that of the 40° wide horizontal band, correlations can be drawn between mean wall luminance and MRSE ($r = 0.95$) and also between mean wall luminance and horizontal illuminance (r = 0.69). This serves to highlight that if controlling luminance in the field of view is of importance, then for the scenes used in this study, even with a wide range of light distributions and surface reflectances, MRSE was more than horizontal illuminance.

In two separate studies, Loe et al[79,80] found that firstly, for a room to appear "light", it needed to have an average luminance within the horizontal band 40° wide of at least 30 cd/m$^2$ and secondly, that for a space to "begin to appear bright", luminance levels within the horizontal band 40° wide need to be approximately 40 cd/m$^2$. The results found in this study show substantial agreement with these findings.

### 4.3.5 Experiment 1: Limitations

The definition of brightness given to study participants should be considered. This was taken from previous work by Vrabel et al[81] and it informed participants to relate very bright to "the light in an outdoor sports area (when all the floodlights are on)" and relate very dim to the brightness "of an outdoor parking lot at night". Whilst defining the ends of the semantic scale has benefits, in this case, the chosen definition caused scale compression. None of the light scenes that participants viewed approached a brightness close to the level of an outdoor sports area, nor did they come close to the dimness of an outdoor parking lot at night. Defining these extremes may have ultimately suggested to participants that they should not choose towards the outer ends of the scale and results of this are evident in Figure 5, where few scenes were scored towards the upper end of the brightness scale.

A range of surface reflectances was presented, but due to the nature of changing reflectance properties, participants experienced these in a fixed order, producing an associated order effect. As such, results across each of the surfaces reflectances could not be compared in an ideal manner.

While this experiment has examined a range of light distributions, it has not explored very extreme distributions. Truly non-uniform distributions were not investigated and it still remains unclear how participants will react to these.

Many past studies have investigated how the spectral power distribution of the lighting affects the perceived brightness of a space and this work is still on-going. The work presented in this chapter did not vary spectral power distribution, with each of the sources used having a CCT of 4000K and a $R_a$ of 80.

# Summary of Chapter 4

Chapter 4 presented work that set out to address Research Question 3:

3. Is MRSE more closely related to subjective perceptions of spatial brightness than mean horizontal workplane illuminance?

It detailed an experiment (Experiment 1) which used a lighting booth to investigate the relationship between MRSE and spatial brightness under varying surface properties and light distributions, but with static source spectral power distributions. It then compared this relationship to the relationship between horizontal illuminance and spatial brightness under the same conditions.

Overall, it presented one original contribution to knowledge. Within Experiment 1, the level of MRSE was a better predictor of spatial brightness than horizontal illuminance, or more specifically, and considering the limitations discussed, the key findings in this chapter have been:

- A simple linear relationship was found to exist between MRSE and spatial brightness.
- A broadly unpredictable relationship was found to exist between horizontal illuminance and spatial brightness.

# 5 Perceived adequacy of illumination, spatial brightness, horizontal illuminance and mean room surface exitance in a small office

## Preamble to Chapter 5

Chapter 5 presents work that had two main objectives. First, this work set out to repeat the objectives examined in Experiment 1, but on a larger scale. Experiment 1, as described in Chapter 4, used a small booth to create various light scenes and Experiment 2 sat participants within a small office space and addressed Research Question 4:

4. Is MRSE more closely related to subjective perceptions of spatial brightness than mean horizontal workplane illuminance?

Second, Experiment 2 conducted further works to address Research Question 5:

5. Is MRSE more closely linked with PAI than mean horizontal workplane illuminance?

More specifically, Chapter 5 presents methods, results, analysis and discussion from an experiment (Experiment 2) that used a small office to investigate the suitability of mean room surface exitance as a predictor of spatial brightness and perceived adequacy of illumination, then compared these results with how horizontal illuminance predicted both items under the same conditions.

Findings highlighted one original contribution to knowledge, such that a predictable relationship existed between mean room surface exitance and perceived adequacy of illumination, but not between horizontal illuminance and perceived adequacy of illumination.

## 5.1 Experiment 2: Introduction

In addition to MRSE relating to the perceived brightness of a space, as discussed in Chapter 2, Cuttle has proposed the criterion of perceived adequacy of illumination (PAI) for use in lighting standards.[23] PAI is the quantity of light within a space that is likely to be judged sufficiently bright, or adequate, for the activity carried out in that particular space. It has been suggested that MRSE[23] is a metric that may correlate with the perceived brightness of a space and in turn, the PAI. A full explanation of the above terms and some design examples are available in Chapter 2 and further reading available elsewhere[20,21,32]

Experiment 1, as outlined within Chapter 4, demonstrated that the level of MRSE to which participants' were exposed, was more closely related to subjective assessments of spatial brightness reported, than the level of horizontal illuminance.[87] However, this work did not require experiment participants' to make assessments of PAI. The reason this was not required is simply that the concept of PAI relies on the occupant of a space relating their perceived level of brightness to the apparent, or proposed, function of the space. When viewing a lighting booth, such as that used in Experiment 1, it is hard to imagine what level of brightness would be reported as adequate, as the space being assessed has no familiar or obvious function.

This chapter presents results from a further experiment conducted in a small, purpose modified office space, which investigated what Experiment 1 had not; the relationship between MRSE and PAI and between spatial brightness and PAI. In addition, it also sought to repeat the procedure from Experiment 1 on a larger sacale and compared how MRSE and horizontal illuminance perform as predictors of both spatial brightness and PAI.

## 5.2 Experiment 2: Methodology

Experiment 2 used a small room as an experimental space. The room used was 5000 mm long, 2900 mm wide and 2850 mm high. The room contained a single work desk and two chairs and was completely shielded from daylight penetration. Lighting was provided by linear T5 fluorescent luminaires on the ceiling, TC-DEL fluorescent wall uplights and T5 fluorescent freestanding floor lamps, all of which were PWM dimmable. All lamps had a manufacturer stated CCT of 4000K and a Ra of 80. Luminaires were circuited, grouped (SC-1, SC2 & SC-3) and dimmed together to produce uplight and downlight components (Figure 7 & Figure 8). Light scenes were programmed using a DALI or DSI interface and a scene set panel. Ceiling and wall luminaires were connected back to a wall mounted DALI scene set panel. The floor standing luminaires contained in-built DSI scene set options. Reflectance values were calculated using luminance and illuminance measurements. Luminance values were recorded using a Konica Minolta LS-110 luminance meter at 300 mm intervals across each of the major room surfaces and converted to MRSE using equations (9) and (10). Prior to beginning each experimental sitting, all lamps were run at full output for a sufficient length of time such that output stabilised. During the experimental procedure, previously recorded MRSE values were verified with spot measurements taken at the start and end of each light scene.

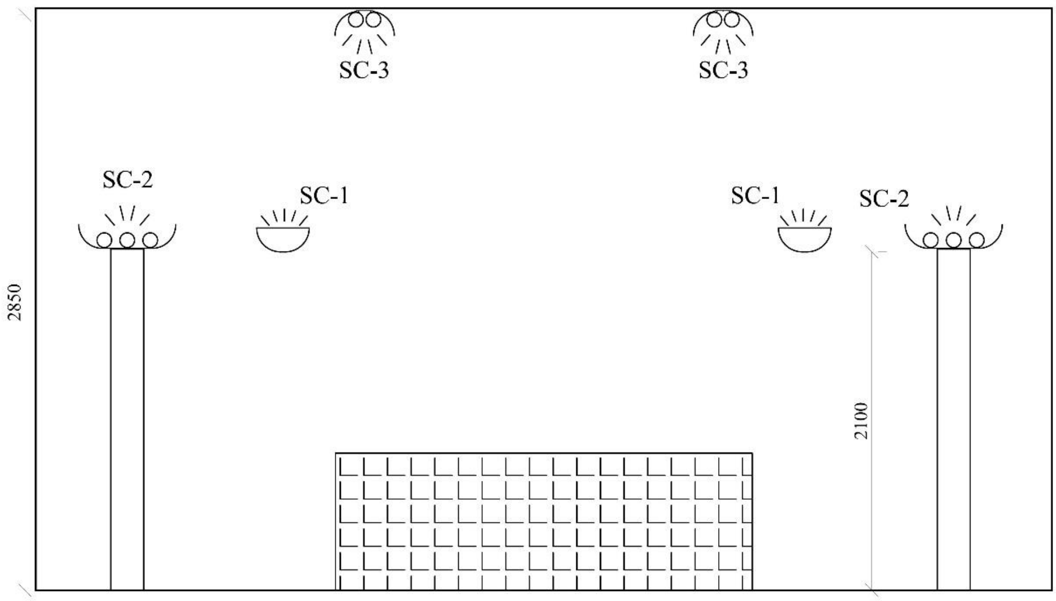


Figure 7 Elevation section of the test space used.

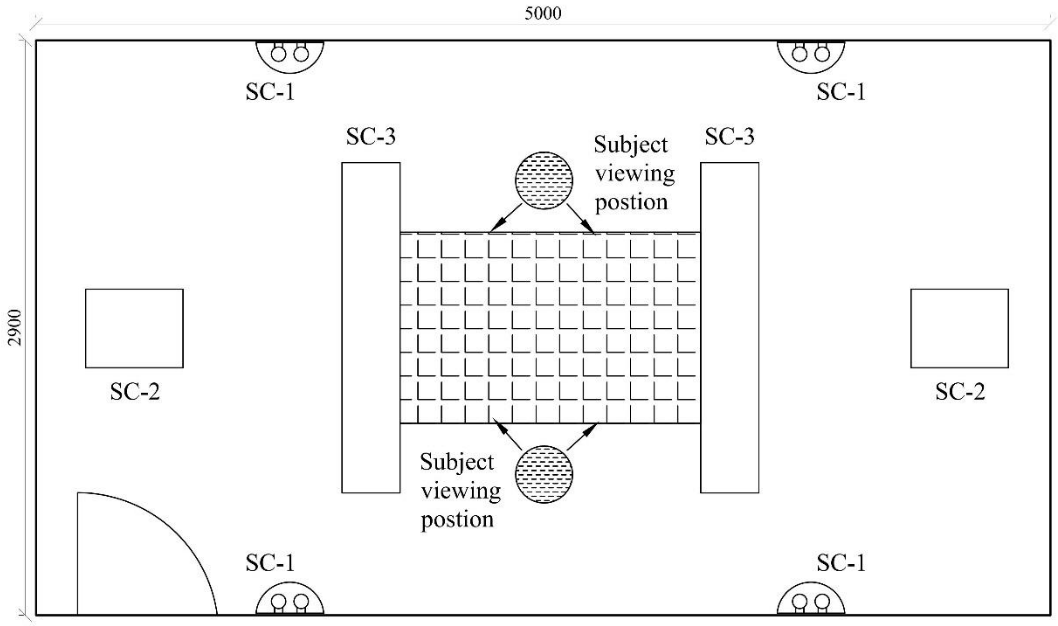


Figure 8 Plan section of the test space used.

The study examined subjective response to spatial brightness and PAI. The study included 26 participants, aged between 18 and 25 ($\mu$ = 20.8, $\sigma$ = 2.3) with no participants using corrective eyewear. In each experiment, participants viewed a range of light scenes. The experiment used groups of two participants and each participant completed three separate sittings. A 300 mm high partition was placed at the centre of the table and used to prevent participants viewing the written responses of the other participant. During each sitting, participants were exposed to nine different light scenes at varying levels of MRSE, with the corresponding level of horizontal illuminance at workplane level (0.8m AFFL) also recorded. Three levels of MRSE were set up; 25 lm/m$^2$, 50 lm/m$^2$ and 100 lm/m$^2$, along with three methods to achieve the distributions of each, being indirect, direct and mixed. Indirect scenes were a combination of SC-1 and SC-2, direct scenes were solely SC-3 and the mixed scenes were a combination of all three switching circuits. The reflectance of the room surfaces were also varied to broadly represent light, medium and dark surface properties. All of these combinations produced a total of 27 light scenes. A graphical breakdown of the light scenes is given in Figure 9 and further detail about surface reflectances, luminance distribution and luminance uniformity is given in Table 8.

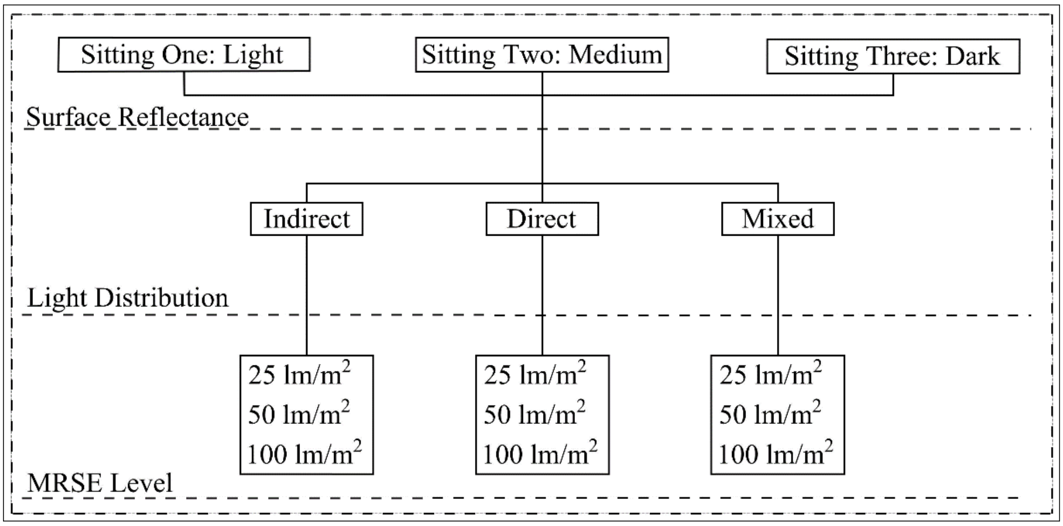


Figure 9 Graphical representation of each light scene programmed. Note that each sitting contained static surface reflectances, but varied levels of MRSE and luminous distribution.

The order of exposure to light scenes was randomised and three scenes were repeated to compare participants' responses to identical scenes. This was used to assess if the order of light scene exposure had a significant impact on assessments. The repeated scenes were scene 7, scene 14 and scene 21 and were chosen to best include for each of the variables; being one scene from each level of MRSE, one scene from each light distribution and one scene from each surface reflectance. The light scene numbers are given in Table 8. Participants were exposed to each scene for two minutes and during each scene, answered a first question that examined PAI, with a binary response required, in addition to a second question that asked about subjective spatial brightness levels, with responses given on a seven point semantic differential scale. Question response polarity was varied at random to prevent directional bias.

Q1. The lighting in the space is adequate – Yes / No

Q2. On the scale below, please rate the brightness of the entire space.

| | | | | | | |
|---|---|---|---|---|---|---|
| very dim | dim | slightly dim | neither dim nor bright | slightly bright | bright | very bright |

Adequate lighting was defined as "the correct quantity of light for use in an office space". Brightness scales were defined using the definition coined by Vrabel et al;[81] "very bright is represented by the light in an outdoor sports area (when all the floodlights are on) and very dim is the level of an outdoor parking lot at night". In addition to this, participants were reminded prior to each scene change that they should relate brightness to the entire space, and not solely their immediate field of view.

## 5.3 Experiment 2: Results and analysis

Responses to PAI were assigned values of one for Yes and two for No, with the percentage of participants responding Yes given in results. Values of one to seven were assigned for responses from very dim to very bright respectively. A full list of the percentage of participants that responded Yes and the mean spatial brightness response ratings, coupled with the standard deviation for all light scenes is given within Table 8.

Using parametric statistical tests requires that data to be drawn from a normally distributed sample. Binary data cannot be normally distributed and as such, non-parametric tests were applied. Distribution of brightness response data was investigated using statistical and graphical methods available through SPSS, namely; measures of central tendency, skewness, frequency histogram, kurtosis, box and whisker plots and probability plots. Results of these tests indicated that the data was not normally distributed and as such, non-parametric statistical tests have been applied.

Table 8 Properties of the 27 lights scenes programmed. Also indicated is the percentage of Yes responses to PAI and the mean subjective spatial brightness rating for each light scene.

| Light Scene Number | Target MRSE (lm/m2) | Surface Reflectance (Ceiling/ Wall/ Floor) | Light Distribution | Recorded MRSE (lm/m2) | Recorded Horizontal Illuminance (lm/m2) | Mean Recorded Luminance (Uo), (cd/m2) | | | | Q1 Yes response to PAI, (%) | Q2 Mean Spatial Brightness Rating (SD) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Floor | Ceiling | Long Wall | Short Wall | | |
| 1 | 25 | Sitting 1 86/84/24 | Indirect | 29 | 38 | 2.6 (0.82) | 16.0 (0.63) | 9.8 (0.52) | 8.4 (0.76) | 15.4 | 2.00 (0.64) |
| 2 | 25 | | Direct | 26 | 98 | 3.8 (0.73) | 8.0 (0.75) | 9.3 (0.71) | 9.5 (0.75) | 11.5 | 1.65 (0.63) |
| 3 | 25 | | Mixed | 26 | 56 | 3.7 (0.72) | 10.1 (0.71) | 8.9 (0.69) | 9.2 (0.73) | 23.1 | 2.46 (0.57) |
| 4 | 50 | | Indirect | 51 | 68 | 4.6 (0.82) | 28.0 (0.64) | 17.0 (0.53) | 15.0 (0.63) | 34.6 | 2.77 (0.61) |
| 5 | 50 | | Direct | 52 | 112 | 7.6 (0.73) | 16.0 (0.75) | 19.0 (0.68) | 19.0 (0.74) | 30.8 | 2.08 (0.65) |
| 6 | 50 | | Mixed | 48 | 85 | 5.8 (0.76) | 20.0 (0.70) | 17.0 (0.65) | 16.0 (0.69) | 42.3 | 3.42 (0.72) |
| 7 | 100 | | Indirect | 101 | 137 | 9.2 (0.82) | 56.0 (0.64) | 34.0 (0.53) | 30.0 (.63) | 50.0 | 4.15 (0.58) |
| 8 | 100 | | Direct | 103 | 224 | 15 (0.73) | 32.0 (0.75) | 37.0 0.70) | 38.0 (0.76) | 46.2 | 3.73 (0.80) |
| 9 | 100 | | Mixed | 103 | 181 | 12 (0.77) | 44.0 (0.70) | 36.0 (0.64) | 34.0 (0.71) | 65.4 | 4.65 (0.75) |
| 10 | 25 | Sitting 2 69/62/24 | Indirect | 27 | 41 | 2.5 (0.79) | 19.0 (0.52) | 8.7 (0.42) | 6.7 (0.59) | 11.5 | 1.96 (0.59) |
| 11 | 25 | | Direct | 25 | 82 | 5.0 (0.67) | 7.3 (0.63) | 8.9 (0.63) | 9.2 (0.67) | 7.7 | 1.50 (0.60) |
| 12 | 25 | | Mixed | 23 | 56 | 3.5 (0.71) | 11.0 (0.57) | 7.7 (0.59) | 7.1 (0.70) | 11.5 | 2.35 (0.67) |
| 13 | 50 | | Indirect | 52 | 77 | 4.7 (0.80) | 36.0 (0.50) | 16.0 (0.43) | 13.0 (0.57) | 30.8 | 2.81 (0.74) |
| 14 | 50 | | Direct | 51 | 163 | 10.0 (0.67) | 15.0 (0.61) | 18.0 (0.61) | 18.0 (0.67) | 23.1 | 2.12 (0.59) |
| 15 | 50 | | Mixed | 50 | 118 | 7.2 (0.72) | 24.0 (0.58) | 17.0 (0.56) | 15.0 (0.73) | 30.8 | 2.96 (0.69) |
| 16 | 100 | | Indirect | 100 | 148 | 9.1 (0.80) | 70.0 (0.51) | 32.0 (0.41) | 24.0 (0.58) | 42.3 | 4.08 (0.83) |
| 17 | 100 | | Direct | 102 | 326 | 20.0 (0.65) | 29.0 (0.62) | 36.0 (0.61) | 37.0 (0.68) | 38.5 | 3.31 (0.45) |
| 18 | 100 | | Mixed | 98 | 235 | 14 (0.71) | 48.0 (0.56) | 33.0 (0.58) | 30.0 (0.70) | 50.0 | 4.08 (0.83) |
| 19 | 25 | Sitting 3 44/38/17 | Indirect | 25 | 42 | 1.7 (0.78) | 22.0 (0.34) | 7.1 (0.29) | 4.6 (0.49) | 11.5 | 1.31 (0.45) |
| 20 | 25 | | Direct | 25 | 146 | 6.0 (0.61) | 6.0 (0.49) | 8.5 (0.41) | 9.0 (0.58) | 3.8 | 1.19 (0.36) |
| 21 | 25 | | Mixed | 23 | 56 | 3.5 (0.71) | 11.0 (0.57) | 7.7 (0.59) | 7.1 (0.70) | 11.5 | 1.88 (0.59) |
| 22 | 50 | | Indirect | 49 | 84 | 3.5 (0.78) | 43.0 (0.35) | 14.0 (0.29) | 9.2 (0.49) | 26.9 | 2.54 (0.76) |
| 23 | 50 | | Direct | 49 | 341 | 12 (0.63) | 12.0 (0.50) | 17.0 (0.47) | 18.0 (0.61) | 23.1% | 1.92 (0.67) |
| 24 | 50 | | Mixed | 50 | 118 | 7.2 (0.72) | 24.0 (0.58) | 17.0 (0.56) | 15.0 (0.73) | 26.9% | 2.40 (0.69) |

| Light Scene Number | Target MRSE (lm/m2) | Surface Reflectance (Ceiling/ Wall/ Floor) | Light Distribution | Recorded MRSE (lm/m2) | Recorded Horizontal Illuminance (lm/m2) | Mean Recorded Luminance (Uo), (cd/m2) | | | | Q1 | Q2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Floor | Ceiling | Long Wall | Short Wall | Yes response to PAI, (%) | Mean Spatial Brightness Rating (SD) |
| 25 | 100 | Sitting 3 44/38/17 | Indirect | 97 | 169 | 7.0 (0.78) | 94.0 (0.35) | 28.0 (0.29) | 18.0 (0.50) | 50.0% | 3.65 (0.73) |
| 26 | 100 | | Direct | 100 | 540 | 24 (0.34) | 24.0 (0.28) | 34.0 (0.27) | 36.0 (0.32) | 38.5% | 3.19 (0.59) |
| 27 | 100 | | Mixed | 98 | 235 | 14.0 (0.71) | 48.0 (0.56) | 33.0 (0.58) | 30.0 (0.70) | 53.8% | 3.96 (0.52) |

### 5.3.1 Experiment 2: Repeated scenes

Repeated scenes were introduced to ensure that the order of light scene exposure had no impact on subjective assessments. As stated previous, three scenes were repeated without participants knowledge; scene 7, scene 14 and scene 21, with the repeated scene being excluded from final results.

The three binary response scores for PAI were tested in pairs using McNemar's Exact. All three scenes produced no statistically significant difference between participants' responses when a scene was viewed first or second time around (scene 7, $X^2(1) = 1.5$, $p = 0.204$; scene 14, $X^2(1) = 0.33$, $p = 0.564$ and scene 21, $X^2(1) = 1.00$, $p = 0.317$). Scores produced from each of the spatial brightness responses were examined using the Wilcoxon signed-rank test. All three scenes repeated produced no statistically significant difference between participants' first response and their second (scene 7, $Z = -1.633$, $p = 0.102$; scene 14, $Z = 0.707$, $p = 0.480$ and scene 21, $Z = -0.333$, $p = 0.739$). It can thus be concluded that the order of exposure had no significant impact on participants' assessments.

### 5.3.2 Experiment 2: Mean Room Surface Exitance and Perceived Adequacy of Illumination

Cochran's Q was applied to investigate the influence of the independent variables on assessments of PAI. To change the reflectances of the room surfaces, they were cleaned and repainted. With this being unavoidable, participants then viewed the scenes in three separate sittings (one for each reflectance) but all in the same order, producing an associated order effect. For this reason, three separate Cochran's Q tests were carried out on the data for each level of surface reflectance, but also for each independent variable, being level of MRSE (3) and light distribution (3).

In sitting one, participants viewed scenes with light surface reflectances as given in Table 8. Applying Cochran's Q to all the data from sitting one indicated significant differences between the proportions, $X^2(2) = 27.25$, $p = 0.001$. Using Cochran’s Q to further analyse the data showed that no significant difference occurred due to light distribution at each level of MRSE (MRSE of $25lm/m^2$, $X^2(2) = 1.4$, $p = 0.497$; MRSE of $50lm/m^2$, $X^2(2) = 0.7$, $p = 0.705$ and MRSE of $100lm/m^2$, $X^2(2) = 2.47$, p = 0.29I) and significant differences were found within each light distribution type due to level of MRSE (Indirect, $X^2(2) = 6.778$, $p = 0.034$; Direct, $X^2(2) = 6.1$, $p = 0.047$ and Mixed, $X^2(2) = 8.27$, $p = 0.013$).

In sitting two, participants viewed scenes with medium surface reflectances as given in Table 8. Applying Cochran's Q to all the data from sitting two indicated significant differences between the proportions, $X^2(2) = 23.524$, $p = 0.003$. Using Cochran’s Q to further analyse the data showed that no significant difference occurred due to light distribution at each level of MRSE (MRSE of $25lm/m^2$, $X^2(2) = 0.333$, $p = 0.846$; MRSE of $50lm/m^2$, $X^2(2) = 0.5$, $p = 0.779$ and MRSE of $100lm/m^2$, $X^2(2) = 0.636$, $p = 0.727$). Significant differences, due to level of MRSE, were found within the direct and the mixed light distribution types (Direct, $X^2(2) = 7.385$, $p = 0.025$ and Mixed, $X^2(2) = 10.0$, $p = 0.007$), but not within the indirect (Indirect, $X^2(2) = 5.765$, $p = 0.056$). It can be noted that whilst the indirect scenes did not produce significant differences between levels of MRSE, the value reported is very close to being significant, i.e. $p < 0.05$.

In sitting three, participants viewed scenes with dark surface reflectances as given in Table 8. Applying Cochran's Q to all the data from sitting three indicated significant differences between the proportions, $X^2(2) = 30.227$, $p < 0.001$. Using

Cochran's Q to further analyse the data showed that no significant difference occurred due to light distribution at each level of MRSE (MRSE of 25lm/m$^2$, $X^2(2) = 1.143$, $p = 0.565$; MRSE of 50lm/m$^2$, $X^2(2) = 0.118$, $p = 0.943$ and MRSE of 100lm/m$^2$, $X^2(2) = 1.13$, $p = 0.568$) and significant differences were found within each light distribution type due to level of MRSE (Indirect, $X^2(2) = 9.5$, $p = 0.009$; Direct, $X^2(2) = 8.714$, $p = 0.013$ and Mixed, $X^2(2) = 9.3$, $p = 0.01$).

### 5.3.3 Experiment 2: Mean Room Surface Exitance and spatial brightness

Repeated measures ANOVA was used to investigate the influence of the different independent variables on spatial brightness assessments. Again, and for the reasons described previously, an order effect existed such that results had to be analysed separately for each level of surface reflectance presented. As such, three separate two by three repeated measures ANOVA were carried out, with level of MRSE (3) and light distribution (3) as the independent variables.

In sitting one, participants viewed scenes with light surface reflectances as given in Table 8. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 0.555$, $p = 0.758$, level of MRSE, $X^2(2) = 2.637$, $p = 0.268$, and the interaction between level of MRSE and light distribution, $X^2(9) = 5.425$, $p = 0.796$. Within subjects effects then showed that subjective assessment of spatial brightness was influenced by level of MRSE, $F(2, 50) = 190.32$, $p < 0.001$, and also by light distribution, $F(2, 50) = 36.57$, $p < 0.001$. There was no significant interaction between level of MRSE and light distribution, $F(4, 100) = 0.438$, $p = 0.78$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was a significant difference between each of the pairs of means ($p < 0.001$). For level of MRSE, there was also a statistically significant difference between each of the pairs of means ($p < 0.001$).

In sitting two, participants viewed scenes with medium surface reflectances as given in Table 8. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 2.506$, $p = 0.268$, level of MRSE, $X^2(2) = 2.239$, $p = 0.312$, and the interaction between level of MRSE and light distribution, $X^2(9) = 15.156$, $p = 0.087$. Within subjects effects showed that subjective assessment of spatial brightness was influenced by level of MRSE, $F(2, 50) = 256.272$, $p < 0.001$, and also by light distribution, $F(2, 50) = 17.755$, $p < 0.001$. There was no significant interaction between level of MRSE and light distribution, $F(4,100) = 0.327$, $p = 0.859$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was again a significant difference between direct and indirect scenes ($p < 0.001$), between direct and mixed ($p < 0.001$) and also between the mixed and indirect scenes ($p = 0.004$). For level of MRSE, there was again a statistically significant difference between each of the pairs of means ($p < 0.001$).

In sitting three, participants viewed scenes with dark surface reflectances as given in Table 8. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 1.034$, $p = 0.596$, level of MRSE, $X^2(2) = 4.841$, $p = 0.089$, and the interaction between level of MRSE and light distribution, $X^2(9) = 8.83$, $p = 0.847$. Within subjects effects then showed that subjective assessment of brightness was influenced by level of MRSE, $F(2, 50) = 262.65$, $p < 0.001$, and also by light distribution, $F(2, 50) = 30.714$, $p < 0.001$. There was no significant interaction between level of MRSE and light distribution, $F(4,100) = 0.866$, $p = 0.487$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was again a significant difference between direct and indirect scenes ($p = 0.003$), between direct and mixed ($p < 0.001$) and also between the mixed and indirect scenes ($p = 0.003$). For level of MRSE, there was a statistically significant difference between each of the pairs of means ($p < 0.001$).

### 5.3.4 Experiment 2: Spatial brightness and perceived adequacy of illumination

Applying a Perason product-moment correlation to both the percentage of Yes responses to PAI and the mean spatial brightness response score produced a strong correlation between the two items ($r = 0.95$, $n = 26$, $p < 0.001$). A scatterplot in Figure 10 summarises the data. In essence, as levels of perceived brightness increased, so did the level of PAI. This demonstrated a strong link between the level of reported perceived brightness and the level of satisfaction with the lighting that participants reported.

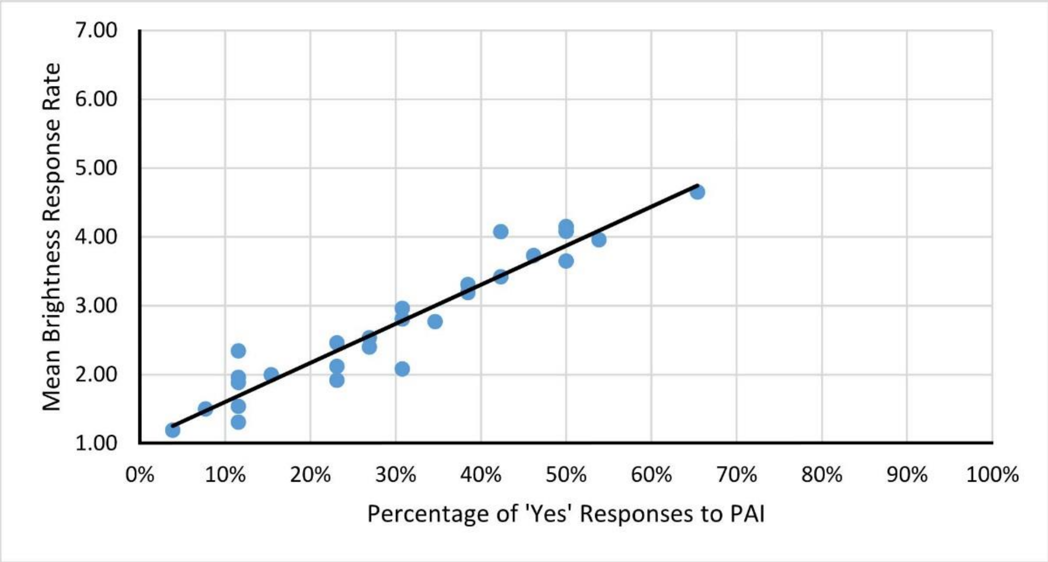


Figure 10 Graphical representation of the correlation experienced between response to spatial brightness and levels of perceived adequacy of illumination.

### 5.3.5 Experiment 2: Mean Room Surface Exitance and mean horizontal illuminance

Plotting the percentage of Yes responses to PAI for each light scene visually indicates the relationship between MRSE and PAI, compared with horizontal illuminance and PAI (Figure 11 & Figure 12). Applying a linear regression model to the level of MRSE and the proportion of Yes PAI responses produces a noticeable relationship between the two variables ($R^2$ = 0.82). Within this experiment, horizontal illuminance was not explicitly controlled as an independent variable and participants were generally exposed to a somewhat small range of values, typically between 50 lux and 250 lux. However, applying a linear regression model to horizontal illuminance and PAI serves as a useful backward inference as to the relationship experienced between the two items. Modelling the data set as a whole produces no predictable relationship between the two items ($R^2$ = 0.19). It can be seen from Figure 12 that three outlying points strongly influenced the regression line. Running the linear regression model and excluding these three points improves the coefficient of determination ($R^2 = 0.56$).

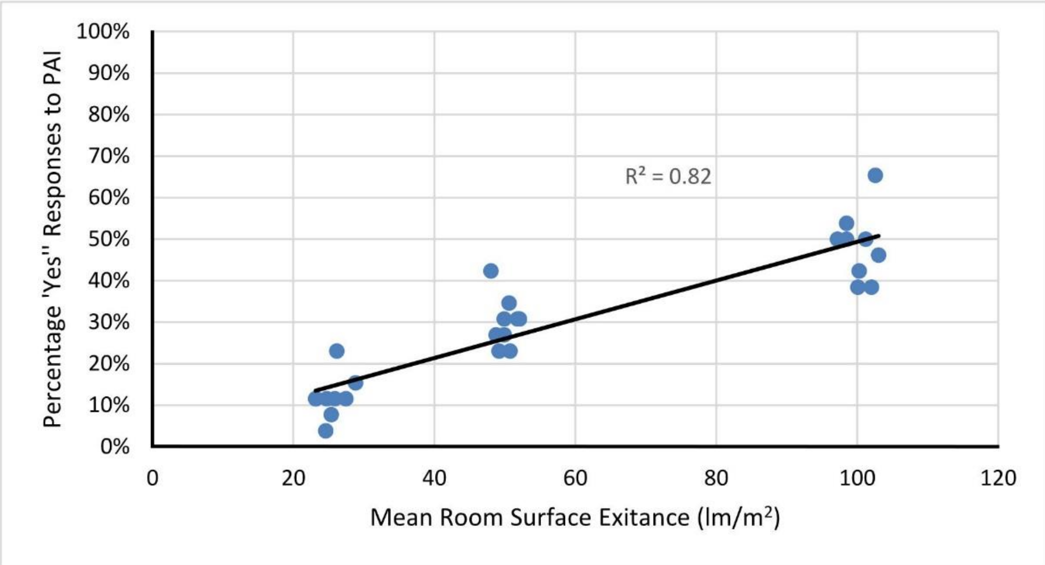


Figure 11 The percentage Yes responses to PAI plotted against the relative level of mean room surface exitance for each light scene presented.

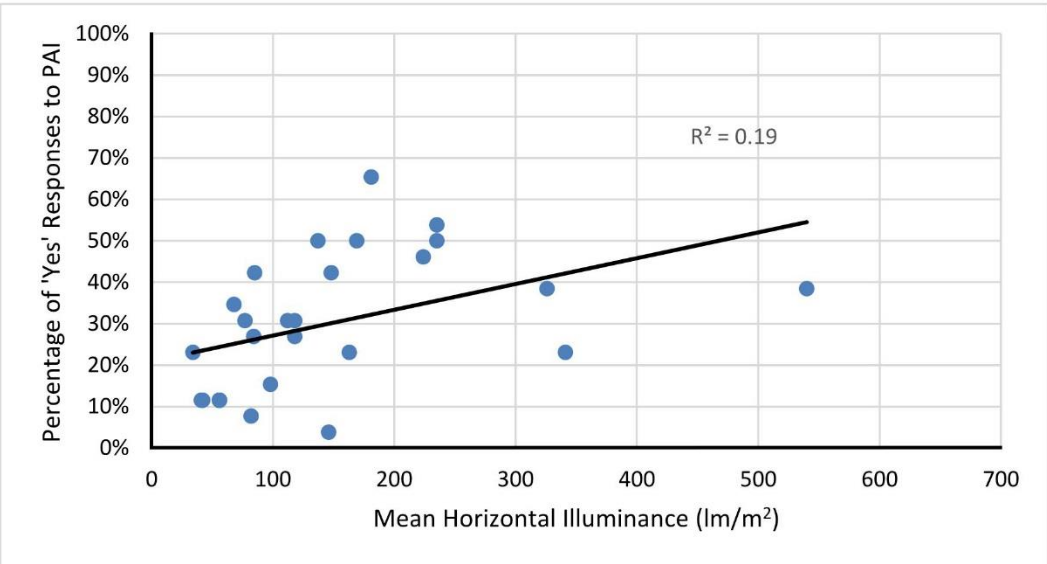


Figure 12 The percentage Yes responses to PAI plotted against the relative level of mean horizontal illuminance for each light scene presented.

Applying the same procedure to the mean spatial brightness response of each light scene visually demonstrates the difference in relationship between MRSE and spatial brightness, compared with horizontal illuminance and spatial brightness (Figure 13 & Figure 14). Applying a linear regression to MRSE and spatial brightness produces a strong relationship between the two items ($R^2$ = 0.79). Applying a linear regression model to horizontal illuminance and spatial brightness indicates no predictable relationship between the two items ($R^2$ = 0.14). From viewing Figure 14, it can be seen that three points within this data set strongly influenced the regression line, so the model was re-run without these points, improving the coefficient of determination ($R^2$ = 0.39).

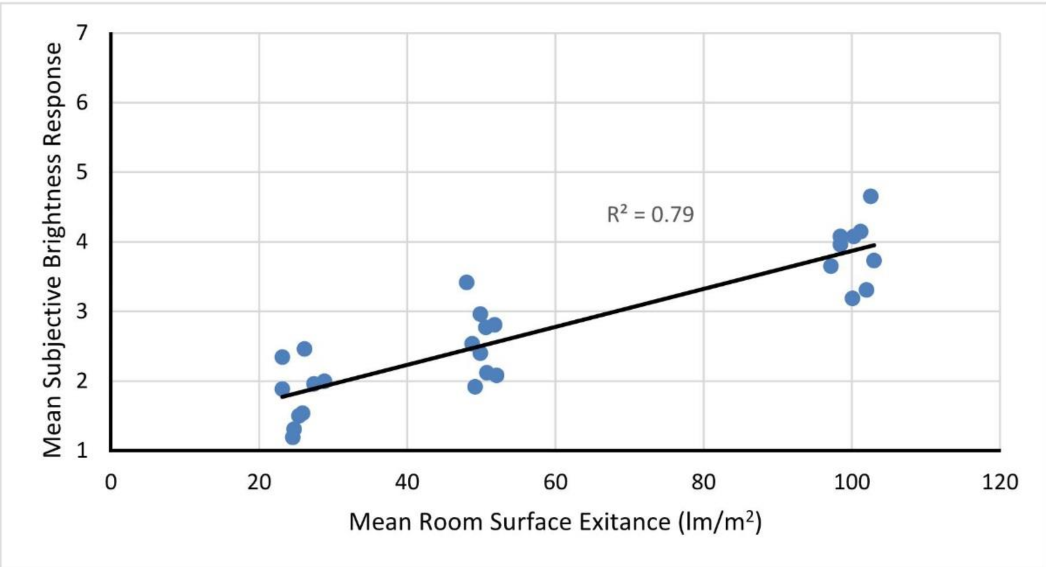


Figure 13 The mean spatial brightness response rate plotted against the relative level of mean room surface exitance for each light scene presented.

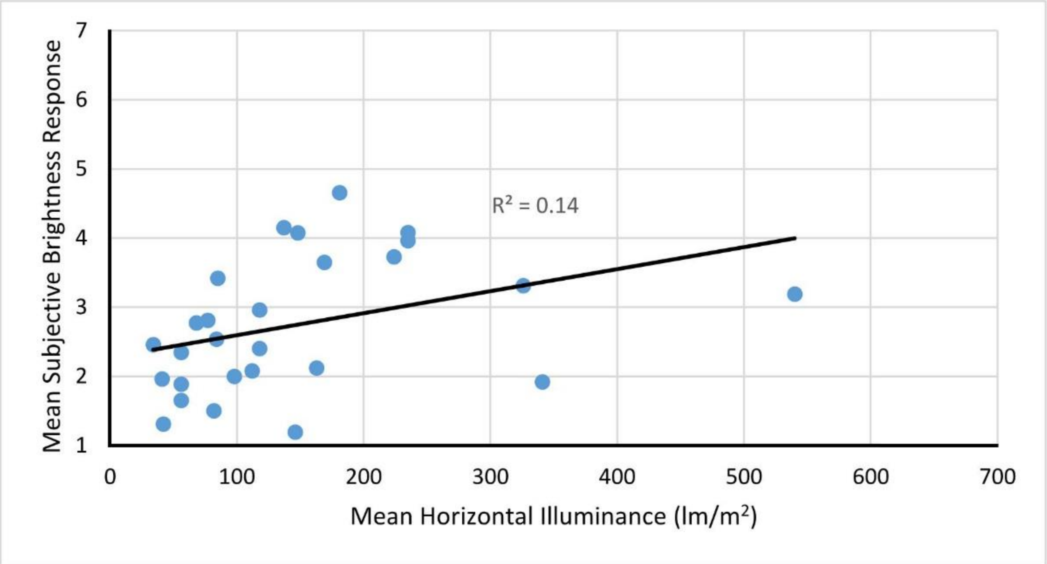


Figure 14 The mean spatial brightness response rate plotted against the relative level of horizontal illuminance for each light scene presented.

## 5.4 Experiment 2: Discussion

Statistical testing showed that regardless of light distribution or surface reflectance, in the light scenes presented, the level of MRSE had a significant impact on subjective assessment of both PAI and spatial brightness. Participants were exposed to two independent variables during each sitting, MRSE and light distribution, however, the analysis demonstrated that level of MRSE had a stronger impact on assessment on both PAI and spatial brightness than did light distribution.

The relationship between luminance and brightness has previously been shown to be logarithmical,[82,83,84,85,86] but the upper levels of luminance used in these experiments was far in excess of what participants in the current study were exposed to. Experiment 1 mimicked the experimental process of the current study, but utilised a scaled booth to make assessments of spatial brightness. This work found a linear relationship between reported levels of spatial brightness and MRSE as denoted in equation (11). Remembering that values one to seven were assigned to each response category from very dim to very bright, the relationship between spatial brightness (B) and MRSE experienced in this study can be approximately summated by:

$$B = 1 + \frac{MRSE}{30} \tag{11}$$

Results found in this study showed substantial agreement with the findings from Experiment 1. This was gauged solely by inputting the data of each experiment into equation (11) and visually examining the outputs. However, and as stated in the discussion of Experiment 1, it should be noted that the maximum value of MRSE used was 100 $lm/m^2$. It is still envisaged that as levels of MRSE increase above this value, ratings of brightness may plateau, perhaps producing the expected logarithmical relationship. Further understanding of this relationship will be a focus for future work.

The concept of PAI very much relies on the premise that people will relate levels of spatial brightness to the feeling of the lighting in a space being appropriate. In Experiment 2 presented, participants related levels of MRSE to spatial brightness and also related levels of MRSE to PAI. With MRSE being so closely linked to both items, correlations could be drawn between both of the dependant variables. Figure 10 graphically indicates the strong correlation that existed between spatial brightness and PAI for the particular light scenes presented in this study.

From the both of the linear regression analyses results, and visually from Figure 11 to Figure 14, it can be seen that for the light scenes used in this study, MRSE was a more accurate predictor of both PAI and spatial brightness than horizontal illuminance. Logically, increasing or decreasing the luminance of the surfaces within a space will have an impact on how dim or bright it appears, but the illumination engineering metrics used to control this phenomena are not yet widely understood. In addition, there is a lesser understanding of how perceived levels of brightness relate to human satisfaction within general interior environments. Loe et al investigated subjective response to a number of items,[80] one of which was brightness, within a range of light scenes in an illuminated interior. They used the average luminance and the luminance distribution standard deviation within the horizontal 40° band to try and assess the lit environment and found strong correlations between the mean luminance in the 40° band and subjective response to brightness. Experiment 2 did not record luminance values within the horizontal 40° band, but did record luminance values on each of the room walls. Using the premise that the mean luminance of the walls is approximately equivalent to that of the 40° band, correlations can be drawn between mean wall luminance and MRSE ($r = 0.92$) and also between mean wall luminance and horizontal illuminance ($r = 0.61$). This serves to highlight that if controlling luminance in the field of view is of importance, then for the scenes used in this study, MRSE did a better job than horizontal illuminance. Additionally, Loe et al[79,80] found that firstly, for a room to appear “light”, it needed to have an average luminance within the horizontal 40° band of at least 30 cd/m$^2$ and secondly, that for a space to “begin to appear bright”, luminance levels within the horizontal 40° band need to be approximately 40 cd/m$^2$.

In addition, the results reported here show substantial agreement with those presented from Experiment 1.[87]

## 5.5 Experiment 2: Limitations

As in Experiment 1, the definition of brightness given to participants' in Experiment 2 should be noted. This was taken from previous work by Vrabel et al[81] and it informed participants to relate very bright to "the light in an outdoor sports area (when all the floodlights are on)" and relate very dim to the brightness "of an outdoor parking lot at night". Whilst defining the ends of the semantic scale has benefits, in this case, the chosen definition caused scale compression. None of the light scenes that participants viewed approached a brightness close to the level of an outdoor sports area, nor did they come close to the dimness of an outdoor parking lot at night. Defining these extremes may have ultimately inferred to participants that they should not choose towards the outer ends of the scale and results of this are evident in the brightness levels reported, where few scenes were scored towards the upper end of the brightness scale.

As in Experiment 1, Experiment 2 used a range of surface reflectances, but due to the manner in which they were changed, participants viewed them in the same order, thus producing an associated order effect. For this reason, results could not be explicitly compared across each of the levels of surface reflectance.

While Experiment 2 has examined a number of light distributions, it has not explored extreme distributions. Truly non-uniform distributions were not investigated and it still remains unclear how participants will react to these.

Many past studies have investigated how spectral power distribution affects the perceived brightness of a space and this work is still on-going. The work presented in this chapter did not vary spectral power distribution, with each of the sources used having a CCT of 4000K and a Ra of 80.

## Summary of Chapter 5

Chapter 5 presented work that had two main objectives. Firstly, it presented a study (Experiment 2) that repeated the process applied in Experiment 1 on a larger scale, to investigate Research Question 4:

4. Is MRSE more closely related to subjective perceptions of spatial brightness than mean horizontal workplane illuminance?

Second, it addressed Research Question 5:

5. Is MRSE more closely linked with PAI than mean horizontal workplane illuminance?

More specifically, Chapter 5 presented research that used a small office as an experimental space. The experiment varied level of MRSE, light distribution and surface reflectance to investigate the relationships between MRSE and PAI, between MRSE and spatial brightness and finally between spatial brightness and PAI. It also compared how MRSE and horizontal illuminance perform as predictors of both PAI and spatial brightness.

It presented one significant original contribution to knowledge. Generally, MRSE was found to better relate to PAI than horizontal illuminance. More specifically, from the results and analysis, and giving due consideration to the limitations discussed, the key findings emerging from Experiment 2 were:

- A simplistic linear relationship was found to exist between level of MRSE and both PAI and spatial brightness.
- A broadly unpredictable relationship was found to exist between level of horizontal illuminance and both PAI and spatial brightness.
- Levels of spatial brightness reported were strongly correlated with levels of PAI reported.

# 6 Spatial brightness, perceived adequacy of illumination, horizontal illuminance and mean room surface exitance in non-uniform light scenes

## Preamble to Chapter 6

Chapter's 4 and 5 have presented data that suggests MRSE to be a better predictor of both spatial brightness and PAI than horizontal illuminance. Chapter 6 presents work that set out to address if the relationships found in Experiment's 1 and 2 would hold true within light scenes that contained extreme non-uniform luminous distributions, as set out in Research Question 6:

6. Do light scenes with non-uniform luminous distributions affect subjective assessments of both spatial brightness and PAI?

More specifically, it presents methods, results, analysis and discussion from an experiment (Experiment 3) that used the same office space and participants as Experiment 2, but exposed participants to a range of non-uniform light scenes.

It ultimately highlights one original contribution to knowledge; such that a clear relationship was found to exist between mean room surface exitance and spatial brightness, but not between mean room surface exitance and perceived adequacy of illumination.

## 6.1 Experiment 3: Introduction

Experiments 1 & 2 found that the level of MRSE had a significant impact on assessments of spatial brightness.[87,88] Experiment 2 also found that the level of MRSE had a significant impact on the reported PAI.[88] Whilst a number of light distributions were used in each of these studies, the distributions couldn't be considered truly non-uniform.

Chapter 6 presents an experiment[89] conducted that used a range of non-uniform light scenes to investigate the influence of extreme luminance distributions on the previously found relationships between MRSE and PAI, between MRSE and spatial brightness and finally between spatial brightness and PAI. It also compares how MRSE and horizontal illuminance perform as predictors of both PAI and spatial brightness in non-uniform lighting conditions.

## 6.2 Experiment 3: Methodology

The experimental set up used was adapted from Experiment 2. It used the same small room as an experimental office space. The room used was 5000 mm long, 2900 mm wide and 2850 mm high. The room contained a single work desk and two chairs and was completely shielded from daylight penetration. Lighting was provided by linear T5 fluorescent luminaires on the ceiling, TC-DEL fluorescent wall uplights and T5 fluorescent freestanding floor lamps, all of which were PWM dimmable. All lamps had a manufacturer stated CCT of 4000K and a Ra of 80. Luminaires were circuited, grouped (SC-1, SC2 & SC-3) and dimmed together to produce uplight and downlight components (Figure 15 and Figure 16). Note that some of the luminaires in the room were not used in this experiment, but are shown in Figure 15 and Figure 16 for completeness. Light scenes were programmed using a DALI or DSI interface and a scene set panel. Ceiling and wall luminaires were connected back to a wall mounted DALI scene set panel. The floor standing luminaires contained in-built DSI scene set options. Reflectance values were calculated using luminance and illuminance measurements. Luminance values were recorded using a Konica Minolta LS-110 luminance meter at 300 mm intervals across each of the major room surfaces and converted to MRSE using equations (9) and (10). Prior to beginning each experiment, all lamps were run at full output for a sufficient length of time such that output stabilised. This was monitored with spot illuminance measurements. During the experimental procedure, previously recorded MRSE values were verified with spot measurements taken at the start and end of each light scene.

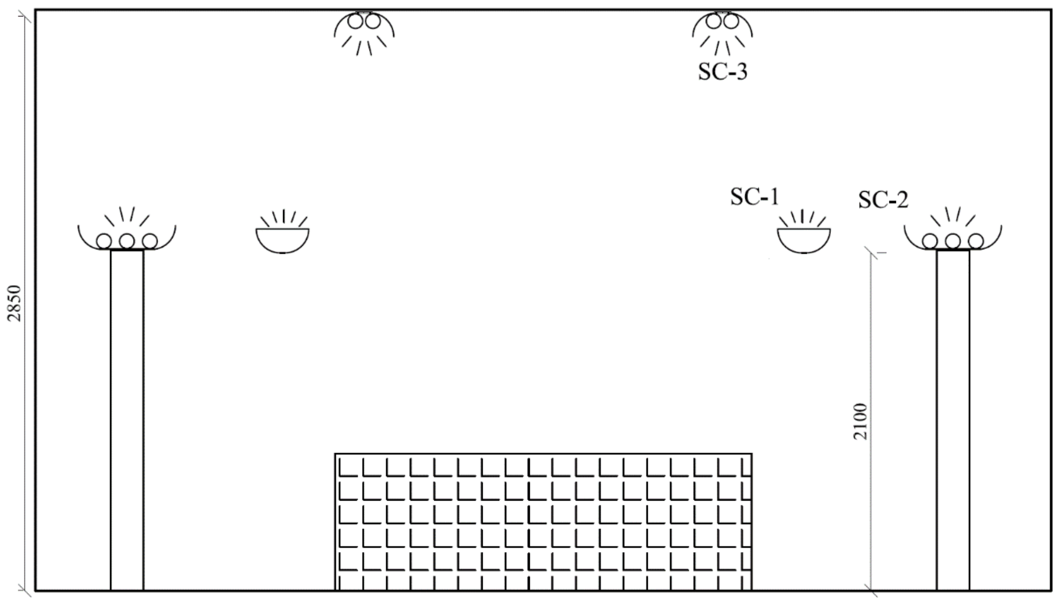

Figure 15 Elevation section of the test space used.

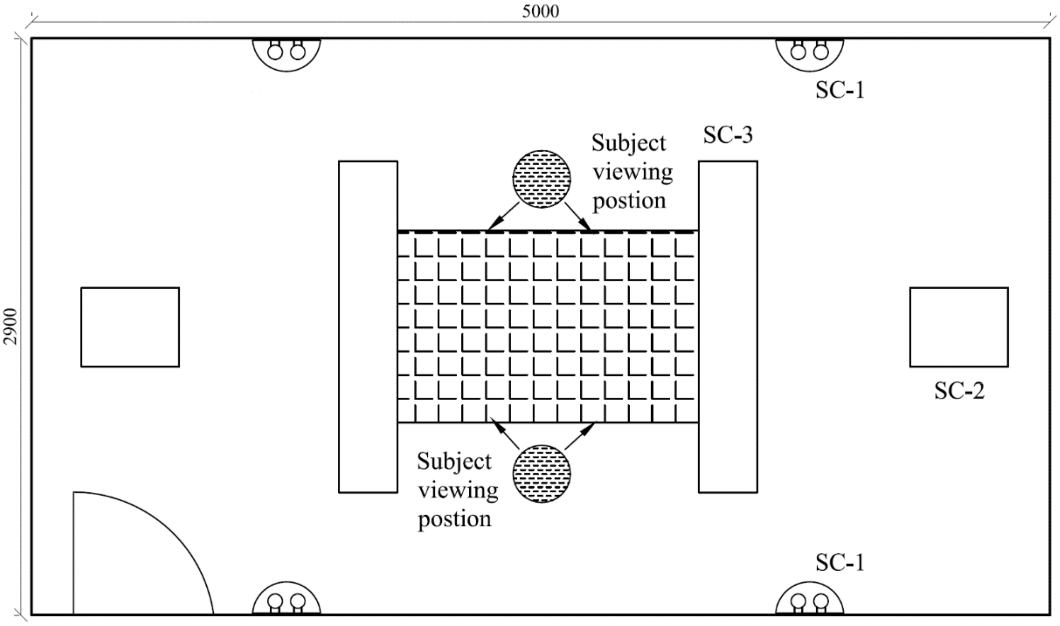

Figure 16 Plan section of the test space used.

The study examined subjective response to spatial brightness and PAI. The study included 26 participants, aged between 18 and 25 (mean = 20.8, standard deviation = 2.3) with no participants using corrective eyewear. In each experiment, participants viewed a range of light scenes specifically set up to be non-uniform in nature. The experiment used groups of two participants and each participant completed three separate sittings. A 300 mm high partition was placed at the centre of the table and used to prevent participants viewing the written responses of the other participant. During each sitting, participants were exposed to nine different light scenes at varying levels of MRSE, with the corresponding level of horizontal illuminance at workplane level (0.8m above floor level) also recorded. Three levels of MRSE were set up; 25 lm/m$^2$, 50 lm/m$^2$ and 100 lm/m$^2$, along with three methods to achieve the distributions of each, being indirect, direct and mixed. Indirect scenes were a combination of SC-1 and SC-2, direct scenes were solely SC-3 and the mixed scenes were a combination of all three switching circuits. The reflectance of the room surfaces were also varied to broadly represent light, medium and dark surface properties. All of these combinations produced a total of 27 light scenes. A graphical breakdown of the light scenes is given in Figure 17 and further detail about surface reflectances, luminance distribution and luminance uniformity is given in Table 9.

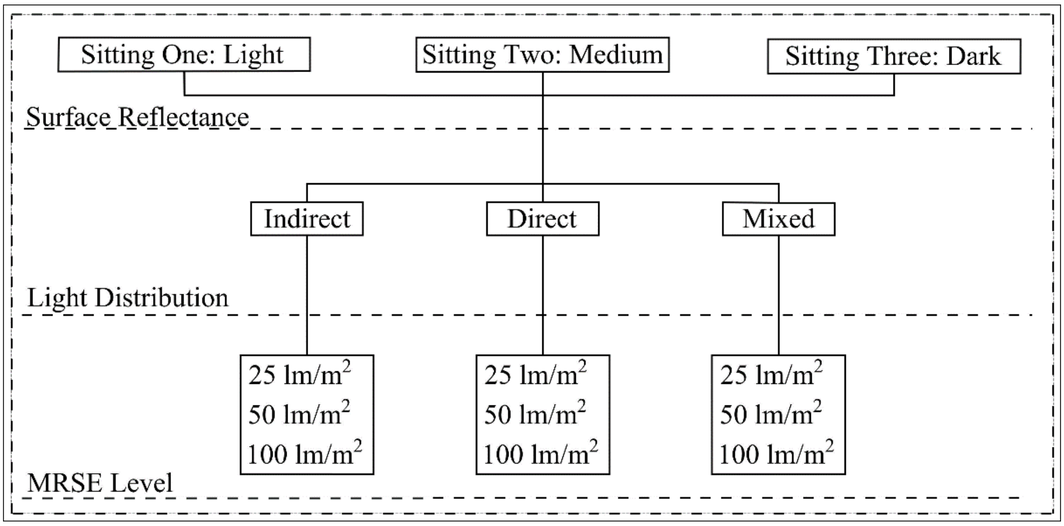


Figure 17 Graphical representation of each light scene programmed. Note that each sitting contained static surface reflectances, but varied levels of MRSE and luminous distribution.

The order of exposure to light scenes was randomised and three scenes were repeated to compare participants' responses to identical scenes. This was used to assess if the order of light scene exposure had a significant impact on assessments. The repeated scenes were scene 7, scene 14 and scene 21 and were chosen to best include for each of the variables; being one scene from each level of MRSE, one scene from each light distribution and one scene from each surface reflectance. The light scene numbers are given in Table 9. Participants were exposed to each scene for two minutes and during each scene, answered a first question that examined

PAI, with a binary response required, in addition to a second question that asked about subjective spatial brightness levels, with responses given on a seven point semantic differential scale. Question response polarity was varied at random to prevent directional bias.

*Q1. The lighting in the space is adequate – Yes / No*

*Q2. On the scale below, please rate the brightness of the entire space.*

| | | | | | | |
|---|---|---|---|---|---|---|
| *very dim* | *dim* | *slightly dim* | *neither dim nor bright* | *slightly bright* | *bright* | *very bright* |

Adequate lighting was defined as "the correct quantity of light for use in an office space". Brightness scales were defined using the definition coined by Vrabel et al;[81] "very bright is represented by the light in an outdoor sports area (when all the floodlights are on) and very dim is the level of an outdoor parking lot at night". In addition to this, participants were reminded prior to each scene change that they should relate brightness to the entire space, and not solely their immediate field of view.

## 6.3 Experiment 3: Results and analysis

Responses to PAI were assigned values of one for Yes and two for No, with the percentage of participants responding Yes given in results. Values of one to seven were assigned for responses from very dim to very bright respectively. A full list of the percentage of participants that responded Yes and the mean spatial brightness response ratings, coupled with the standard deviation for all light scenes is given within Table 9.

Using parametric statistical tests requires that data to be drawn from a normally distributed sample. Binary data cannot be normally distributed and as such, non-parametric tests were applied. Distribution of brightness response data was investigated using statistical and graphical methods available through SPSS, namely; measures of central tendency, skewness, frequency histogram, kurtosis, box and whisker plots and probability plots. Results of these tests indicated that the data was not normally distributed and as such, non-parametric statistical tests have been applied.

Table 9 Properties of the 27 lights scenes programmed. Also indicated is the percentage of Yes responses to PAI and the mean subjective spatial brightness rating for each light scene.

| **Light Scene Number** | **Target MRSE ($lm/m^2$)** | **Surface Reflectance (Ceiling/ Wall/ Floor)** | **Light Distribution** | **Recorded MRSE ($lm/m^2$)** | **Recorded Horizontal Illuminance ($lm/m^2$)** | **Mean Recorded Luminance ($cd/m^2$), ($U_o$)** | | | | | **Q1 *Yes* response to PAI, (%)** | **Q2 Mean Spatial Brightness Rating (SD)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | **Floor** | **Ceiling** | **Wall 1** | **Walls 2&4** | **Wall 3** | | |
| 1 | 25 | Sitting 1 86/84/24 | Indirect | 26 | 30 | 2.2 (0.59) | 14.0 (0.26) | 10.0 (0.52) | 8.7 (0.40) | 5.0 (0.84) | 3.8 | 1.69 (0.54) |
| 2 | 25 | | Direct | 26 | 47 | 3.6 (0.55) | 8.1 (0.61) | 12.0 (0.68) | 9.3 (0.55) | 7.2 (0.85) | 3.8 | 1.54 (0.57) |
| 3 | 25 | | Mixed | 24 | 36 | 2.8 (0.56) | 10.0 (0.41) | 10.1 (0.63) | 8.4 (0.48) | 5.7 (0.84) | 7.7 | 1.92 (0.62) |
| 4 | 50 | | Indirect | 48 | 55 | 4.2 (0.59) | 27.0 (0.25) | 19.0 (0.51) | 16.0 (0.41) | 9.3 (0.84) | 11.5 | 2.46 (0.50) |
| 5 | 50 | | Direct | 52 | 95 | 7.2 (0.55) | 16.0 (0.62) | 24.0 (0.67) | 19.0 (0.53) | 14.0 (0.86) | 7.7 | 2.35 (0.55) |
| 6 | 50 | | Mixed | 52 | 77 | 5.9 (0.56) | 23.0 (0.37) | 22.0 (0.59) | 18.0 (0.48) | 12.0 (0.83) | 11.5 | 2.58 (0.49) |
| 7 | 100 | | Indirect | 100 | 114 | 8.7 (0.59) | 56 (0.25) | 39.0 (0.51) | 34.0 (0.41) | 19.0 (0.84) | 15.4 | 4.19 (0.79) |
| 8 | 100 | | Direct | 101 | 184 | 14.0 (0.54) | 31.0 (0.60) | 46.0 (0.68) | 36.0 (0.53) | 28.0 (0.85) | 11.5 | 3.88 (0.64) |
| 9 | 100 | | Mixed | 103 | 169 | 12.4 (0.56) | 48.3 (0.37) | 44.2 (0.59) | 37.8 (0.49) | 25.2 (0.83) | 15.4 | 4.41 (0.84) |
| 10 | 25 | Sitting 2 69/62/24 | Indirect | 24 | 29 | 2.2 (0.50) | 17.0 (0.12) | 8.6 (0.45) | 7.6 (0.28) | 3.2 (0.84) | 3.8 | 1.65 (0.62) |
| 11 | 25 | | Direct | 25 | 65 | 5.0 (0.46) | 7.2 (0.47) | 12.0 (0.62) | 8.9 (0.41) | 6.2 (0.79) | 0 | 1.38 (0.49) |
| 12 | 25 | | Mixed | 24 | 47 | 3.61 (0.47) | 12.0 (0.22) | 10.0 (0.61) | 8.27 (0.35) | 4.6 (0.81) | 7.7 | 1.77 (0.70) |
| 13 | 50 | | Indirect | 48 | 58 | 4.4 (0.50) | 34.0 (0.12) | 17.0 (0.46) | 15.0 (0.28) | 6.3 (0.84) | 7.7 | 2.46 (0.57) |
| 14 | 50 | | Direct | 49 | 127 | 9.7 (0.46) | 14.0 (0.47) | 24.0 (0.58) | 17.0 (0.42) | 12.0 (0.79) | 7.7 | 2.12 (0.58) |
| 15 | 50 | | Mixed | 50 | 94 | 7.2 (0.47) | 24.0 (0.23) | 21.0 (0.57) | 17.0 (0.34) | 9.4 (0.81) | 11.5 | 2.19 (0.56) |
| 16 | 100 | | Indirect | 101 | 112 | 9.2 (0.50) | 70.0 (0.12) | 36.0 (0.44) | 32.0 (0.27) | 13.0 (0.85) | 11.5 | 3.96 (0.65) |
| 17 | 100 | | Direct | 99 | 257 | 20.0 (0.45) | 28.0 (0.46) | 48.0 (0.60) | 35.0 (0.40) | 24.0 (0.79) | 11.5 | 3.54 (0.69) |
| 18 | 100 | | Mixed | 98 | 191 | 15.0 (0.45) | 46.0 (0.24) | 41.0 (0.59) | 33.0 (0.36) | 19.0 (0.79) | 15.4 | 3.88 (0.70) |
| 19 | 25 | Sitting 3 44/38/17 | Indirect | 25 | 33 | 1.8 (0.45) | 22.0 (0.05) | 7.4 (0.37) | 7.2 (0.16) | 1.9 (0.82) | 3.8 | 1.62 (0.56) |
| 20 | 25 | | Direct | 24 | 112 | 6.1 (0.37) | 6.0 (0.34) | 13.0 (0.51) | 8.5 (0.30) | 5.4 (0.69) | 0 | 1.54 (0.50) |
| 21 | 25 | | Mixed | 25 | 47 | 3.6 (0.47) | 12.0 (0.22) | 10.0 (0.61) | 8.3 (0.35) | 4.7 (0.81) | 3.8 | 1.73 (0.59) |
| 22 | 50 | | Indirect | 49 | 66 | 3.5 (0.45) | 44.0 (0.05) | 15.0 (0.36) | 14.0 (0.16) | 3.8 (0.82) | 7.7 | 2.27 (0.52) |
| 23 | 50 | | Direct | 49 | 225 | 12.0 (0.37) | 12.0 (0.34) | 26.0 (0.50) | 17.0 (0.30) | 11.0 (0.68) | 7.7 | 1.96 (0.59) |

| Light Scene Number | Target MRSE ($lm/m^2$) | Surface Reflectance (Ceiling/ Wall/ Floor) | Light Distribution | Recorded MRSE ($lm/m^2$) | Recorded Horizontal Illuminance ($lm/m^2$) | Mean Recorded Luminance ($cd/m^2$), ($U_o$) | | | | | Q1 *Yes* response to PAI, (%) | Q2 Mean Spatial Brightness Rating (SD) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Floor | Ceiling | Wall 1 | Walls 2&4 | Wall 3 | | |
| 24 | 50 | | Mixed | 50 | 145 | 7.8 (0.39) | 28.0 (0.12) | 20.0 (0.55) | 16.0 (0.23) | 7.2 (0.75) | 11.5 | 2.50 (0.57) |
| 25 | 100 | | Indirect | 99 | 131 | 7.1 (0.33) | 87.0 (0.05) | 30.0 (0.37) | 29.0 (0.15) | 7.6 (0.83) | 15.4 | 3.62 (0.92) |
| 26 | 100 | | Direct | 98 | 449 | 24.0 (0.37) | 24.0 (0.34) | 51.0 (0.51) | 34.0 (0.29) | 21.0 (0.71) | 11.5 | 3.54 (0.69) |
| 27 | 100 | | Mixed | 102 | 273 | 15.0 (0.38) | 45.0 (0.13) | 39.0 (0.57) | 39.0 (0.27) | 13.0 (0.77) | 15.4 | 3.96 (0.76) |

### 6.3.1 Experiment 3: Repeated scenes

Repeated scenes were introduced to investigate if the order of light scene exposure had a significant impact on subjective assessments. As stated previous, three scenes were repeated without participants knowledge; scene 7, scene 14 and scene 21, with the repeated scene being excluded from final results.

The three binary response scores for PAI were tested in pairs using McNemar's Exact. All three scenes produced no statistically significant difference between participants' responses when a scene was viewed first or second time around (scene 7, $X^2(1) = 0.25$, $p = 0.62$; scene 14, $X^2(1) = 1.11$, $p = 0.32$ and scene 21, $X^2(1) = 0.92$, $p = 0.19$). Scores produced from each of the spatial brightness responses were examined using the Wilcoxon signed-rank test. All three scenes repeated produced no statistically significant difference between participants' first response and their second (scene 7, $Z = 1.12$, $p = 0.38$; scene 14, $Z = 0.94$, $p = 0.19$ and scene 21, $Z = -1.21$, $p = 0.21$). It can thus be concluded that the order of exposure had no significant impact on participants' assessments.

### 6.3.2 Experiment 3: Mean Room Surface Exitance and Perceived Adequacy of Illumination

Cochran's Q was applied to investigate the influence of the independent variables on assessments of PAI. To change the reflectances of the room surfaces, they were cleaned and repainted. With this being unavoidable, participants then viewed the scenes in three separate sittings (one for each reflectance) but all in the same order, producing an associated order effect. For this reason, three separate Cochran's Q tests were carried out on the data for each level of surface reflectance, but also for each independent variable, being level of MRSE (3) and light distribution (3).

In sitting one, participants viewed scenes with light surface reflectances as given in Table 9. Applying Cochran's Q to all the data from sitting one, no significant differences between the proportions were found, $X^2(2) = 4.38$, $p = 0.82$. Using Cochran’s Q to further analyse the data showed that no significant difference occurred due to light distribution at each level of MRSE (MRSE of 25lm/m$^2$, $X^2(2) = 0.5$, $p = 0.78$; MRSE of 50lm/m$^2$, $X^2(2) = 0.29$, $p = 0.87$ and MRSE of 100lm/m$^2$, $X^2(2) = 0.25$, $p = 0.88$) and no significant differences were found within each light distribution type due to level of MRSE (Indirect, $X^2(2) = 1.75$, $p = 0.42$; Direct, $X^2(2) = 1.0$, $p = 0.61$ and Mixed, $X^2(2) = 0.86$, $p = 0.65$).

In sitting two, participants viewed scenes with medium surface reflectances as given in Table 9. Applying Cochran's Q to all the data from sitting two, no significant differences between the proportions were found, $X^2(2) = 5.69$, $p = 0.68$. Using Cochran’s Q to further analyse the data showed that no significant difference occurred due to light distribution at each level of MRSE (MRSE of 25lm/m$^2$, $X^2(2) = 2.0$, $p = 0.37$; MRSE of 50lm/m$^2$, $X^2(2) = 0.33$, $p = 0.86$ and MRSE of 100lm/m$^2$, $X^2(2) = 0.25$, $p = 0.88$) and no significant differences were found within each light distribution type due to level of MRSE (Indirect, $X^2(2) = 1.0$, $p = 0.61$; Direct, $X^2(2) = 2.8$, $p = 0.25$ and Mixed, $X^2(2) = 1.0$, $p = 0.61$).

In sitting three, participants viewed scenes with dark surface reflectances as given in Table 9. Applying Cochran's Q to all the data from sitting three, no significant differences between the proportions were found, $X^2(2) = 7.46$, $p = 0.487$. Using Cochran’s Q to further analyse the data showed that no significant difference occurred due to light distribution at each level of MRSE (MRSE of 25lm/m$^2$, $X^2(2) = 1.0$, $p = 0.61$; MRSE of 50lm/m$^2$, $X^2(2) = 1.33$, $p = 0.86$ and MRSE of 100lm/m$^2$,

$X^2(2) = 0.22$, $p = 0.91$) and no significant differences were found within each light distribution type due to level of MRSE (Indirect, $X^2(2) = 2.33$, $p = 0.31$; Direct, $X^2(2) = 3.5$, $p = 0.17$ and Mixed, $X^2(2) = 2.0$, $p = 0.36$).

### 6.3.3 Experiment 3: Mean Room Surface Exitance and spatial brightness

Repeated measures ANOVA was used to investigate the influence of the different independent variables on spatial brightness assessments. Again, and for the reasons described previously, an order effect existed such that results had to be analysed separately for each level of surface reflectance presented. As such, three separate two by three repeated measures ANOVA were carried out, with level of MRSE (3) and light distribution (3) as the independent variables.

In sitting one, participants viewed scenes with light surface reflectances as given in Table 9. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 2.78$, $p = 0.25$, and for the interaction between level of MRSE and light distribution, $X^2(9) = 11.82$, $p = 0.22$, but not for level of MRSE, $X^2(2) = 6.81$, $p = 0.03$. For level of MRSE, F values are reported using degrees of freedom corrected with the Greenhouse-Geisser factor ($\varepsilon = 0.802$). Within subjects effects then showed that subjective assessment of spatial brightness was influenced by level of MRSE, $F(1.6, 40.1) = 227.5$, $p < 0.001$, and also by light distribution, $F(2, 50) = 9.54$, $p < 0.001$. There was no significant interaction between level of MRSE and light distribution, $F(4, 100) = 0.37$, $p = 0.87$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was a significant difference between direct and indirect scenes ($p = 0.042$) and also between direct and mixed ($p < 0.001$), but with no statistically significant difference being concluded between the mixed and indirect scenes ($p = 0.197$). For level of MRSE, there was a statistically significant difference between each of the pairs of means ($p < 0.001$).

In sitting two, participants viewed scenes with medium surface reflectances as given in Table 9. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 1.94$, $p = 0.38$, level of MRSE, $X^2(2) = 5.02$, $p = 0.081$, and the interaction between level of MRSE and light distribution, $X^2(9) = 10.31$, $p = 0.33$. Within subjects effects showed that subjective assessment of spatial brightness was influenced by level of MRSE, $F(2, 50) = 206.36$, $p < 0.001$, and also by light distribution, $F(2, 50) = 5.75$, $p = 0.006$. There was no significant interaction between level of MRSE and light distribution, $F(4,100) = 0.91$, $p = 0.46$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was a significant difference between direct and indirect scenes ($p = 0.027$) and also between direct and mixed ($p < 0.001$), but with no statistically significant difference being concluded between the mixed and indirect scenes ($p = 0.92$). For level of MRSE, there was again a statistically significant difference between each of the pairs of means ($p < 0.001$).

In sitting three, participants viewed scenes with dark surface reflectances as given in Table 9. Mauchly's test of sphericity demonstrated that for these results, sphericity could be assumed for light distribution, $X^2(2) = 2.48$, $p = 0.29$, level of MRSE, $X^2(2) = 1.47$, $p = 0.48$, and the interaction between level of MRSE and light distribution, $X^2(9) = 13.85$, $p = 0.13$. Within subjects effects then showed that subjective assessment of brightness was influenced by level of MRSE, $F(2, 50) = 229.37$, $p < 0.001$, and also by light distribution, $F(2, 50) = 6.34$, $p = 0.004$. There was no significant interaction between level of MRSE and light distribution, $F(4,100) = 0.631$, $p = 0.64$.

Post-hoc paired comparisons, using a Bonferroni correction, were made to examine which pairs of means differed. For light distribution, there was a significant difference between direct and indirect scenes ($p = 0.044$) and also between direct and mixed ($p = 0.01$), but with no statistically significant difference being concluded between the mixed and indirect scenes ($p = 0.59$). For level of MRSE, there was again a statistically significant difference between each of the pairs of means ($p < 0.001$).

### 6.3.4 Experiment 3: Spatial brightness and perceived adequacy of illumination

Applying a Perason product-moment correlation to both the percentage of Yes responses to PAI and the mean spatial brightness response score produced a correlation between the two items ($r = 0.87$, $n = 26$, $p < 0.001$). A scatterplot in Figure 18 summarises the data. Experiment 2 found that as levels of reported spatial brightness increased, so did levels of reported PAI. The data in Figure 18 shows a relationship that differs from that previously found. Here, with extreme non-uniform light scenes, despite the levels of reported spatial brightness increasing, the level of reported PAI never increases beyond 20% of the population.

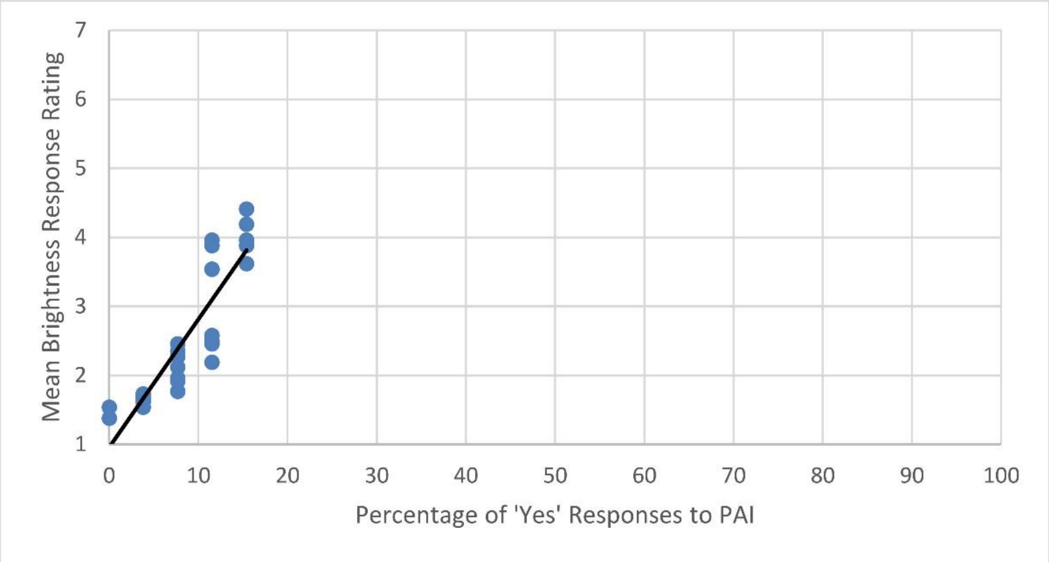


Figure 18 Graphical representation of the correlation experienced between response to spatial brightness and levels of perceived adequacy of illumination.

### 6.3.5 Experiment 3: Mean Rom Surface Exitance and mean horizontal illuminance

Graphing the percentage of *Yes* responses to PAI for each light scene visually indicates the relationship between MRSE and PAI, compared with horizontal illuminance and PAI (Figure 19 and Figure 20). Applying a linear regression model to the level of MRSE and the proportion of *Yes* PAI responses produces a noticeable relationship between the two variables ($R^2 = 0.72$). Within this experiment, horizontal illuminance was not explicitly controlled as an independent variable and participants were generally exposed to a somewhat small range of values, typically between 50 lux and 250 lux. However, applying a linear regression model to horizontal illuminance and PAI serves as a useful backward inference as to the relationship experienced between the two items. Modelling the data set as a whole produces no predictable relationship between the two items ($R^2 = 0.25$).

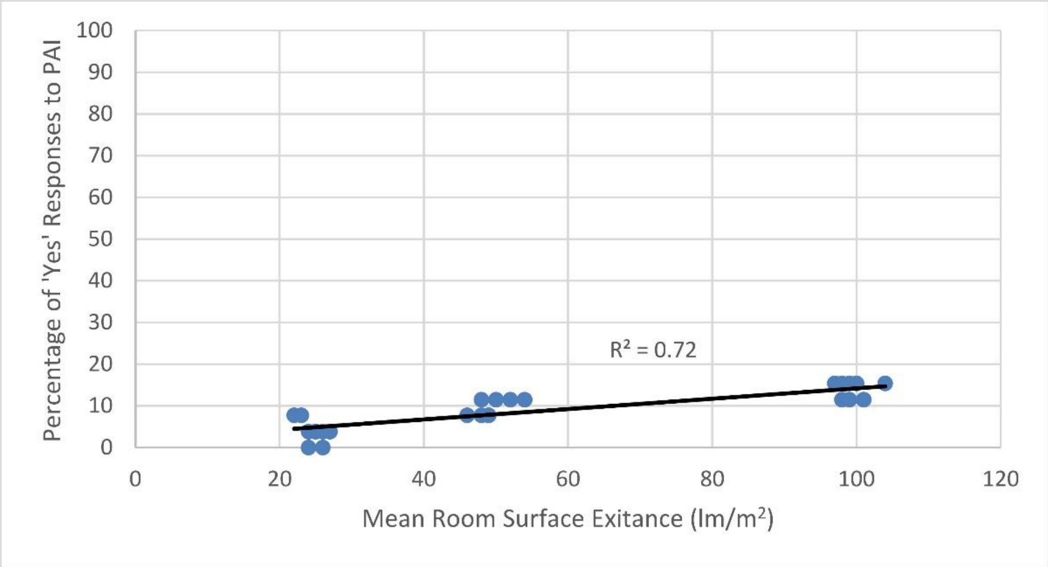


Figure 19 The percentage Yes responses to PAI plotted against the relative level of mean room surface exitance for each light scene presented.

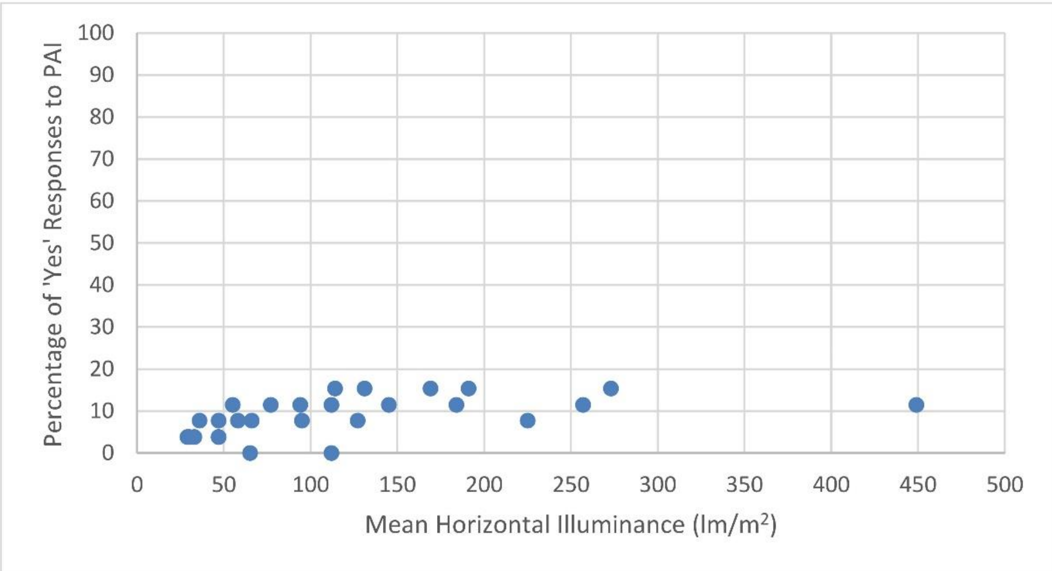


Figure 20 The percentage Yes responses to PAI plotted against the relative level of mean horizontal illuminance for each light scene presented.

Applying the same procedure to the mean spatial brightness response of each light scene visually demonstrates the difference in relationship between MRSE and spatial brightness, compared with horizontal illuminance and spatial brightness (Figure 21 and Figure 22). Applying a linear regression to MRSE and spatial brightness produces a strong relationship between the two items ($R^2$ = *0.95*). Applying a linear regression model to horizontal illuminance and spatial brightness indicates no predictable relationship between the two items ($R^2$ = *0.36*).

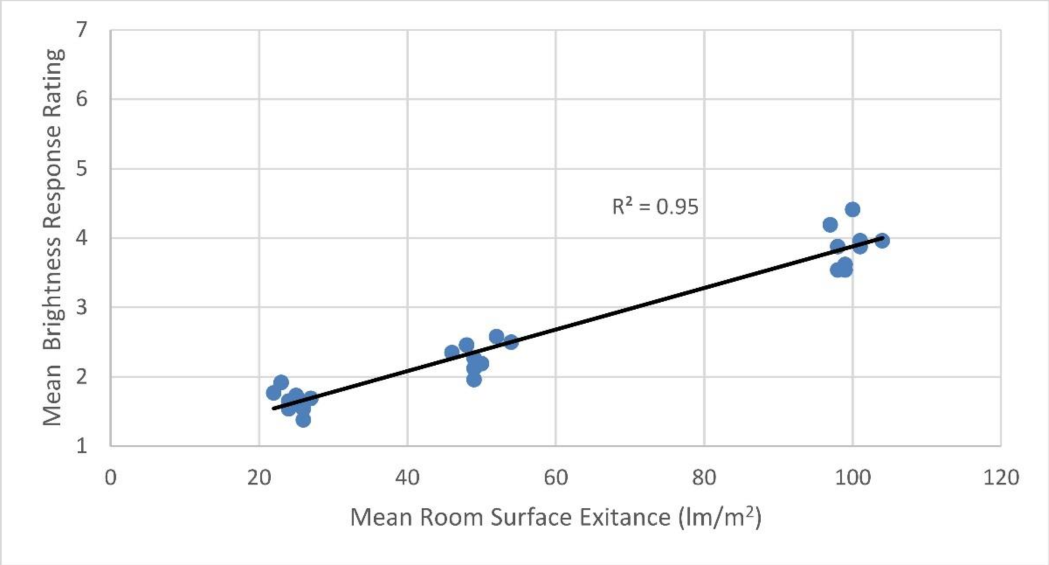


Figure 21 The mean spatial brightness response rate plotted against the relative level of mean room surface exitance for each light scene presented.

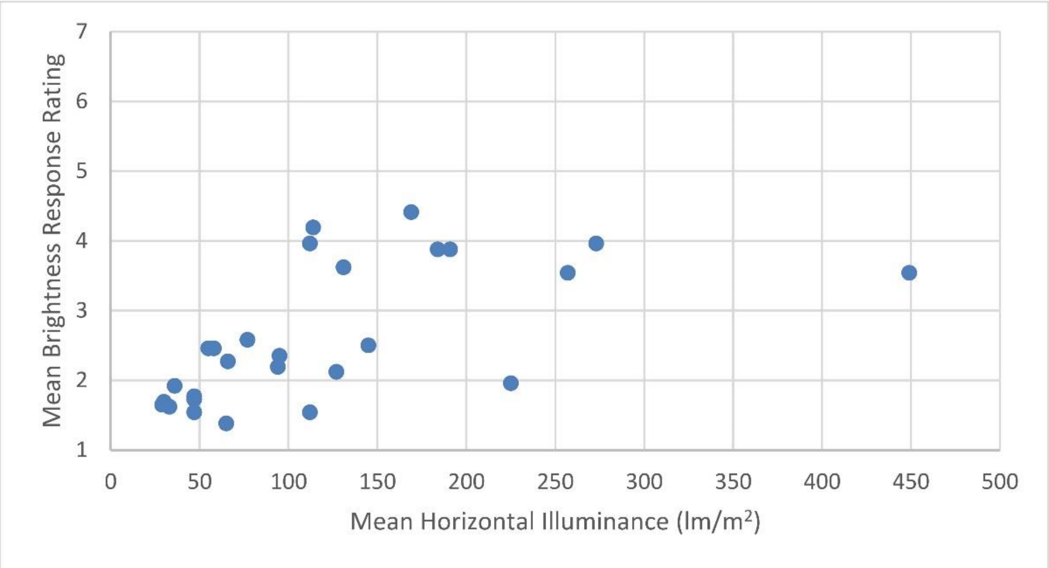


Figure 22 The mean spatial brightness response rate plotted against the relative level of horizontal illuminance for each light scene presented.

### 6.3.6 Experiment 3: Discussion

The concept of PAI assumes that people will relate levels of spatial brightness to the feeling of the lighting in a space being appropriate and Experiments 1 and 2 have shown this assumption to hold true.[87,88] In these previous experiments, participants were exposed to a range of broadly uniform light scenes and statistical testing showed that regardless of light distribution or surface reflectance, the level of MRSE had a significant impact on subjective assessment of both PAI and spatial brightness. However, Experiment 3 presents findings that differ. Here, participants have related MRSE to levels of spatial brightness, but not to levels of PAI. Participants in the current study were exposed to a number of non-uniform light scenes spread over three sittings, with two independent variables being controlled during each sitting, being MRSE and light distribution. Regardless of the increase in MRSE, there was no significant increase in reported PAI. This suggests that whilst the space felt bright enough for participants, as the rating of spatial brightness was similar to Experiment 2, the rather non-uniform light distribution made them feel that the upper levels of MRSE were not ‘the correct quantity of light for use in an office space’.

This differs from previous work and suggests that there is more to ‘adequacy’ than spatial brightness; that the light distribution needs to be appropriate for the activity. The rather non-uniform light distribution used here is not very common in offices, but might perhaps be acceptable within a gallery or restaurant environment. Understanding where this disparity in assessments of PAI begins or ends, in terms of luminance distribution, will be the focus of future work. Additionally, whilst correlations could still be drawn between spatial brightness and PAI, the levels of

PAI reported were far below what has previously been reported for identical levels of MRSE.

The relationship between luminance and brightness has previously been shown to be logarithmical,[82,83,84,85,86] but the upper levels of luminance used in these experiments was far in excess of what participants in the current study were exposed to. Experiments 1 and 2 mimicked the experimental process of Experiment 3, but exposed participants to light distributions that could be considered broadly uniform. Experiments 1 and 2 found a linear relationship between reported levels of spatial brightness and MRSE as denoted in equation (11). Remembering that values one to seven were assigned to each response category from very dim to very bright, the relationship between spatial brightness (B) and MRSE experienced in Experiment 3 can be approximately summated by:

$$B = 1 + \frac{MRSE}{30} \quad (11)$$

Results found in this study showed substantial agreement with the findings from Experiment's 1 and 2. This was gauged solely by inputting the data of each experiment into equation (11) and visually examining the outputs. However, and as stated in the discussion of Experiments 1 and 2, it should be noted that the maximum value of MRSE used was 100 lm/m$^2$. It is still envisaged that as levels of MRSE increase above this value, ratings of brightness may plateau, perhaps producing the expected logarithmical relationship.

Experiments 1 and 2 have shown MRSE to be a more accurate predictor of both PAI and spatial brightness than horizontal illuminance[87,88] and results found in this study show agreement with this. From both of the linear regression analyses results, and visually from Figure 19 to Figure 22, it can be seen that for the light scenes used in this study, MRSE was a more accurate predictor of both PAI and spatial brightness than horizontal illuminance. Logically, increasing or decreasing the luminance of the surfaces within a space will have an impact on how dim or bright it appears, but the illumination engineering metrics used to control this phenomena are not yet widely understood. In addition, there is a lesser understanding of how perceived levels of brightness relate to human satisfaction within general interior environments. Loe et al investigated subjective response to number of items,[80] one of which was brightness, within a range of light scenes in an illuminated interior. They used the average luminance and the luminance distribution standard deviation within the horizontal 40° band to try and assess the lit environment and found strong correlations between the mean luminance in the 40° band and subjective response to brightness. Experiment 3 did not record luminance values within the horizontal 40° band, but did record luminance values on each of the room walls. Using the premise that the mean luminance of the walls is approximately equivalent to that of the 40° band, correlations can be drawn between mean wall luminance and MRSE ($r = 0.96$) and also between mean wall luminance and horizontal illuminance ($r = 0.63$). This serves to highlight that if controlling luminance in the field of view is of importance, then for the scenes used in this study, MRSE did a better job than horizontal illuminance. Additionally, Loe et al[80] found that firstly, for a room to appear "light", it needed to have an average luminance within the horizontal 40° band of at least 30 cd/m$^2$ and secondly, that for a space to "begin to appear bright", luminance levels within the horizontal 40° band need to be approximately 40 cd/m$^2$. Experiments 1 and 2 produced results with similar conclusions and the results from this study show substantial agreement with previous findings.

### 6.3.7 Experiment 3: Limitations

The definition of brightness given to experiment participants should be noted. This was taken from previous work by Vrabel et al[81] and it informed participants to relate very bright to "*the light in an outdoor sports area (when all the floodlights are on)*" and relate very dim to the brightness *"of an outdoor parking lot at night*". Whilst defining the ends of the semantic scale has benefits, in this case, the chosen definition caused scale compression. None of the light scenes that participants viewed approached a brightness close to the level of an outdoor sports area, nor did they come close to the dimness of an outdoor parking lot at night. Defining these extremes may have ultimately inferred to participants that they should not choose towards the outer ends of the scale and results of this are evident in the brightness levels reported, where few scenes were scored towards the upper end of the brightness scale.

This study presented a range of surface reflectances, but due to the manner in which they were changed, participants viewed them in the same order, thus producing an associated order effect. For this reason, results could not be explicitly compared across each of the levels of surface reflectance.

Many past studies have investigated how spectral power distribution affects the perceived brightness of a space and this work is still on-going. The work presented in this chapter did not vary spectral power distribution, with each of the sources used having a CCT of 4000K and a Ra of 80.

# Summary of Chapter 6

Chapter 6 presented an experiment (Experiment 3) that set out to investigate Research Question 6:

6. Do light scenes with non-uniform luminous distributions affect subjective assessments of both spatial brightness and PAI?

More specifically, Chapter 6 presented a further experiment that used the same small office space and participants as Experiment 2. Within the space, it exposed participants to a range of non-uniform light scenes that varied in level of MRSE, light distribution and surface reflectance to investigate the relationships between MRSE and PAI, between MRSE and spatial brightness and finally between spatial brightness and PAI. It also compared how MRSE and horizontal illuminance perform as predictors of both PAI and spatial brightness.

Generally, one main original contribution to knowledge was presented. It was found that the linear relationship between MRSE and spatial brightness experienced in Experiments 1 and 2 was repeated, but the previously found relationship between MRSE and PAI was not repeated. Regardless of the increase in MRSE, there was never a significant increase in PAI. This suggests that this disparity was due to the highly non-uniform nature of the light scenes presented.

# 7 Thesis Conclusion

## 7.1 Context

Cuttle has proposed an entirely new methodology for designing general interior lighting installations. The premise to this suggestion is that the lighting design profession needs to switch from its most widely applied design metric, being the illuminance on a horizontal plane, to something different; something that better relates to what people see and the appearance of a space. Cuttle has suggested that this criterion is the PAI, with MRSE being a metric that may correlate with it.

Cuttle’s proposal has received both positive a negative feedback, as outlined in Section 2.8, and the research presented within this thesis has endeavoured to address issues raised from this negative feedback and investigate the merit of the claims.

## 7.2 The research findings

The following section re-states each of the research questions addressed and presents a brief summary of the methods and outcomes arising from each of the process and experiments conducted.

1. Is the MRSE formula proposed by Cuttle robust and accurate under all conditions?

This research investigated and critically examined the MRSE formula proposed by Cuttle and subsequently demonstrated why it can be erroneous under certain conditions. In addition, an alternative formula, equation (9), has been developed, tested and proposed to calculate MRSE, with this formula being accurate under any given conditions.

2. Is it possible to easily and accurately compute MRSE using currently available lighting analysis software?

This research developed a script that is capable of calculating MRSE using Radiance as a platform. This is not intended for widespread and long-term use, as Radiance is a cumbersome and complex program to run, but it is rather intended for use in the short-term by those who possess the skills to apply it. It also serves as proof of concept, such that software developers in the future can apply it to sit within a more streamlined front end.

3. Is it possible to simplistically, and accurately, measure MRSE within complex, real-world environments?

This research developed a methodology that utilises a combination of HDR imaging and Radiance to measure MRSE in real world environments. Essentially, the procedure records a number of calibrated HDR images of a space, with the direct flux being removed from each. What remains is the indirect flux and an average value of a number of these views has been validated such that the value recorded was within an acceptable percentage error (>10%) when compared with physical measurements using a luminance meter and calculations using software.

4. Is MRSE more closely related to subjective perceptions of spatial brightness than mean horizontal workplane illuminance?

This research developed a series of experiments, with each addressing the above question under a range of light distributions and surface properties. In general, the level of MRSE experienced had a significant impact on the assessment of spatial brightness. Whilst the level of horizontal illuminance was not explicitly controlled, it did not have the same significant impact on assessments of spatial brightness and throughout each experiment, did not produce a strong coefficient of determination.

5. Is MRSE more closely linked with PAI than mean horizontal workplane illuminance?

This research developed two experiments that examined the relationship between MRSE and PAI. The first of these used light distributions that could be considered broadly uniform and the second used light scenes that were very much non-uniform. When light scenes were uniform, the level of MRSE had a significant impact on the reported PAI. Again, the level of horizontal illuminance was not explicitly controlled, but considering analysis of results to be a backwards inference and the limitations that go with it, then the level of horizontal illuminance was a lesser predictor of PAI.

6. Do light scenes with non-uniform luminous distributions affect subjective assessments of both spatial brightness and PAI?

This thesis presented a single experiment that examined the relationship between MRSE and both spatial brightness and PAI under extreme non-uniform light distributions. It was found that, despite the level of MRSE always having a significant impact on the reported spatial brightness, the level of MRSE never had a significant impact upon the reported PAI. This result serves to highlight that the level of perceived spatial brightness is not always the sole item of importance when assessing a person's satisfaction with lighting.

## 7.3 Impact

This research has investigated a much discussed and well publicised topic of interest and concern amongst lighting designers, researchers and legislators. This work has produced the following contributions to knowledge:

1. The first came about through critical analysis on the MRSE formula derived by Cuttle. This formula was shown to be erroneous and an alternative formula proposed, examined and demonstrated to be accurate under all conditions.

2. The second contribution was the development and validation of a Radiance script that is capable of calculating MRSE through currently available software. This addressed a major concern of the lighting community with Cuttle's ideas.

3. The third was the development and examination of new script that facilitates the measurement of MRSE in the field using readily accessible software and camera technology. This will lay a solid foundation for the development of more user friendly equipment for widespread use.

4. The fourth was a finding that a simplistic linear relationship existed between level of MRSE and spatial brightness, regardless of changes in room surface reflectance or shifts in light distribution.

5. The fifth was a finding that, within scenes which contained broadly uniform light distributions, a simplistic linear relationship existed between level of MRSE and PAI.

6. The sixth was a finding that, within scenes which contain extreme non-uniform light distributions, the level of MRSE did not have a significant impact on the reported PAI.

Ultimately, each of these contributions is important and an original contribution to knowledge, but also no more than the first step in a number of different directions, with each moving towards the possible widespread application of MRSE in lighting practice. The probable impact of this work is best summated by quoting, as given previously in this thesis, from a review paper by Boyce and Semt[45] that dealt with emerging lighting metrics and how these might impact lighting quality.

> *At the moment, the worth of mean room surface exitance and target/ambient illumination ratio as metrics for determining desirable light distributions are matters of belief rather than proof. What is required is some experimental evidence that mean room surface exitance is related to peoples' perception of the amount of light in a space and that that, in turn, is more closely linked to their satisfaction with the lighting than illuminance on the horizontal working plane.*

Later in the same paper, the authors suggest that once a number of questions are addressed, then the use of MRSE would show potential to improve lighting quality.

> *If all these questions can be answered positively, then it should be possible to develop lighting criteria based on these metrics and, hence, reorient lighting recommendations away from lighting a task on the horizontal working plane towards the lighting of the space and the objects in it. The result should be better lighting.*

The work in this thesis has addressed a number of the questions raised by Boyce and Smet and produced publishable results. The potential implication of applying MRSE in lighting practice, as observed in this work, is a possible improvement in the perceived quality of general indoor lighting installations.

## 7.4 Limitations and further work

With each of the above mentioned contributions being the first piece of research in each respective area, there are some limitations with the methods used and further work necessary to build upon the various findings.

When considering the computation of MRSE in lighting software, what this thesis has presented is fit for purpose, but could be refined. The script written is bespoke and cumbersome to apply, with at least a basic knowledge of command line functions required to do so. Further work in this area would take this script and embed it within a graphical user interface, such that it can be applied either within currently available freeware or a newly produced program. This would facilitate more widespread access to its use.

Similarly, the method developed to measure MRSE in the field uses somewhat complex technology and has some minor limitations. When applying the method, there is an inherent variability in choosing the value of threshold luminance and this has an impact on the returned value of indirect illuminance. In addition, on occasion, lighting designers will encounter situations where the value of indirect luminance within a space is actually greater than the value of direct luminance in the same field of view and this anomaly will skew the results returned. Further work in this area would again look at alternative methods that better deal with the above limitations, but would also take the process developed and embed it within a clean user interface, such that it can become easier to apply and be used by a wider audience.

When considering the relationship between MRSE and spatial brightness, the research completed has provided an important contribution to knowledge, but a number of limitations could not be avoided.

Due to the complex nature of presenting experiment participants with surfaces that randomly varied their properties, a series of experiments were designed that relied on the experimental set up being re-painted to change the surface properties. This produced an associated order affect, such that data could not be analysed across each of the different surface properties. Whilst it can still be concluded that MRSE had a significant impact on spatial brightness regardless of surface reflectance, this limitation makes it harder to estimate the magnitude of the effect relative to each of the other independent variables. Future work may look to build an apparatus that can vary surface properties at random and in doing so, produce further knowledge as to the magnitude of impact that room surface reflectance has on assessments of spatial brightness.

To reduce the quantity of independent variables within each of the experiments, the SPD of the light sources used for each was not varied. In addition, equipment to document the SPD of the light sources used was not available at the time of completion. There is much research happening surrounding the effect that SPD has on assessments of spatial brightness and once a consensus is reached from this research, perhaps further work might tie varying SPDs into assessments of spaces with MRSE as a brightness metric.

As discussed within each relevant core chapter, there is a strong possibility that the scale definition given to experiment participants influenced their decision. Re-examining with an alternative set of participants within a similar experimental set up and methodology, but an alternative scale definition, would help to confirm the findings that this research has produced, with particular focus on equation (11).

When considering the relationship between MRSE and PAI, this current work has tested only a single function, i.e. an office space. Further research would look to examine a range of spaces and try to determine if the level of MRSE necessary to achieve PAI varies according to space function. For example, it would be intuitive to imagine that a doctors' surgery would require a higher level of MRSE to meet a given level of PAI than would the doctors' waiting area.

In addition, further work would look to examine at what point a shift, in terms of luminance distribution, do ratings of PAI move from mostly satisfactory to unsatisfactory. The experiments presented within this thesis exposed participants to light scenes that were either broadly uniform, or either extremely non-uniform. The various levels of variation in luminous distribution that lie between these two extremes were not investigated.

# Appendix 1

A number of times with this text, items are mentioned as being available to download.  These are all available at the link given below.

https://www.dropbox.com/l/lC62txkbVpcW1AQ8HPfydu

# 8 Reference list

[1] Bean, A.R., Bell, R.I. *"The CSP Index: A practical measure of office lighting quality"*, Lighting Research and Technology, 1992, Vol 24, pp215-225.

[2] Loe, D.L., Rowlands, E. *"The art and science of lighting: A strategy for lighting design"*, Lighting Research and Technology, 1996, Vol 28, pp153-164.

[3] Veitch, J.A., Newsham, G.R. *"Determinants of lighting quality 1: State of the science"*, Journal of the Illuminating Engineering Society, 1998, Vol 27, pp92-106.

[4] Cuttle, C. *Lighting by Design*, 1st edition, Oxford, Architectural Press, 2003.

[5] Boyce, P.R., *"Lighting Quality for All?"*, Proceedings of the SLL International Lighting Conference, Dublin, April 2013.

[6] Boyce P. R. *Lighting Quality: The Unanswered Questions*. Proceedings of the first CIE symposium on lighting quality, Ottawa 1998.

[7] Loe, D.L. and McIntosh, R. 2009. *Reflections on the last One Hundred Years of Lighting in Great Britain*. The Society of Light and Lighting as part of CIBSE. Page Bros. Norwich.

[8] Veitch, J.A., Newsham, G.R. *"Preferred luminous conditions in open-plan offices: Research and practice recommendations"*, Lighting Research and Technology, 2000, Vol 32, pp199-212.

[9] Al Marwaee, M., Carter, D.J. *"A field study of tubular daylight guidance installations"*, Lighting Research and Technology, 2006, Vol 38, pp241-258.

[10] Boyce, P.R. *Human Factors in Lighting*, London: Taylor and Francis, 2003.

---

[11] Veitch, J.A., Galasiu, A.D. *"Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review"* Energy and Buildings 2006, Vol 38, pp728-742.

[12] Wen, Y-J., Agogino, A.M. *"Control of wireless-networked lighting in open-plan offices"*, Lighting Research and Technology 2011, Vol 43, pp235-248.

[13] Maniccia, D., Rutledge, B., Rea, M.S., Morrow, W. *"Occupant use of manual lighting controls in private offices"*, Journal of the Illuminating Engineering Society 1999, Vol 28, pp42-56.

[14] Newsham, G., Veitch, J. *"Lighting quality recommendations for VDT offices: A new method of derivation"*, Lighting Research and Technology, 2001, Vol 33, pp97-116.

[15] Moore, T., Carter, D.J., Slater A.I. *"Long-term patterns of use of occupant controlled office lighting"*, Lighting Research and Technology 2003, Vol 34, pp207-219.

[16] Boyce, P.R., Veitch, J.A., Newsham, G.R., Jones, C.C., Heerwagen, J., Myer, M., Hunter, C.M., *"Occupant use of switching and dimming controls in offices"*, Lighting Research and Technology 2006, Vol 38, pp358-378

[17] Boyce, P.R., Veitch, J.A., Newsham, G.R., Jones, C.C., Heerwagen, J., Myer, M., Hunter, C.M., *"Lighting quality and office work: two field simulation experiments"*, Lighting Research and Technology 2006, Vol 38, pp191-223.

[18] Newsham, G. R., Veitch, J. A., Arsenault, C., Duval, C. *"Effect of dimming control on office worker satisfaction and performance"* Proceedings of the IESNA Annual Conference, Tampa, FL. New York: IESNA, 2004.

[19] Duff, J. T. (2012) *The 2012 SLL Code for Lighting: the Impact on Design and Commissioning*, Journal of Sustainable Engineering Design: Vol. 1: Iss. 2, Article 4.

[20] Cuttle, C. *Lighting by Design*, 2nd edition, Oxford, Architectural Press, 2008.

[21] Cuttle, C. *"Towards the third stage of the lighting profession"*, Lighting Research and Technology, March 2010; vol. 42, 1: pp. 73-93.

[22] Cuttle C. *Perceived adequacy of illumination: A new basis for lighting practice*: Proceedings of the 3rd Professional Lighting Design Convention, Professional Lighting Designers Association, Madrid, 2011.

[23] Cuttle, C. *"A new direction for general lighting practice"*, Lighting Research and Technology, February 2013; vol. 45, 1: pp. 22-39.

[24] Cuttle, C. *"Correspondence: The lumen dumper's solution"*, Lighting Research and Technology, June 2013; vol. 45, 3: pp. 391-393.

[25] Illuminating Engineering Society of North America, *The IESNA Lighting Handbook*, 10th Edition, New York: IESNA.

[26] Society of Light and Lighting, *The SLL Lighting Handbook*, 2009, London; CIBSE.

[27] The Society of Light and Lighting (SLL). 2009. *The SLL Code for Lighting*. ISBN-978-906846-07-7. London: SLL.

[28] Society of Light and Lighting. 2012. *The SLL Code for Lighting*. CIBSE. Page Bros. Norwich.

[29] Rea, M.S., and M.J. Ouellette, 1991. *Relative visual performance: A basis for application*. Lighting Research & Technology, 23(3): 135-144.

[30] Boyce P.R., 1985. *Movement under emergency lighting: The effect of illuminance*. Lighting Research & Technology,17: 51-71

[31] Lynes J, Bedocs L. *Electric Lighting for Buildings*. RIBA/CIBSE Open Learning Project and Thorn Lighting Ltd., 1998.

[32] Duff JT and Kelly K. *A new approach to interior lighting design: Early stage research in Ireland*. Journal of Sustainable Engineering Design: Vol. 1: Iss. 4. pp. 13-19.

[33] Cuttle C. *Cubic illumination*. Lighting Research and Technology 1997; 29: 1–14.

[34] Venning B. *Cuttle's Theory, the profession responds*. SLL Newsletter. Vol3, Iss 1. Jan/Feb 2010. pp 7.

[35] Macrae, I. *Comment 1: A new direction for general lighting practice*, Lighting Research and Technology, February 2013; vol. 45, 1: pp. 22-39.

[36] Poulton, K. *Cuttle's Theory, the profession responds*. SLL Newsletter. Vol3, Iss 1. Jan/Feb 2010. pp 7.

[37] Shaw, K. *Cuttle's Theory, the profession responds*. SLL Newsletter. Vol3, Iss 1. Jan/Feb 2010. pp 7.

[38] Brandston, HM. *Comment 3: Towards the third stage of the lighting profession*, Lighting Research and Technology, March 2010; vol. 42, 1: pp. 73-93.

[39] Wilde, MB. *Comment 2: A new direction for general lighting practice*, Lighting Research and Technology, February 2013; vol. 45, 1: pp. 22-39.

[40] Loe, DL. *Cuttle's Theory, the profession responds*. SLL Newsletter. Vol3, Iss 1. Jan/Feb 2010. pp 7.

[41] Loe, DL. "*Brightness, lightness, and providing a preconceived appearance to the interior"*, Lighting Research and Technology, September 2004; vol. 36, 3: pp. 215.

[42] Raynham, P. *Cuttle's Theory, the profession responds*. SLL Newsletter. Vol3, Iss 1. Jan/Feb 2010. pp 7.

[43] Bedocs, L. *Comment 1: Towards the third stage of the lighting profession*, Lighting Research and Technology, March 2010; vol. 42, 1: pp. 73-93.

[44] Boyce, PR. *Cuttle's Theory, the profession responds*. SLL Newsletter. Vol3, Iss 1. Jan/Feb 2010. pp 7.

[45] Boyce PR and Smet K. LRT symposium 'Better metrics for better lighting' – a summary. Lighting Research and Technology, vol. 46, 6. Pp. 619-636.

[46] Hoggett, N. *Cuttle's Theory, the profession responds*. SLL Newsletter. Vol3, Iss 1. Jan/Feb 2010. pp 8.

[47] Mansfield, KP. *Comment 2: Towards the third stage of the lighting profession*, Lighting Research and Technology, March 2010; vol. 42, 1: pp. 73-93.

[48] Raynham P. Room lighting in the absence of a defined visual task and the impact of mean room surface exitance. *Lighting Research and Technology*. First published 27 November, 2014, doi:10.1177/1477153514561071.

[49] Raynham PJ, Bean AR. Calculation of transfer factors in the European utilization factor method. *Lighting Research and Technology*, 2006; 38: 341–357.

[50] Duff J. Research Note: On the magnitude of error in a formula to calculate mean room surface exitance. *Lighting Research and Technology*. In Press.

[51] Duff J, Antonutto G and Torres S. On the calculation of mean room surface exitance. Lighting Research and Technology. First published 1 July, 2015, doi:10.1177/1477153515593579.

[52] Ward G, Shakesphere R. *Rendering with Radiance*. San Francisco: M. Kaufmann, 2004.

[53] Ward G. The RADIANCE lighting simulation and rendering system. *Proceedings of SIGGRAPH 94: Computer Graphics Annual Conference* Series. Orlando, FL: Association for Computing Machinery's Special Interest Group on Computer Graphics, 1994: 459–72.

[54] Ward G, Rubinstein F, Clear R. A ray tracing solution for diffuse inter-reflection. *Computer Graphics* 1988; 22: 85–92.

[55] MN Inanici. *Evaluation of high dynamic range photography as a luminance data acquisition system*. Lighting Research and Technology, June 2006; vol. 38, 2: pp. 123-134.

[56] J. Mardaljevic, B. Painter, and M. Andersen. *Transmission illuminance proxy HDR imaging: A new technique to quantify luminous flux*. Lighting Research and Technology, March 2009; vol. 41, 1: pp. 27-49.

[57] Ward G. Photosphere. /http://www.anyhere.com/

[58] The Society of Light and Lighting (SLL). 2009. *The SLL Code for Lighting*. ISBN-978 906846-07-7. London: SLL.

[59] Illuminating Engineering Society of North America, *The IESNA Lighting Handbook*, 10th Edition, New York: IESNA.

[60] Committee of European Standards. 2011. EN 12464-1:2011. *Light and Lighting - Lighting of workplaces. Part 1: Indoor Workplaces*. London: CEN.

[61] Fotios S and Atli D. Comparing Judgements of Visual Clarity and Spatial Brightness Through an Analysis of Studies Using the Category Rating Procedure. *Leukos*, 2012; 8(4); 261-281.

[62] Loe D. Measuring the lit appearance of a space. *Light and Lighting*. Vol 11, December 1999: 35–37.

[63] Society of Light & Lighting. 2002. *Code for Lighting*. Oxford (UK): Butterworth-Heinemann.

[64] Bullough JD. Spectral sensitivity modelling and nighttime scene brightness perception. *Leukos.* 2015. vol. 11, 1: 11-17.

[65] Bullough JD, Radetsky L and Basenecker U. Influence of spectral power distribution on scene brightness at different light levels. *Leukos.* 2014. vol. 10, 1: 3-9.

[66] Boyce PR. Investigations of the subjective balance between illuminance and lamp colour properties. *Lighting Research and Technology* 1977; 9: 11–24.

[67] Fotios SA, Levermore GJ. The perception of electric light sources of different colour properties. *Lighting Research and Technology* 1997; 29: 161–171.

[68] Hu X, Houser KW, Tiller DK. Higher colour temperature lamps may not appear brighter. *Leukos* 2006; 3: 69–81.

[69] Alman DH. Errors of the standard photometric system when measuring the brightness of general illumination light sources. *Journal of the Illuminating Engineering Society* 1977; 6:55–62.

[70] Ju J, Chen D, Lin Y. Effects of correlated color temperature on spatial brightness perception. *Color Research and Application* 2012; 37:450–454.

[71] Harrington RE. Effect of color temperature on apparent brightness. *Journal of the Optical Society of America* 1954; 44: 113–116.

[72] Levermore GJ. Perception of lighting and brightness from HID light sources. *Lighting Research and Technology* 1994; 26: 145–150.

[73] Berman SM, Jewett DL, Fein G, Saika G, Ashford F. Photopic luminance does not always predict perceived room brightness. *Lighting Research and Technology* 1990; 22:37–41.

[74] Rea MS. New Benefit Metrics for More Valuable Lighting. *Journal of Light & Visual Environment* 2013, doi: IEIJ130000498.

[75] Rea MS. *Value Metrics for Better Lighting*. Washington: SPIE Press, 2013.

[76] Fotios S, Atli D, Cheal C, Hara N. Lamp spectrum and spatial brightness at photopic levels: Investigating prediction using S/P ratio and gamut area. *Lighting Research and Technology* 2014, doi:10.1177/1477153514546784.

[77] Fotios S, Atli D, Cheal C, Houser K and Logadóttir Á. Lamp spectrum and spatial brightness at photopic levels: A basis for developing a metric. *Lighting Research and Technology*. 2013; 47, 3: 80-102.

---

[78] Rea MS, Mou X and Bullogh JD. Scene brightness of illuminated interiors. *Lighting Research and Technology*. Published online, April 21 2015. doi:10.1177/1477153515581412.

[79] Loe DL, Mansfield KP, and Rowlands E. Appearance of the lit environment and its relevance in lighting design: experimental study. *Lighting Research and Technology*. September 1994; vol. 26, 3: pp. 119-133.

[80] Loe DL, Mansfield KP, and Rowlands E. A step in quantifying the appearance of a lit scene. *Lighting Research and Technology*. December 2000; vol. 32, 4: pp. 213-222.

[81] Vrabel PL, Bernecker CA, Mistrick RG. 1998. Visual performance & visual clarity under electric light sources: Part II - Visual Clarity. *Journal of Illuminating Engineering Soc*. 27(1):29–41.

[82] Fechner GT. *Elementeder Psychopysik*. Breitkopf und Hartel, Munich, 1860.

[83] Adams QE, Cobb PW. The effect of foveal vision on bright and dark surroundings. *The Journal of experimental Psychology*, 1992. 5 39-45.

[84] Stevens SS.  To honour Fechner and repeal his law. *Science*, 1961. 3446 80-86.

[85] Hurvich LM and Jameson D. Visual scaling. *Handbook of Sensory Physiology*. 1972, Vol 7 Berlin: Springer.

[86] H-W Bodmann and M La Toison. Predicted Brightness – Luminance Phenomena. Lighting Research and Technology. Vol 26 No 3 1994 pp 135-143.

87 Duff JT, Cuttle C and Kelly K.  Spatial brightness, horizontal illuminance and mean room surface exitance in a lighting booth. Lighting Research and Technology. In press.

---

88 Duff JT, Cuttle C and Kelly K. Perceived adequacy of illumination, spatial brightness, horizontal illuminance and mean room surface exitance in a small office. *Lighting Research and Technology*. In press.

[89] Duff JT, Cuttle C and Kelly K. Spatial brightness, perceived adequacy of illumination, horizontal illuminance and mean room surface exitance in non-uniform light scenes. *Lighting Research and Technology*. In press.