AN INVESTIGATION OF ALTERNATIVE DAYLIGHT METRICS

Longyu Guan

A thesis submitted to

Institute for Environmental Design and Engineering

University College London (UCL)

in candidacy for the degree of Doctor of Philosophy

June 2020

Abstract

With the innovation of technology, both our lit environment and the way people perform indoor tasks have changed. Good visual performance became relatively easy to achieve, and as a result the emphasis of lighting design has moved away from the lighting of working planes. Whilst task illuminance is still in use there is now much more emphasis on the appearance of the room and the people in them. In fact, the term “working plane” has been nominally removed in the European electrical lighting standard. Therefore, it is necessary to question the use of working planes in daylight designs.

For many years daylight factor has been the dominant metric used to describe the amount of daylight in a room. However, it only considers light falling onto the working plane and thus it may not be the best metric to describe daylight adequacy in modern buildings. A few alternative metrics have been proposed such as the metrics by Climate-based daylight modeling (DA, UDI) which recently have raised a lot interests. In addition, a number of new lighting parameters (MRSE, cubic illuminance and cylindrical illuminance) have also been proposed but only applied to electrical lighting. This research studied a new metric for daylight, derived from MRSE, to find out if the new metric was better at predicting user perceptions of daylight adequacy than the existing working plane based metrics.

Impact Statement

This research explored the possibility of implementing new lighting parameters into daylighting. During the process a new lighting metric, mean indirect cubic illuminance (MICI), was developed based the existing concept of mean room surface exitance (MRSE).

Through case studies, MRSE was soon found out to be difficult to apply in open or complexed building geometries. The metric of MICI was tested in a range of conditions and found to be a better predictor of peoples' perceptions of daylight than any existing metric. This has provided a tool that may be used to improve the daylighting in buildings. Moreover, by comparing the results of this study with previous work on MRSE it is clear that MICI may well work for electric lighting as well as daylight.

To enable further development of the concepts of MICI and MRSE a tool has been developed that can calculate both of these parameters in any room of known geometry and surface luminance.

Publications

J. Unwin and L. Guan, “Clear as Daylight,” *The Lighting Journal,* vol. Lighting Journal October 2016, pp. 16-19, 2016.

P. Raynham, J. Unwin and L. Guan, “A New Metric to Predict Perceived Adequacy of Illumination,” *Lighting Research and Technology,* vol. 51, no. 4, pp. 642-648, 2019.

In progress:

L. Guan, R. Bunn, J. Unwin and P. Raynham, “Perceived Adequacy of Daylight and Daylighting Metrics: A Study in Existing Buildings”.

L. Guan, P. Raynham and J. Unwin, “Perceived Adequacy of Daylight and Daylighting Metrics: A controlled experiment study”

L. Guan, P. Raynham and J. Unwin, “Mean Indirect Cubic Illuminance: An Investigation of Alternative Daylight Metric”

Declaration

This thesis has been completed solely by the PhD candidate, Longyu Guan. The research work contained in the thesis was done by the candidate, unless otherwise stated. It has not been submitted for any other degrees. All sources of information have been acknowledged and references have been provided.

Acknowledgements

I would like to express my sincere gratitude to my supervisors, Prof. Peter Raynham and Dr. Jemima Unwin both from University College London, for their advice, support, enthusiasm and encouragement throughout my PhD study. It has been a very rewarding and illuminating experience for me and I am so grateful that my supervisors were always there to provide help and guidance. I feel lucky to have them as my supervisors.

I would also like to thank Dr. Kevin Mansfield, Dr. Stephen Cannon-Brookes and Prof. Ben Croxford who have also provided help and advice throughout my study.

My families also receive my deepest love and gratitude for their support and dedication during my study.

Table of Contents

List of Figures

List of Tables

List of Acronyms

ADF	Average Daylight Factor
ASE	Annual Sunlight Exposure
CBDM	Climate-based Daylight Modelling
DA	Daylight Autonomy
DA_{con}	Continuous Daylight Autonomy
DF	Daylight Factor
ERC	External Reflected Component
ipRGCs	Intrinsically Photoreceptive Retinal Ganglion Cells
IRC	Internal Reflected Component
LiDOs	Lighting Design Objectives procedure
MICI	Mean Indirect Cubic Illuminance
MRSE	Mean Room Surface Exitance
PAI	Perceived Adequacy of Illumination
PBI	Perceived Brightness of Illumination
POEs	Post Occupancy Evaluations
SC	Sky Component
sDA	Spatial Daylight Autonomy
TAIR	Target/Ambient Illumination Ratio
UDI	Useful Daylight Illuminance

Chapter One: Introduction

1.1 Daylighting today[1]

Daylight is a gift of nature and the benefits it brings have been advocated for centuries, as seen in an ancient limestone relief that shows the Egyptian Queen Nefertiti holding up her daughters to the rays of the sun [1] (*Figure 1-1*, left). More recently, the writer and playwright George Bernard Shaw used a revolving shed to optimise his daylit working conditions [1] (*Figure 1-1*, right). As electrical lighting increasingly replaced daylight in buildings, the effect of light on well-being was largely forgotten until the discovery of the intrinsically photoreceptive retinal ganglion cells (ipRGCs) which influence circadian, hormonal and behavioural systems [2]. The role of light as a stimulus for these systems is unquestioned, however whether ipRGC activation should be maximized or minimized in buildings is unknown [3]. Despite this, the advantages of daylight are unquestioned as it provides high retinal illuminance and information about the external environment. This is why daylight propagation in spaces where people spend most of their time, is an important area of exploration.

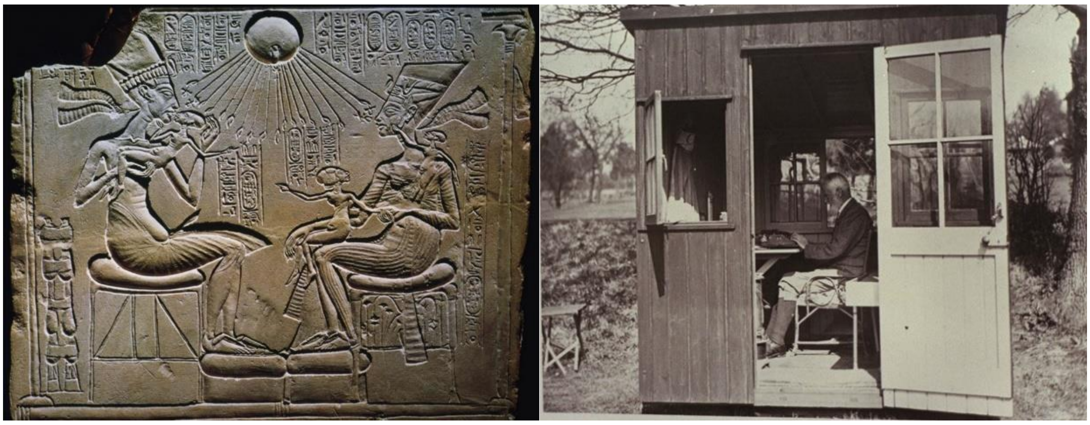


Figure 1-1: Nefertiti limestone relief (left) *[4]* and Shaw's revolving shed (right) *[5]*

As nowadays technologies innovate at a very fast rate, both our lit environment and the way people perform indoor tasks have changed a lot. High efficacy light bulbs, advanced laser printing and self-luminous displays have made it easy to achieve good visual performance. As a result, people started to argue that visual performance is no longer that important and should not be the basis for recommending light levels in most commercial applications [6].

---

[1] Much of this section has been previously published in the article "Clear as Daylight" [103].

The same has happened in daylighting. *Figure 1-2* compares a typical office in the 1970s with one of the present day. From the image of the 1970s, it is clear that the desktop (i.e. the horizontal working plane) is the most important task area. However, in working environments today, people find that the horizontal desk plane is no longer the only important task area. The most task-intensive planes are arguably computer screens on which good visual performance is easy to achieve (by “zooming in” for example). As the use of computers means that people can work from anywhere, the main reason to attend a workplace is to communicate with colleagues, which involves looking at their faces. Therefore, it could also be argued that facial communication is also an important task.

Figure 1-2: Daylit office room in 70s (left) vs present (right)

1.2 Do we have the right daylight metrics?

With visual performance playing a less important role, questions arise: what should be the new focuses for daylighting designs now? And how can we tell whether a room is adequately daylit? There are arguments that Perceived Adequacy of Illumination (PAI) should be the new basis for general lighting practice [7] [8]. PAI refers to the quantity of light within a space that is likely to be judged sufficient for activities the space houses. Since the working plane illuminance started losing its significance, it is reasonable to put more emphasis on appearance of the room and people in it.

In terms of daylighting metrics, daylight factor is the ratio of interior to exterior illuminance over a horizontal plane and has been the dominant metric for daylight design for over 50 years. As the working environments have evolved, do we have the right daylight metrics now? There are new metrics developed for electrical lighting. Are those metrics also useful for daylighting? These are the questions that drive the researcher to conduct this PhD study.

The fundamental research question of this study is:

> *Is light on the working plane the only metric for daylight? If not, are better metrics possible?*

1.3 Study objectives and thesis structure

To address the above questions, this PhD research was set out to:

- Review existing daylight metrics and compare them with possible new metrics
- Study user perceptions of daylight adequacy in real buildings and a laboratory study
- Compare user responses to old and new daylight metrics

Chapter 2 reviews existing popular daylight metrics and discussed a number of potential alternative metrics from electrical lighting.

Chapter 3 identifies one candidate, Mean Room Surface Exitance (MRSE), as the alternative daylight metric. However, under tests in real building it was soon found out to be difficult to apply in complex geometry. A new metric, Mean Indirect Cubic Illuminance (MICI), was hence developed and the focus of this PhD research became to study the relationship between the new metric MICI to user perceptions of daylight adequacy. Chapter 3 also studies the relationship between MICI and MRSE.

Chapter 4 outlines the research objective and any potential study benefits. Since the focus of research had been changed in Chapter 3, the research objective stated in Chapter 4 is more detailed and specific. A research hypothesis is also given at the end of Chapter 4.

Chapter 5 discusses the methodologies of all the studies conducted in this PhD research. Since computer simulation played a significant part in the studies, this chapter also introduces some of the core mechanics behind lighting simulation tools.

Chapter 6 explains the post occupancy case studies where the relationship between MICI and user perceptions of daylight adequacy was investigated in three real buildings. The results are also compared with a number of selected existing daylight metrics.

Chapter 7 discusses the controlled environment study where the correlations between MICI and human responses were analysed in two controlled spaces. Results are compared also with working plain illuminances.

Chapter 8 summarizes and analyses the results from all the studies conducted in previous chapters.

Chapter 9 compares and discusses the findings of this research and compares the findings with the results of previous studies.

Chapter 10 discusses the potential implementations of MICI in lighting practice, including both daylighting and artificial lighting.

Chapter 11 summarises all the findings of this PhD research. Research impacts, imitations and further study suggestions are also given in this chapter.

Table 1- 1 summarises the structure of the thesis:

Chapter number and title	**Summary of chapter contents**
Chapter one: Introduction	• Research background • Fundamental research question
Chapter two: A review of the current metrics	Literature reviews of: • Current daylight metrics • Potential daylight metrics from electrical lighting
Chapter three: Evolution of MRSE into MICI	• Addressing problems of MRSE • Introducing MICI • Comparison study of MICI and MRSE
Chapter four: Research objectives	• Refined research objective • Potential study benefits • Research hypothesis
Chapter five: Research methodology	• Research methodology overview • Discussions on the computer simulation
Chapter six: POE case studies	Detailed descriptions of the POE case studies, including detailed study methodology, results, analyses and discussions.
Chapter seven: Controlled experiment	Detailed descriptions of the controlled environment study, including detailed study methodology, results, analyses and discussions.
Chapter eight: Discussion	• Recap on all the studies conducted • Discussions on the combined results from all studies
Chapter nine: A comparison to previous studies	Result comparisons with Duff and Cuttle’s studies
Chapter ten: Implementations of MICI in lighting	Discussions on the potential implementations of MICI in both daylighting and artificial lighting practices.
Chapter eleven: Conclusion	• Research findings/conclusion • Research impacts • Research limitations • Suggestions for future works

Table 1- 1: Chapter structure and key contents

1.4 Methodology overview

This PhD research mainly conducted two types of studies:

- Case studies of real buildings
- Laboratory study of controlled environments

The case studies were conducted in the form of Post Occupancy Evaluations (POEs), where a well-established POEs survey – Building Usage Studies (BUS) methodology was used. Computer simulations (RADIANCE and DAYSIM) were also used to calculate each of the studied daylight metrics. More detailed description of the study methodology is given in Chapter 5 and Chapter 6.

The laboratory study was a controlled experiment where two daylit spaces were set up to be similar in many ways such as room geometry, furniture and view but differed in the indoor light levels. A questionnaire was developed which also contains the BUS rated lighting questions. Onsite measurements and computer simulations (RADIANCE and DAYSIM) were used to calculate values of daylight metrics. More detailed description of the study methodology is given in Chapter 5 and Chapter 7.

Chapter two: A review of the current metrics

2.1 Chapter introduction

This chapter serves as a literature review aiming to gain an understanding of the existing popular daylight metrics, which include:

- Daylight factor
- Climate-based daylight metrics
- Median daylight illuminance

This review also included a few alternative lighting design concepts, which are originally developed for the electrical lighting but have the potentials to be implemented in daylighting:

- Mean room surface exitance
- Cubic illuminance
- Cylindrical illuminance

Discussions covered their history, calculation methods, advantages and criticisms. A summary of each metrics' strength and weakness is also given at the end of this chapter.

2.2 Daylight factor

2.2.1 The development of daylight factor

Daylight factor can be traced back to the beginning of 20th century when Percy J. Waldram proposed sky factor. He noticed the significant variations in sky luminance due to different weather, then decided instead of measuring the interior illumination as an absolute value it is better to express daylight accessibility as a ratio of simultaneous illuminances of interior and exterior [9]. This sky factor ratio was widely adopted and officially recognised by the Commission Internationale de l'Eclairage (CIE) in 1929 [10]. Both daylight factor and sky factor share exactly the same mathematical expression (Equation 1), with the only difference being sky factor is based on a uniform sky model.

$$Sky/Daylight\ Factor = \left(\frac{E_{indoor}}{E_{outdoor}}\right) \times 100\% \qquad \text{Equation 1}$$

In 1942, Moon and Spencer developed the overcast sky model which has a luminance ratio from the horizon to zenith of 1:3, and it is expressed as [11]:

$L_\alpha/L_Z = (1 + 2sin\alpha)/3$ Equation 2

Where L_α is the sky luminance at the horizon;

L_Z is the sky luminance at the zenith;

α is the sky altitude angle.

CIE later adopted this sky model as the CIE Standard Overcast Sky and decided to replace the uniform sky with this new model for daylighting calculations [12]. In 1963 CIE revised the definition of daylight factor as the ratio of the internal and external illuminance on a horizontal plane from an unobstructed hemisphere of overcast sky [12]. Since then the daylight factor concept had been fully established.

Currently, the up to date definition of daylight factor according to the CIE International Lighting Vocabulary (ILV) is [13]:

> *"ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded."*

Although the new definition removed the term "overcast sky" and instead suggested that daylight factor can be calculated under "a sky of assumed or known luminance distribution". In practice, however, most daylight factor calculations were still under the consumption of the CIE Standard Overcast Sky.

Daylight factor is dependent on the room geometry, window transmittance and the indoor surface reflectance. It can be divided into three components: Sky Component (SC)-direct daylight from the sky, External Reflected Component (ERC)-indirect daylight from external reflection and Internal Reflected Component (IRC)-indirect daylight from internal reflection [14]. To calculate each component of daylight factor, there are both numerical methods and graphical methods.

2.2.2 Numerical calculation methods

For SC, the general formula is to simply sum up the illuminance contribution from the whole visible sky [15]:

$$E = \int_{\beta_1}^{\beta_2} \int_{\alpha_1}^{\alpha_2} L_\alpha \cdot sin\alpha \cdot cos\alpha \cdot d\alpha \cdot d\beta$$

Equation 3

Where the azimuth angle from β_1 to β_2 and elevation angle from α_1 to α_2 define the visible part of the sky (*Figure 2-1*).

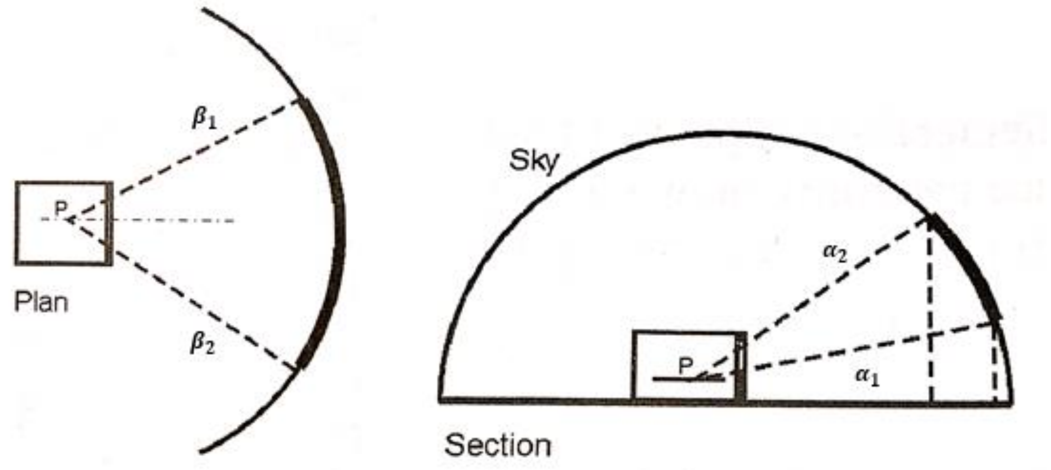


Figure 2-1: Angles of visible sky *[15]*

For calculating ERC, the method is the same as SC except the luminance of external obstructions ($L_{\alpha,\ shaded}$) is often assumed as 10% of luminance from the unshaded sky [14]:

$$L_{\alpha,shaded} = 0.1 \cdot L_\alpha$$

Equation 4

Alternatively, ERC can also be approximately calculated as a percentage of SC using Puskas's luminous centroid method [14]:

$$ERC = f \cdot SC$$

$$f = \frac{7}{30(1+2sin\alpha_{cen})}$$

Equation 5

Where α_{cen} is the angular position of the luminous centroid (*Figure 2-2*), and it can be approximately calculated by:

$$\alpha_{cen} \approx 0.7\alpha_F + 0.1\alpha_D$$

Equation 6

Where α_F and α_D are the obstruction angles as indicated in *Figure 2-2* below.

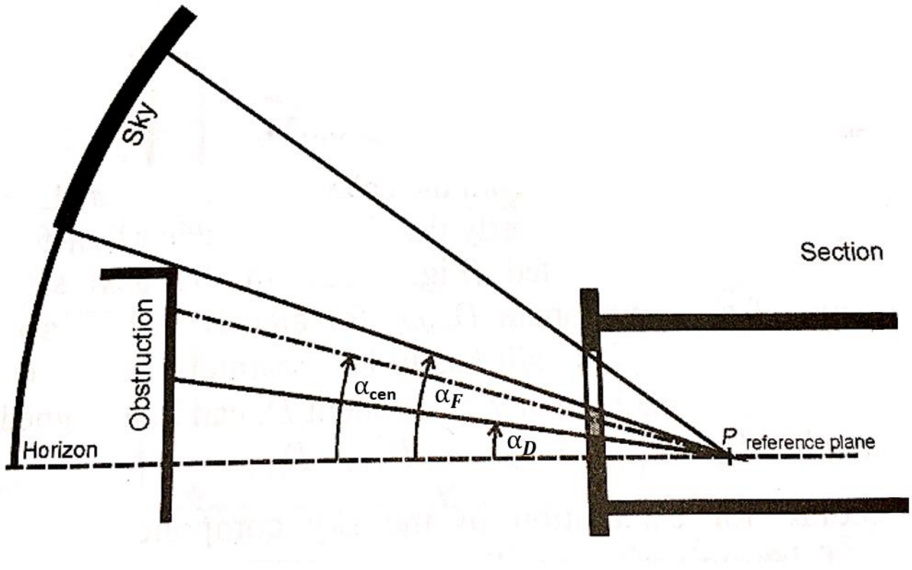


Figure 2-2: Angular position of the luminous centroid for external obstruction *[14]*

As for IRC, in practice it is usually calculated using a formula based on the Sumpner's Law which states that in any closed system the flux emitted must equal the flux absorbed [16]. Therefore, in a daylit room the total amount of light flux entered the window should be equal to the flux absorbed by the room surfaces. If put aside the direct component of the light flux in the room, the first reflected flux (the source of all the inter-reflected flux) should also equal to the inter-reflected flux absorbed by the room surfaces. Hence the basic formula behind the IRC calculation is [17]:

Average inter-reflected component of the illumination within the interior

$$= \frac{\text{First reflected flux from interior surfaces}}{\text{A (1-R)}} \qquad \text{Equation 7}$$

Where A is the area of all the major surfaces in the room (ceiling, walls, floor and windows);

R is the average reflectance of all the major surfaces in the room (ceiling, walls, floor and windows).

At first, the first reflected flux was calculated by simply treating all flux entering the room as of equal weight, that is to assume all the flux entering through the window is evenly absorbed by room surfaces. Arndt's formula for IRC [17]:

$$IRC = \frac{A_w \cdot R}{A \cdot (1-R)} \cdot S \qquad \text{Equation 8}$$

Where A_{w} is the window area;

S is what known today as the “Vertical Sky Component” – the ratio of the illuminance normal to the centre of window and the outdoor illuminance, i.e. $\mathrm{S} = \frac{\text{illumintion normal to window}}{\text{total outdoor illumination}}$.

This approach (Arndt’s approach) was then challenged by Hopkinson, Longmore and Petherbridge [17] as they argued that the primary flux of daylight is often very unevenly distributed across the interior. The ceiling never receives any direct light from the sky and the floor never receives direct light from the ground. In practice the ceiling surface usually has high reflectance and the floor often has low reflectance. Therefore, Arndt’s simplification of giving equal weight to all the entering flux tends to over-estimate the amount of inter-reflected light and lead to inaccurate results.

To solve this problem, Hopkinson proposed the split flux method [17], where the entering daylight flux is split into two parts: (a) the flux entering the room directly from the sky or from obstructions which are above the horizon, and (b) the flux directly from the ground. Then the two parts (a) and (b) will be firstly reflected by the lower and upper room surfaces (separated by the plane of the mid-height of the window) respectively. The formula therefore becomes:

$$IRC = \frac{A_w}{A \cdot (1-R)} \cdot (C_1 R_{fw} + C_2 R_{cw}) \qquad \text{Equation 9}$$

Where C_1 is the sky flux received through the window;

C_2 is the ground flux received through the window;

$\mathrm{R_{fw}}$ is the average reflectance of the floor and those parts of the wall below the plane of the mid-height of the window (excluding the window wall);

$\mathrm{R_{cw}}$ is the average reflectance of the floor and those parts of the wall above the plane of the mid-height of the window (excluding the window wall).

After simplification and testing of the C_1/ C_2 ratio under the CIE overcast sky, the final form of the empirical formula proposed by Hopkinson, Longmore and Petherbridge is:

$IRC = \frac{0.85\ A_w}{A(1-R)}\left(CR_{fw} + 5R_{cw}\right)$ Equation 10

Where 0.85 is the assumed window transmittance;

C is a coefficient given in *Table 2-1* below.

Angle of obstruction from centre of window (degree above horizontal)	C*
0 (no obstruction)	39
10	35
20	31
30	25
40	20
50	14
60	10
70	7
80	5

*the C value is dependent on the assumption: The ground and any external obstructions have a brightness 1/10 of the mean sky brightness.

Table 2-1: the proposed C values for the IRC calculation by Hopkinson, Longmore and Petherbridge *[17]*

Hopkinson’s split flux formula showed sufficient accuracy when tested and compared with other methods [17]. It was later adopted by the Building Research Establishment (BRE) as the BRE split flux method and became the standard formula for calculating IRC for many architects and lighting practitioners.

There is also an Average daylight Factor (ADF) formula based on Sumper’s theorem, originally developed by Lynes [18] and improved by Crisp and Littlefair [19].

$$ADF = \frac{TS_W\theta}{A(1-R^2)}\%$$ Equation 11

Where T is the window transmittance;

S_W is the area of the window (m^2);

θ is the angle of visible sky (in degree);

A is the total area of the room surfaces: ceiling, floor, walls and window (m^2);

R is the average reflectance of room surfaces: ceiling, floor and walls.

This empirical formula provides the quickest way to roughly predict the mean daylight factor. However, a study by Naeem and Wilson [20] compared the ADF formula with computer simulations and on-site measurements and found out that it can overestimate daylight factor by 30%.

2.2.3 Graphical calculation methods

In order to make the calculation easier for designers, various graphical tools were also developed. Daylight protractors are the most popular methods to quickly estimate the SC and ERC. Initially developed in the 1940s [21], the BRS daylight protractor has a total of 5 sets for different slopes of glazing and unglazed apertures. Each set consists of two protractors: a primary protractor (top semicircle in *Figure 2-3*) which gives the SC and ERC values for a window with infinite length, and an auxiliary protractor (bottom semicircle in *Figure 2-3*) which gives the correction factor for the actual length of the window.

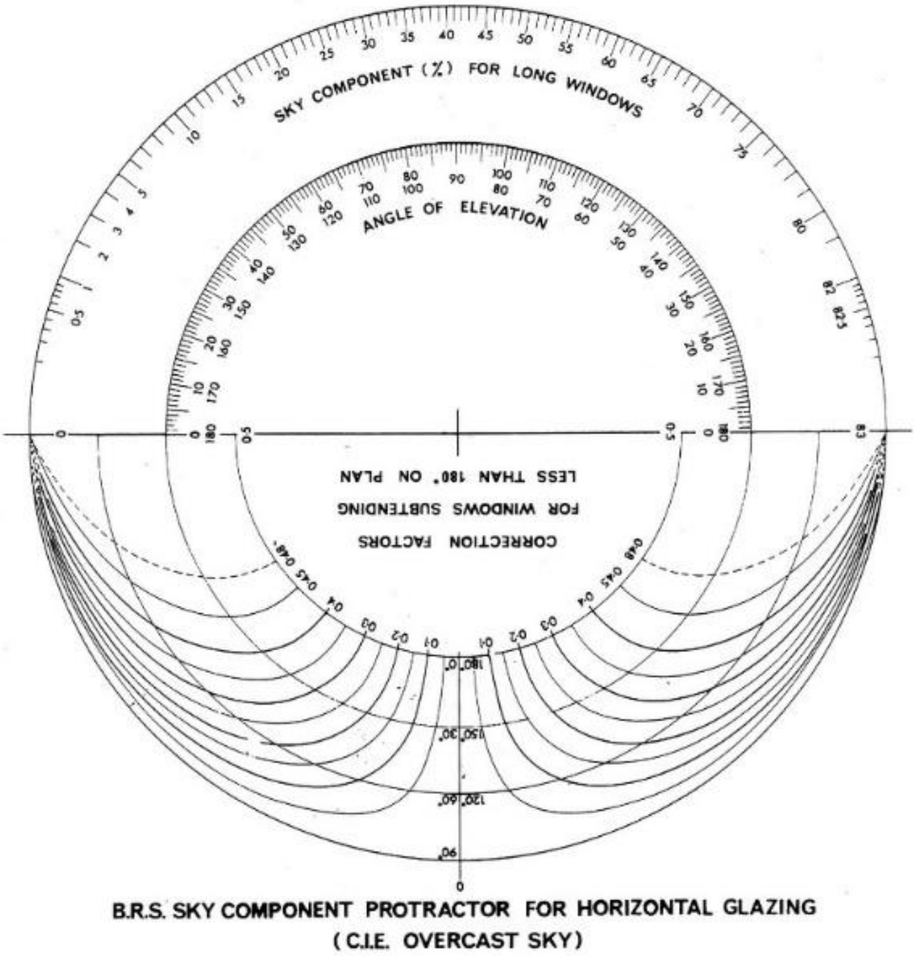


Figure 2-3: The BRS daylight protractor *[22]*

Other graphical methods for calculating the SC includes Pilkington sky dot method, Waldram diagrams [22] and more [23]. However, when compared with the daylight protractor, these methods require a bit more work than simply overlaying the protractor onto architectural drawings. In practice, methods with the most simplicity are more likely to be accepted by designers.

For IRC, Building Research Station (BRS, the former of BRE) developed nomograms based on the split flux formula (Equation 9). It allows designers to quickly calculate IRC with the given window area to total surface area ratio and the average room surface reflectance (*Figure 2-4*).

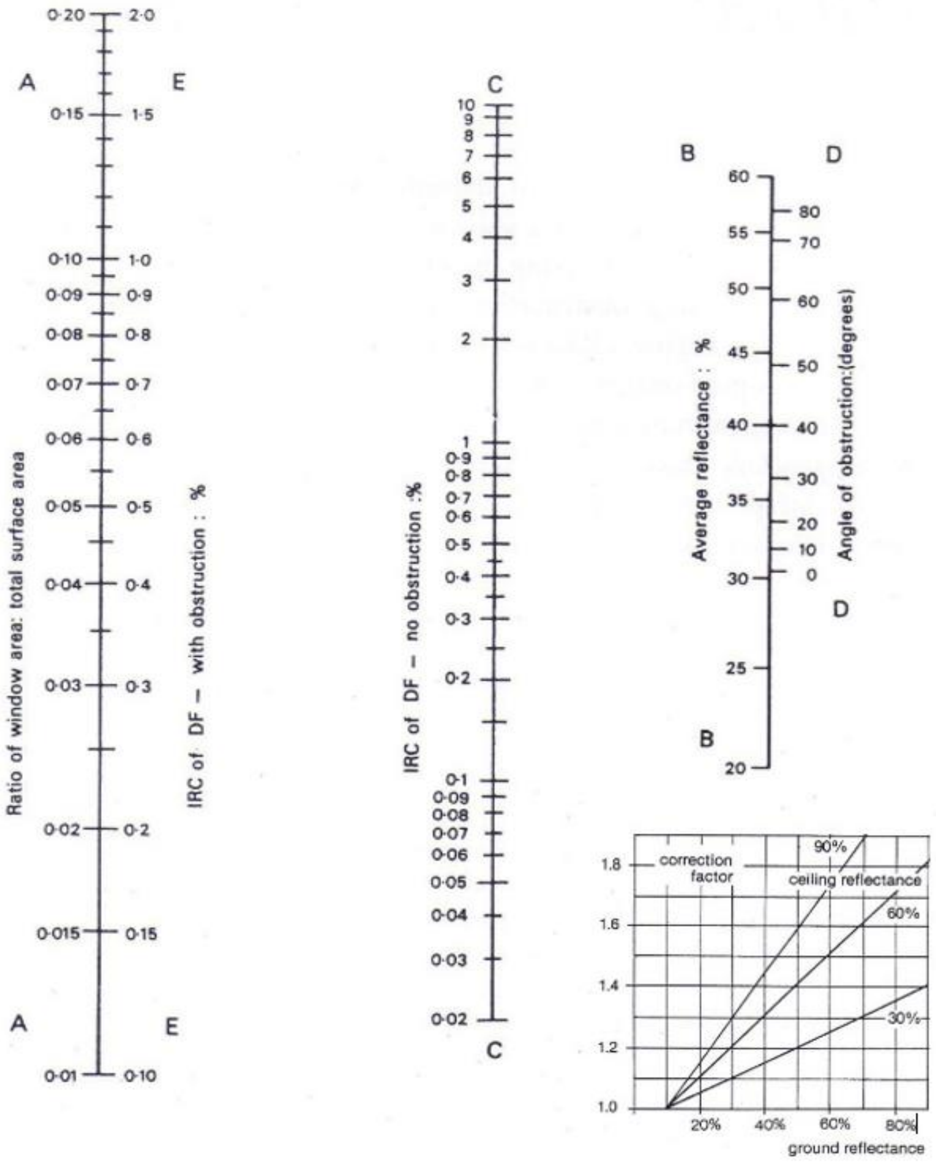


Figure 2-4: The BRS nomogram *[22]*

In additional to the diagrams, BRS even further simplified the process and produced daylight tables which allow both SC and IRC to be quickly looked up. However, the daylight tables only provide rough estimations and are “most appropriate for use in the early design stage when even scale drawings are not readily available” [22].

2.2.4 Summary of daylight factor

The greatest advantage of daylight factor is its simplicity. It is a purely geometrical measure, considering the fact it is mostly based on the overcast sky (i.e. the worst daylight condition). Peter Tregenza described daylight factor as a “speed limit” [24], as it is simple to specify yet has an evident relationship with the daylighting in a room. Daylight factor may not promote good daylight practice but can be used to stop bad daylighting designs.

The main criticism of daylight factor is that it addresses only one simple sky condition. Daylight factor does not consider factors such as building orientation, time of the date, climate conditions, direct and diffused sunlight, and these elements in real life can greatly affect the daylighting indoor. Also, daylight factors only focus on the working plane. Satisfying a daylight factor requirement may result in excessive amount of daylight under clear sky conditions, and even cause visual discomfort. A study found that the ratio of the vertical illuminance on the window plane to the external illuminance (i.e. Vertical Sky Component [25]) is actually more consistent and better correlated with the real interior lighting conditions than the working plane illuminance and daylight factors [26].

2.3 Climate-based daylight modelling

2.3.1 Fundamental concepts

To address the criticisms of daylight factor, the concept of Climate-based Daylight Modelling (CBDM) was gradually developed. CBDM is a complexed process of predicting indoor daylight parameters, and to put it in simple terms a typical CBDM procedure for calculating the indoor daylighting includes:

(1) For each time step (usually every 1 hour), basic climate data such as global and diffused irradiance are obtained from a weather file (usually a TRY file [27]).

(2) Then the irradiance data are converted to the sky luminance using Perez's luminous efficacy model [28].

(3) After that the sky luminance distribution model can be generated (based on Kittler's sky model [29]).

(4) The sky model needs subdivided into small patches (Tregenza's sky subdivision theory [30]) and the luminance of each patch can be calculated according to the created sky luminance distribution model.

(5) A 3D model of the interior and the exterior (if applicable; e.g. external obstructions) needs to be created. Also, the calculation points will need to be defined.

(6) Based on the 3D geometry and surface properties, daylight coefficients (Tregenza's daylight coefficient theory [31]) are calculated for each calculation points. The coefficients are not just limited to the sky luminance, and the same method can be applied to both the ground reflections and the direct sunlight (different software/programmes vary on the exact subdividing & coefficient method).

(7) Once all the daylight coefficients are calculated, they are temporarily stored on the computer. By multiplying these coefficients with the hourly luminance data and adding up the illuminance contributions from all components (skylight, sunlight and ground reflection), the illuminance value for each calculation point for every time step can be calculated.

These key CBDM concepts will be discussed in detail in the following sections (Section 2.3.2 and 2.3.3).

2.3.2 Understanding "climate-based"

"Climate-based" means that the sky luminance data used in daylight calculation are not just from an empirical sky model (e.g. Overcast Sky model), but also taking into account the dynamic climate conditions from meteorological recorded data. From 1960s to 1990s, there have been numerous studies on the sky luminous distribution models [32] [33] [34]. Among them, the most influential ones are Kittler's sky models. He firstly developed the Clear Sky model in 1967 [35], and then realised that any homogenous sky can actually be characterised by a diffusion indicatrix function $f(x)$ (which expresses the scattering effect of sunlight) and a Vertical Gradation Function $\varphi(Z)$ (which relates the luminance of a sky patch to its zenith angle). In 1997, Kittler and Darula finished General Sky model [29] which was later adopted by CIE in the standard ISO 15469 [36]. This General Sky model consists of 15 type of sky conditions, and its mathematical expression is:

$$\frac{L_a}{L_z} = \frac{f(\chi) \cdot \varphi(Z)}{f(Z_s) \cdot \varphi(0°)}$$

$$\varphi(Z) = 1 + a\ exp\ (b/\cos Z)$$

$$f(\chi) = 1 + c(exp(d\ \chi)) - exp\left(d\frac{\pi}{2}\right) + e\cos^2\chi \qquad \text{Equation 12}$$

Where χ (sky patch to solar angle), Z (sky patch zenith angle) and Z_s (solar zenith angle) are shown in *Figure 2-5*. And a, b, c, d, e are coefficients depending on the atmospheric conditions, given in *Table 2-2*.

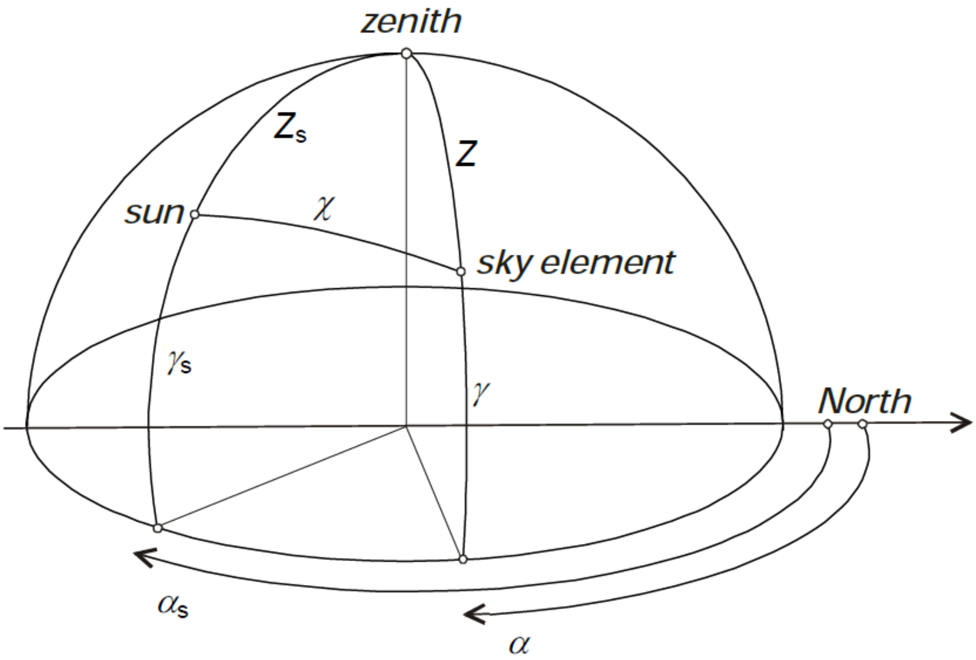
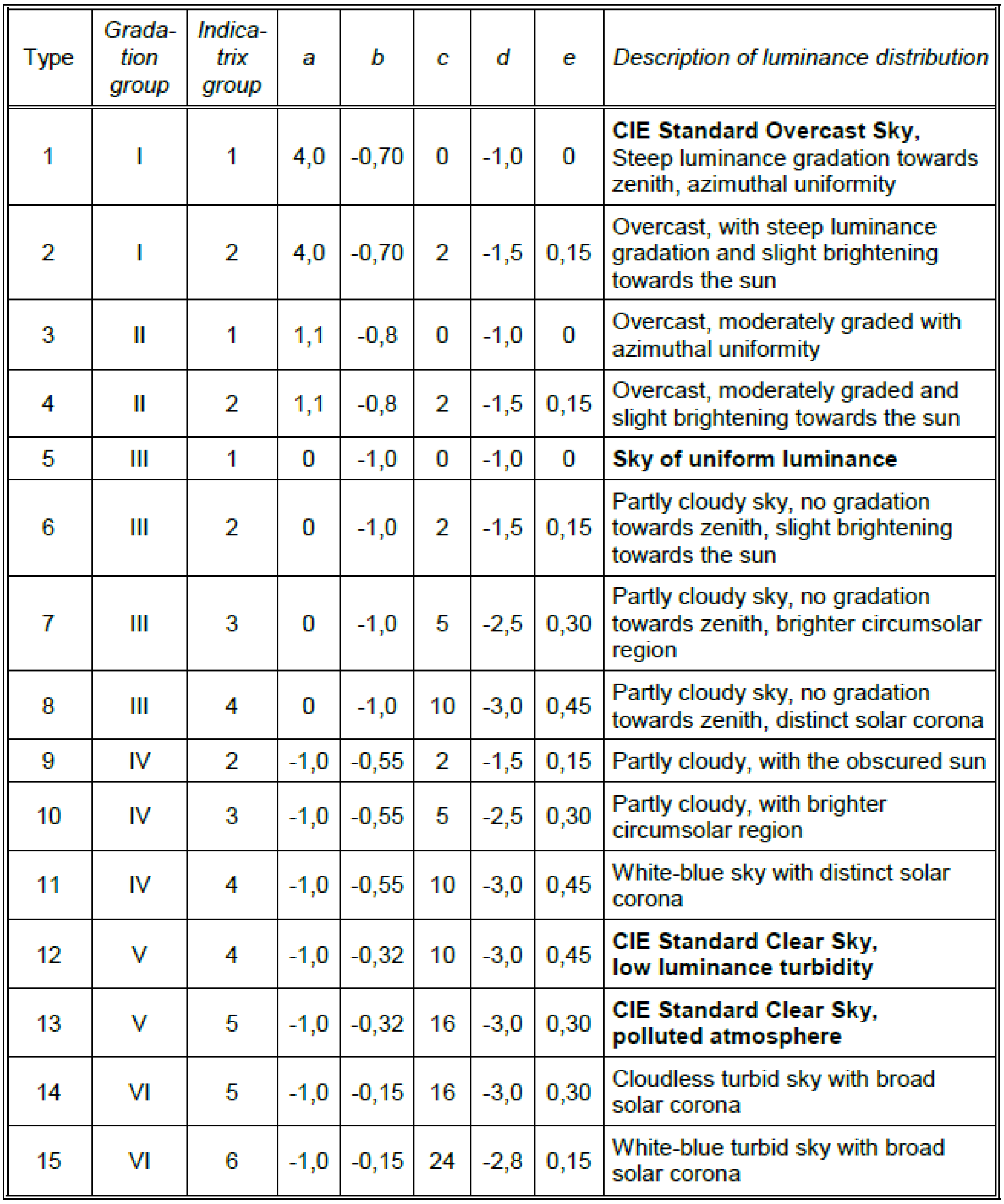


Figure 2-5: Angles of the sun and the sky patch *[36]*



Type	*Grada-tion group*	*Indica-trix group*	*a*	*b*	*c*	*d*	*e*	*Description of luminance distribution*
1	I	1	4,0	-0,70	0	-1,0	0	**CIE Standard Overcast Sky,** Steep luminance gradation towards zenith, azimuthal uniformity
2	I	2	4,0	-0,70	2	-1,5	0,15	Overcast, with steep luminance gradation and slight brightening towards the sun
3	II	1	1,1	-0,8	0	-1,0	0	Overcast, moderately graded with azimuthal uniformity
4	II	2	1,1	-0,8	2	-1,5	0,15	Overcast, moderately graded and slight brightening towards the sun
5	III	1	0	-1,0	0	-1,0	0	**Sky of uniform luminance**
6	III	2	0	-1,0	2	-1,5	0,15	Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun
7	III	3	0	-1,0	5	-2,5	0,30	Partly cloudy sky, no gradation towards zenith, brighter circumsolar region
8	III	4	0	-1,0	10	-3,0	0,45	Partly cloudy sky, no gradation towards zenith, distinct solar corona
9	IV	2	-1,0	-0,55	2	-1,5	0,15	Partly cloudy, with the obscured sun
10	IV	3	-1,0	-0,55	5	-2,5	0,30	Partly cloudy, with brighter circumsolar region
11	IV	4	-1,0	-0,55	10	-3,0	0,45	White-blue sky with distinct solar corona
12	V	4	-1,0	-0,32	10	-3,0	0,45	**CIE Standard Clear Sky, low luminance turbidity**
13	V	5	-1,0	-0,32	16	-3,0	0,30	**CIE Standard Clear Sky, polluted atmosphere**
14	VI	5	-1,0	-0,15	16	-3,0	0,30	Cloudless turbid sky with broad solar corona
15	VI	6	-1,0	-0,15	24	-2,8	0,15	White-blue turbid sky with broad solar corona

Table 2-2: 15 types of CIE skies *[36]*

To make sky models related to real climate, Perez et al. developed the All-weather Sky model [28] [37]. This model uses global and direct/diffused irradiance/illuminance data (which are common parameters in thermal modelling weather files) to calculate the Sky Clearness (ϵ) and the Sky Brightness (Δ). Based on the two parameters, it then adjusts coefficient a, b, c, d, e from the Diffusion indicatrix Function and Vertical Radiation Function. By substituting a, b, c, d, e in the general sky model formula (Equation 1), a “climate-based” sky luminance distribution can be generated.

2.3.3 Understanding “daylight modelling”

Computers started to play an increasingly important role in the daylight calculation since the early 90s. In theory, Equation 3 (which subdivides the sky hemisphere into infinite number of small segments) should be the ideal formula for a computer simulation. However, in reality even a computer has its limits, and the calculation of the inter-reflected light will consume a lot of computing power. In 1987, Tregenza [30] proposed a sky subdivision model in which he subdivided the sky dome into horizontal bands (with vertical angle of π/15 radians), then further divided each band into circular zones with (middle) width around 0.2 radians. The sky hence was subdivided into finite 151 circular patches (*Figure 2-6*, left), and each patch can be treated as an individual light source in daylight calculations. Although his original intention was to help the sky luminance measurements, this sky subdividing concept was widely adopted by daylight simulation software. In 1989, CIE recommended a total 145 patch no-gap (good for daylight modelling) subdivision model based on Tregenza’s work [38] (*Figure 2-6*, right).

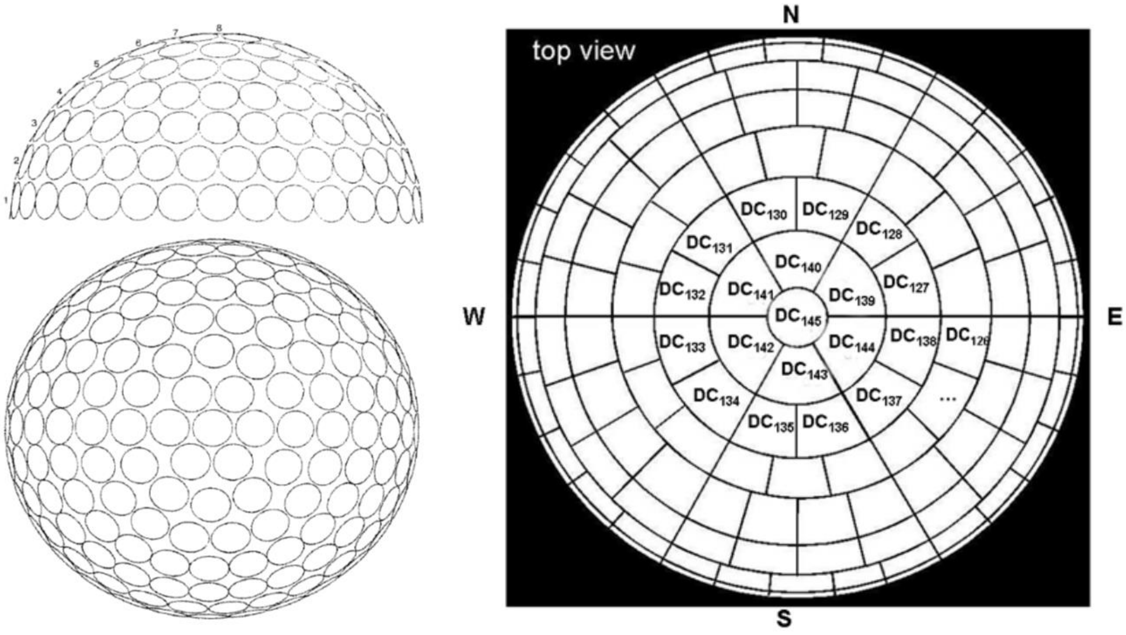


Figure 2-6: Tregenza’s sky subdivision model (left) *[30]* and 145 patch no-gap subdivision model (right) *[39]*

Another important concept for daylight modelling is the daylight coefficient, which is also proposed by Tregenza [31]. After the sky being subdivided, each sky patch can be considered as an individual light source, and the contribution to the interior illuminance at a point from a single sky patch can be expressed as:

$$\Delta E = D_{\alpha\beta} \cdot L_{\alpha\beta} \cdot \Delta S_{\alpha\beta}$$ Equation 13

$L_{\alpha\beta}$ is the luminance of the sky patch which, as discussed, can be calculated using Perez's sky model based on climate data. $\Delta S_{\alpha\beta}$ is the angular size of the sky patch which is completely dependent on the sky subdivision model. Daylight coefficient $D_{\alpha\beta}$ is a factor decided by on the room geometry, external surroundings, surfaces reflectance and the window transmittance. Apart from direct daylight, the same concept can also be applied to diffuse daylight, sunlight and ground reflection to calculate parameters such as "coefficient of direct sunlight" and "coefficient of ground reflection". Once all coefficients have been calculated, they will be temperately stored in the computer. Summing up the illuminance contribution (ΔE) from all components (daylight, sunlight and ground reflections) will give the total illuminance of the reference point. Equations below given two examples of how indoor illuminance is calculated in CBDM:

Reinhart's approach [40]: (145 daylight coefficient, 3 ground coefficient and 65 sunlight coefficient)

$$E(x) = \sum_{\alpha=1}^{145} D_\alpha^{diffuse}(x) L_\alpha^{diffuse} \Delta S_\alpha^{diffuse} + \sum_{\alpha=1}^{3} D_\alpha^{ground}(x) L_\alpha^{ground} \Delta S_\alpha^{ground} + \sum_{\alpha=1}^{65} D_\alpha^{direct}(x) L_\alpha^{direct} \Delta S_\alpha^{direct}$$

Equation 14

Mardeljevic's approach [41]: (145 direct and diffuse daylight coefficient, 145 indirect sunlight coefficient and 5010 direct sunlight coefficient)

$$E = D^{i\ 145} L^{145} \Delta S^{145} + D^{d\ 145} L^{145} \Delta S^{145} + D_\beta^{i\ 145} L^{sun} S^{sun} + D_\beta^{d\ 5010} L^{sun} S^{sun}$$

Equation 15

By switching the luminance values for different time of day/dates in the year and different climate conditions, the indoor illuminance can be modelled for given time steps and period. This whole process is called CBDM.

2.3.4 CBDM metrics

Because climate datasets were often recorded and selected as typical meteorological conditions for a whole year, it is best to consider the dataset in its entirety. Subsampling a dataset (e.g. taking only one day or one month) will inevitably cause biases. Therefore, CBDM usually runs a complete year with hourly time steps and as a result there will be over 4000 illuminance values generated for every reference point. In order to effectively analyse these data, CBDM metrics were developed.

Daylight Autonomy (DA) is one of the earliest CBDM metric [42]. It expresses the percentage of the occupied times of the year when the minimum illuminance requirement at the reference point is met by daylight alone. DA has two variations, Continuous Daylight Autonomy (DA_{con}) and Spatial Daylight Autonomy (sDA). DA_{con} considers the partial credit when the daylight illuminance lies below the minimum level. For example, if the illuminance threshold is 500 lx and only 400 lx has been achieved at a given time step, then a partial credit of 400 lx/500 lx=0.8 will be added to that time step. sDA focuses on the percentage of space that meets the illuminance threshold. For example, an sDA300-80% value of 50% means that 50% of the calculation points in a given space receive at least 300 lx during 80% of the annual occupied hours. In addition, there is the Annual Sun Exposure (ASE) [43] which is similar to sDA but with a much higher illuminance threshold (over 1000 lx) to show the presence of sunlight penetration.

Useful Daylight Illuminance (UDI) is a relatively new CBDM metric [44] [45]. It is very similar to DA, except UDI divides the working plane illuminances into 3 bands: “Fell-short” (<100 lx, requires artificial lighting), “Useful” (100-500 lx are effective as sole source or in conjunction with artificial lighting; 500-2000 lx are considered as desirable or at least tolerable) and “Exceeded” (>2000 lx, likely to cause visual/thermal discomfort). For example, a $UDI_{100\text{-}2000}$ value of 50% means the illuminance of the reference point lies within the “useful” band for half of the yearly working hours.

2.3.5 Discussions of CBDM metrics and CBDM in general

Both UDI and DA have been proposed as alternative daylight metrics to measure daylight adequacy. In fact, UDI has been made a mandatory criterion for the Priority Schools Building Programme (PSBP) [46] in UK, and sDA has also been integrated in the latest version of the US green building assessment scheme Leadership in Energy and Environmental Design (LEED) [47]. UDI and DA are rational products from CBDM. With one single number, they can effectively summarise the annual daylight availability on the working plane. UDI even further takes into account visual/thermal comfort by dividing illuminance values into different ranges, and studies have also shown that there is a “strong” anti-correlation between UDI and electric lighting energy usage [44] [45].

The main disadvantage of CBDM metrics is their added complexity, and the fact that they require CDBM to calculate. There are only a few programmes that allow CBDM calculation, and as Mardeljevic [48] pointed out most of them are underdeveloped (e.g. lacking user interfaces) and require “hard-won” skill to master. Even if with fully optimised CBDM programmes, lighting practitioners may still prefer a more “inexpensive” approach (such as ADF) for saving both the calculation time and resources.

Another criticism of CBDM metrics (especially UDI) is that they only measure the occurrence of illuminance value on a horizontal plane and perform poorly on describing the overall light distribution and the room appearance. Sometimes it is even difficult to figure out where exactly the windows are, if only looking at the UDI results without any architectural drawing (UDI right next to the window is also low due to the “exceeded” illuminance level). This is the reason why the researcher argues that the current CBDM metrics (DA, UDI and ASE) are more effective as parameters for energy consumption and shading design aspects of daylighting, instead of describing the actually indoor lighting conditions.

As for CBDM method in general, the researcher believes that it is the future of daylight calculation, however there are obstacles that need to be conquered. Put its complexity aside, the current way of acquiring climate data is also questionable. As introduced, the sky luminance used in CBDM is derived from only basic irradiance/illuminance data in thermal modelling weather file. The luminance distribution model is based on the same framework as the CIE General Sky model (Equation 12), therefore just like CIE skies it cannot predict the effect of random cloud which can greatly affect the sky luminance distribution [49]. This makes “climate-based” sky more like an upgrade to the CIE Sky, rather than a revolutionary progression. Mardaljevic suggested a climate dataset from International Daylight Measurement Programme (IDMP), which directly contains sky luminance data from sky scanning [50]. However, IDMP only set up 15 monitoring stations around the globe and only produced very few viable datasets. For the future of CBDM, more such climate station with sky scanning devices should be set up (specifically for daylight modelling, not as an auxiliary of thermal modelling). As for now, the use of CBDM needs to be further explored. Just like Tregenza described [24], CBDM should "lead the exploration into new and non-numerical measures of lighting" and it is "a tool to be used creatively".

2.4 Median Daylight illuminance

2.4.1 A new assessment method for indoor daylight provision

To avoid the complexity of "full-blown" CBDM while providing some "connectivity" to the local climate, Mardaljevic, Christofferson and Raynham [51] proposed:

> *"change the basis of daylight evaluation in standards from relative values based on a single sky (i.e. the daylight factor), to the annual occurrence of an absolute value for illuminance (i.e. lux) estimated from the cumulative availability of diffuse illuminance as determined from climate data, for instance standardised climate files."*

Instead of using the overcast sky, they suggested to derive the internal illuminance values from annual data for diffuse horizontal illuminance appropriate to the location of the evaluated building/space. To make the transition modest, it was proposed to use the median external diffuse horizontal illuminance value determined from climate file and convert it into a recommended target daylight factor. Equation 16 gives the equation for the target daylight factor (D_T).

$$D_T\ \% = \frac{E_T \times 100}{H_T} \qquad \text{Equation 17}$$

Where E_T is the target illuminance on the working plane;

H_T is the external diffuse horizontal illuminance.

This proposal was accepted by CEN (the European Committee for Standardization) and recently integrated into the standard EN 17037: Daylight in Buildings [52] as the new evaluation method for daylight provision to the interior. To comply with the standard, a target illuminance (E_T) and a target minimum illuminance (E_{TM}) need to be achieved across a specified fraction of the reference plane (F_{plane}) for a fraction of the year (F_{time}). Benchmarks of three levels (minimum, medium and high) of recommendation for assessment of daylight are given in the standard, and the minimum recommendation level should be provided. *Table 2-3* gives the recommendations for a daylit space with a vertical and/or inclined daylight opening, and *Table 2-4* gives the corresponding target daylight factors relative to the median external diffuse illuminance levels for different target internal illuminances. Note that the reference plane of the target illuminance is based on a horizontal plane 0.85m above the floor.

A similar set of tables for horizontal daylight openings are also given in the standard, and it is suggested to add more cities/locations to take into account more precise role of latitude and climate.

Level of recommendation for vertical and inclined daylight opening	Target illuminance E_T (lx)	Fraction of space for target level $F_{plane,\%}$	Minimum target illuminance E_{TM} (lx)	Fraction of space for minimum target level $F_{plane,\%}$	Fraction of daylight hours $F_{time,\%}$
Minimum	300	50%	100	95%	50%
Medium	500	50%	300	95%	50%
High	750	50%	500	95%	50%

Table 2-3: Recommendation of daylight provision by daylight openings in vertical and inclined surface (from EN 17037 *[52]*)

Nation	Capital	Geographical latitude φ [°]	Median External Diffuse Illuminance	D_T to exceed 100 lx	D_T to exceed 300 lx	D_T to exceed 500 lx	D_T to exceed 700 lx
Cyprus	Nicosia	34.88	18100	0.6%	1.7%	2.8%	4.1%
Malta	Valletta	35.54	16500	0.6%	1.8%	3.0%	4.5%
Greece	Athens	37.90	19400	0.5%	1.5%	2.6%	3.9%
Portugal	Lisbon	38.73	18220	0.5%	1.6%	2.7%	4.1%
Turkey	Ankara	40.12	19000	0.5%	1.6%	2.6%	3.9%
Spain	Madrid	40.45	16900	0.6%	1.8%	3.0%	4.4%
Italy	Rome	41.80	19200	0.5%	1.6%	2.6%	3.9%
Former Yugoslav Republic of Macedonia	Skopje	42.00	15400	0.6%	1.9%	3.2%	4.9%
Bulgaria	Sofia	42.73	18700	0.5%	1.6%	2.7%	4.0%
Romania	Bucharest	44.50	18200	0.5%	1.6%	2.7%	4.1%
Croatia	Zagreb	45.48	17000	0.6%	1.8%	2.9%	4.4%
Slovenia	Ljubljana	46.22	17000	0.6%	1.8%	2.9%	4.4%
Switzerland	Bern	46.25	16000	0.6%	1.9%	3.1%	4.7%
Hungary	Budapest	47.48	18100	0.6%	1.7%	2.8%	4.1%
Austria	Wien	48.12	16000	0.6%	1.9%	3.1%	4.7%
Slovakia	Bratislava	48.20	16300	0.6%	1.8%	3.1%	4.6%
France	Paris	48.73	15900	0.6%	1.9%	3.1%	4.7%
Luxembourg	Luxembourg	49.36	16000	0.6%	1.9%	3.1%	4.7%
Czech Republic	Prague	50.10	14900	0.7%	2.0%	3.4%	5.0%
Belgium	Brussels	50.90	15000	0.7%	2.0%	3.4%	5.0%
UK	London	51.51	14100	0.7%	2.1%	3.5%	5.3%
Poland	Warsaw	52.17	14700	0.7%	2.0%	3.4%	5.1%
Netherlands	Amsterdam	52.30	14400	0.7%	2.1%	3.5%	5.2%
Germany	Berlin	52.47	13900	0.7%	2.2%	3.6%	5.4%
Ireland	Dublin	53.43	14900	0.7%	2.0%	3.4%	5.0%
Lithuania	Vilnius	54.88	15300	0.7%	2.0%	3.3%	4.9%
Denmark	Copenhagen	55.63	14200	0.7%	2.1%	3.5%	5.3%
Latvia	Riga	56.57	13600	0.7%	2.2%	3.7%	5.5%
Estonia	Tallinn	59.25	13600	0.7%	2.2%	3.7%	5.5%
Sweden	Stockholm	59.65	12100	0.8%	2.5%	4.1%	6.2%
Norway	Oslo	59.90	12400	0.8%	2.4%	4.0%	6.0%
Finland	Helsinki	60.32	13500	0.7%	2.2%	3.7%	5.6%
Iceland	Reykjavik	64.13	11500	0.9%	2.6%	4.3%	6.5%

Table 2-4: Values of D_T for daylight openings to exceed an illuminance level of 100, 300, 500 or 750 lx for a fraction if daylight hours $F_{time,\%}$ = 50% for 33 capitals of CEN national members (from EN 17037 *[52]*)

2.4.2 Thoughts on the new EN standard for daylight

This new assessment method provides an enhancement to the standard daylight factor approach. It kept the simplicity of daylight factor, and by introducing the median diffuse horizontal illuminance to the equation it found a smart and simple way of integrating some of the climate characteristics to the calculation. As Mardaljevic described [53], it offers "secure footing to assist the transition to full-flown climate-based daylighting metrics at some later date".

The criticism of this method is that although the standard uses the term "reference plane", all the benchmarks provided for the target illuminance/daylight factor were still based on the horizontal plane that is 0.85m above the floor (namely the working plane). There are no recommended light levels given for any other important surfaces or for the volume of the space. In the electrical lighting filed, the traditional "working plane" concept has long been abandoned by the standards. The European standard EN 12464-1: Lighting of workplaces [54] completely removed the term "working plane" in 2002 and moved its focus to task illuminance instead. Other measures were also introduced in the standard to ensure a good lighting environment, which include wall/ceiling illuminance, surround/background illuminance and cylindrical illuminance (which will be further discussed in Section 2.5.3).

2.5 Summary of existing daylight metrics

So far this chapter has reviewed a number of current popular daylight metrics, from the daylight factor, climate-based daylight metrics to the newly proposed median daylight illuminance. The key features of each metric and their pros and cons can be summarized as *Table 2- 5* below:

Daylight metrics		Illumination target	Sky model	Pros	Cons
Daylight factor	Point daylight factor	Reference point on the horizontal working plane	CIE Overcast Sky (mostly)	Simplicity	Does not reflect the local climate; based only on working plane
	Average daylight factor	Horizontal working plane	CIE Overcast Sky (mostly)	Simple and can be easily calculated by the ADF formula	Does not reflect the light distribution; ADF formula tends to overestimate
CBDM metrics		Horizontal working plane	Real climate weather data	Local climate considered	Requires extra work & resources to calculate
Median Daylight Illuminance		Horizontal working plane	Median External Diffuse Illuminance + Overcast sky distribution model	Simple but provides a metric that will work well in any location	More complex to calculate than daylight factor

Table 2- 5: Strength and weakness of daylight metrics

Note: it should be pointed out all of the above daylight metrics share a common problem that is they only focus on the horizontal working plane.

2.6 Metrics from the electrical lighting

Most of the current daylight metrics face a common problem of only concentrating upon light on the working plane. As the horizontal working plane starts losing its meaning in modern daylit environments, it will be beneficial to look at some spatial qualities of light. There have been quite a few spatial metrics proposed for electrical lighting, such as mean room surface exitance, cubic illuminance and cylindrical illuminance. This section will discuss the possibilities of implementing these metrics in daylighting designs.

2.6.1 Mean room surface exitance

Mean room surface exitance (MRSE) was firstly introduced by Cuttle in 2009 [7]. Exitance is the luminous flux emitted by a surface per unit area (*Figure 2-7*). It equals the illuminance of the surface (E) multiplied by the surface reflectance (R). Expressed in lumens per square meter, hence it has the unit lux.

$Exitance = E \cdot R$ Equation 18

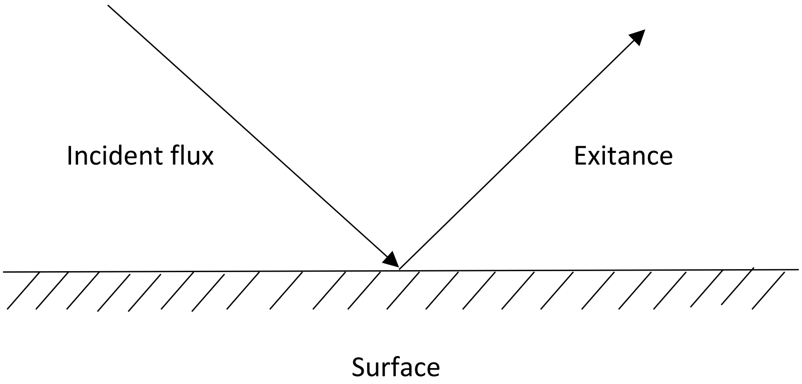


Figure 2-7: Surface exitance

Mean room surface exitance by its definition is the average exitance from all room surfaces, hence it is calculated by:

$MRSE = \frac{\sum E_S \cdot R_S \cdot A_S}{A_r}$ Equation 19

Where E_s is the illuminance of each room surface;

R_s is the reflectance of each room surface;

A_s is the area of each room surface;

A_r is the total area of room surfaces.

According to Sumpner's Law [16], it can be assumed that the total light flux in a room is evenly absorbed by all room surface, hence:

$\Phi = E_{AV} \cdot A_r \cdot \alpha \quad \rightarrow \quad E_{AV} = \frac{\Phi}{A_r \alpha} = \frac{\Phi}{A_r(1-R)}$ Equation 20

Where ϕ is the total amount light flux in the room;

E_{AV} is the average illuminance of room surfaces;

R is the average reflectance of room surface;

α is the room absorptance, α=1–R.

Therefore, MRSE can also be calculated by:

$MRSE = E_{AV} \cdot R = \frac{\Phi R}{A_r(1-R)}$ Equation 21

The term “MRSE” may be new, however its concept is not new to daylight at all. Comparing Equation 7 and Equation 20, it can be found that MRSE is essentially what we have been calculating for the inter-reflected component of daylight illumination. And in the early days of addressing daylight visual comfort, average field luminance was used to calculate glare index which numerically just equals MRSE divided by π [15].

MRSE is also arguably the metric that best correlated with the perceived adequacy of illumination (PAI) [7] [8]. PAI is the degree to which a space that is likely to be judged sufficiently bright or adequate for the activities carried out in the space. Cuttle proposed to use MRSE as an indicator of PAI and it has been tested in a number of experiments carried out by Duff and Kelly [55] [56] [57] [58].

Duff’s tests include a lighting booth experiment where 26 participants rated on the PAI (Yes/No – whether the lighting is adequate) and the perceived spatial brightness (7 scales from “very dim” to “very bright”) of the entire booth under 27 different lighting scenes (different combinations of 3 surface reflectance settings, 3 means of lighting distribution and 3 MRSE levels), and two office setup experiments with the lighting being both uniformly and non-uniformly distributed (also 26 participants answered the same questions under 27 lighting scenes that were similarly arranged as in the lighting booth experiment). The studies concluded that MRSE had a very strong correlation with subjects’ perception of the spatial brightness throughout each experiment, whereas the horizontal illuminance did not have the same impact on the assessments of the spatial brightness. As for PAI, it was found that when the light distribution of lighting scenes was broadly uniform the level of MRSE had a significant impact on the reported PAI, however when under extreme non-uniform light distribution there was no significant change in reported PAI regardless of the increase in MRSE.

The limitation of Duff et al’s work is that the impact of MRSE values above 100 lx were not explored and thus the top end of the “very dim” to “very bright” scale was not explored (this will be further discussed in Section 6.2.2).

Whilst the exact nature of the relationship between MRSE and PAI still needs to be further researched, it is logical to believe that they should be related as MRSE in a given space will be correlated with the indirect light received at any point within the volume of this space and hence also linked with the indirect illuminance received by a person's eyes. Also, the use of MRSE is not totally at odds with existing standards, as the lighting standard EN12464-1 [54] already started to recommend illuminances on major room surfaces coupled with guidance of surface finishes which effectively forces a minimum MRSE. Moreover, the current draft of the next version of EN 12464-1 due for publication in 2020 references the work of Cuttle in an annex.

2.6.2 Cubic illuminance

Cubic illuminance is a concept also proposed by Cuttle [59] and by his definition:

> *"Cubic illumination is the specification of the directional distribution of incident luminous flux at a point in space in terms of pairs of opposed planar illuminances normal to three mutually perpendicular axes intersecting at the point."*

To put it in simple terms, cubic illuminance moves away from the illumination at a point on a surface to the distribution of illumination at a point in space. It considers the reference point as a tiny cube and measures the illuminance values on six faces of the cube (*Figure 2-8*).

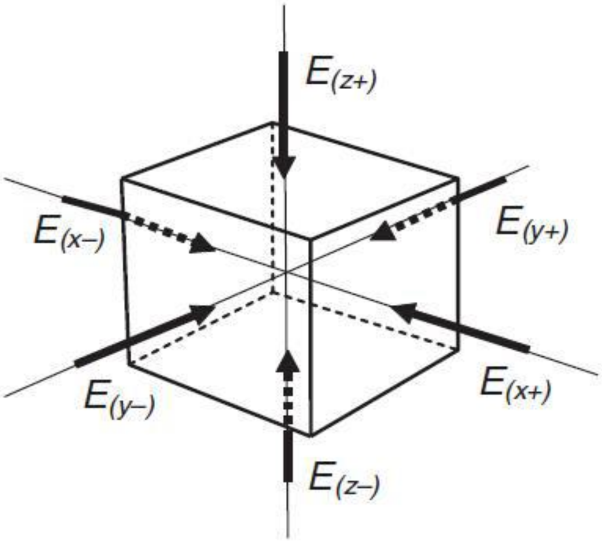


Figure 2-8: Cubic illuminance *[59]*

Because it contains so much information, cubic illuminance is harder to measure or calculate than planer illuminance. Cuttle suggested using direct illuminance and MRSE to approximately work out the cubic illuminance in a room [59]. His approach simply assumes illuminance values on all six faces of the cube ($E_{(i)}$) equal the direct illuminance ($E_{tgt(d)(i)}$) plus MRSE.

$$E_{(i)} = E_{tgt(d)(i)} + MRSE \qquad \text{Equation 22}$$

Where (i) represents and includes all six faces of the cube (X+, X-, Y+, Y-, Z+, Z-).

Cubic illuminance works very well with the light field theory [60] [61]and can be used to derive illumination vectors.

The total illumination vector ($'E$) of a reference point equals:

$$'E = \left('E_{(X)}, 'E_{(Y)}, 'E_{(Z)}\right) \qquad \text{Equation 23}$$

Where $'E_{(X)} = E_{(X+)} - E_{(X-)}$

$'E_{(Y)} = E_{(Y+)} - E_{(Y-)}$

$'E_{(Z)} = E_{(Z+)} - E_{(Z-)}$

The symmetrical vector ($\sim E$) equals:

$$\sim E = \left(\sim E_{(X)}, \sim E_{(Y)}, \sim E_{(Z)}\right) \qquad \text{Equation 24}$$

Where $\sim E_{(X)} = \mathrm{Min}(\ \sim E_{(+X)}, \sim E_{(-X)})$

$\sim E_{(Y)} = \mathrm{Min}(\ \sim E_{(+Y)}, \sim E_{(-Y)})$

$\sim E_{(Z)} = \mathrm{Min}(\ \sim E_{(+Z)}, \sim E_{(-Z)})$

And the magnitude of total illumination vector ($|E|$) equals:

$$|E| = \sqrt[2]{'E_{(X)}{}^2 + 'E_{(Y)}{}^2 + 'E_{(Z)}{}^2} \qquad \text{Equation 25}$$

Cubic illuminance was proposed as a basis to investigate the spatial distribution of illumination. Drawing the illumination vectors (examples see *Figure 2-9*) can reveal the indoor “light flow” and possibly predict the shadowing pattern (the arrow indicates the direction of the total illuminance vector at each reference point, and the size of the sphere indicates the magnitude of the total illuminance vector). This can be quite useful for buildings like sculpture galleries or daylit churches.

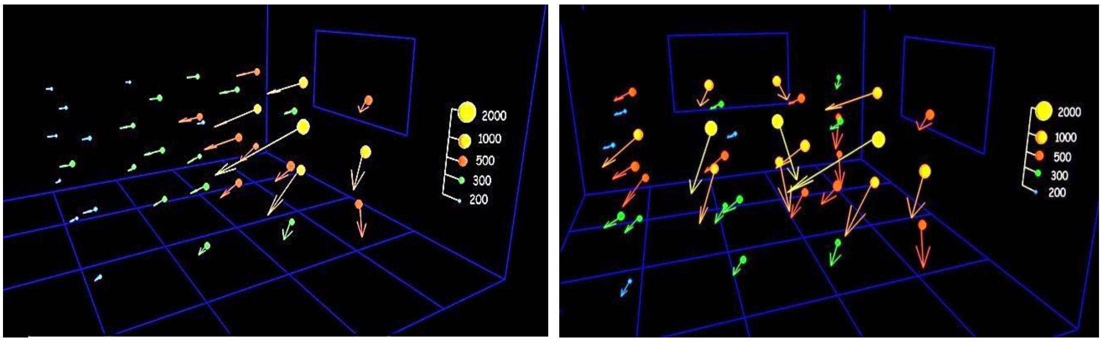


Figure 2-9: Indoor daylight flow: based on a box shaped room with one (left) or two (right) window openings under the CIE overcast sky

In addition, cubic illuminance can also be used to derive other useful metrics, such as Cylindrical Illuminance, Planar Illuminance, Scalar Illuminance and Hemispherical Illuminance. In summary, cubic illuminance can be a powerful tool for more advanced daylighting designs.

2.6.3 Cylindrical illuminance

Cylindrical illuminance is one of the new metrics that has been included in electrical lighting standards [54]. It is the illuminance on the curved surface of a small cylinder centred at the reference point (*Figure 2-10*).

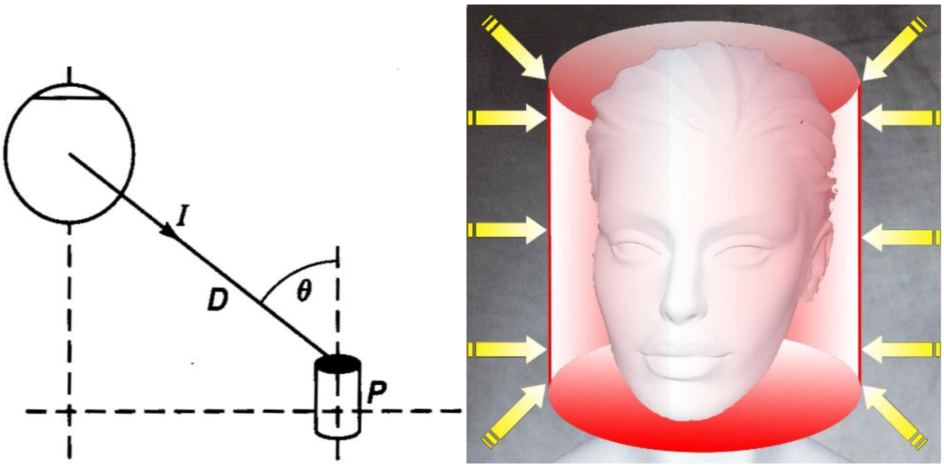


Figure 2-10: Cylindrical illuminance *[62]*

Cylindrical illuminance (E_{cyl}) is calculated by:

$$E_{cyl} = \frac{I \cdot sin\theta}{D^2 \pi} \qquad \text{Equation 26}$$

Where I is the luminous intensity from the source;

θ and D are respectively the incident angle and the distance (*Figure 2-10*)

Also $\mathrm{E}_{\mathrm{cyl}}$ can be derived from cubic illuminance:

$$E_{cyl} = \frac{|E|e.e_{(x,y)}}{\pi} + \frac{(\ \sim E_{(X)} + \ \sim E_{(Y)})}{2} \qquad \text{Equation 27}$$

In considering the human’s face as a cylinder, high cylindrical illuminance may help ensure good visual communication. Dividing cylindrical illuminance by the horizontal illuminance ($\mathrm{E}_{(\mathrm{Z}+)}$) equals the facial modelling index. Cylindrical illuminance is often evaluated at 1.2 m above the floor for seated people and 1.6 m above the floor when people are standing [54].

2.6.7 Summary of the spatial metrics

Strengths and weaknesses of the discussed spatial lighting metrics were summarized in *Table 2- 6*.

Metrics	Target illumination	Pros	Cons
MRSE	Surface exitance of major room surfaces	Single number correlated with PAI	With limited studies and need to be further tested
Cubic illuminance	Light in the volume of space	Contains extensive amount of information about the light in the space	Complexity; hard to measure/calculate
Cylindrical illuminance	Curved cylinder surface (people's head) at the sitting/standing heights	Useful for lighting designs of visual communication	Focus only on a curved surface (people's head)

Table 2- 6: Strength and weakness of the discussed spatial lighting metrics

2.7 Chapter summary

This chapter reviewed the current popular daylight metrics. The literature review started with the dominate daylight metric – daylight factor and introduced its history and discussed different calculation methods for it. After addressing the main criticism of daylight factor, which is the lack of real weather information, the discussion moved on to CBDM and its fundamental concepts. A number of CBDM metrics including DA, UDI and ASE were discussed and the criticisms of CBDM in general (mainly the added complexity) were outlined. The newest proposed median daylight illuminance was then introduced as an improvement over the standard daylight factor approach by adding some "connectivity" to the local climate data. The development of daylight metrics has come a long way in terms of improving the sky model and calculating the light levels on the horizontal working plane, however working plane is no longer the sole focus within a daylit environment yet all of the current popular daylight metrics are only based upon it.

The literature review then switched to the electrical lighting searching for established spatial lighting metrics that have the potential to be implemented in daylighting. Three of spatial metrics were outlined and discussed including MRSE, cubic illuminance and cylindrical illuminance. MRSE in particular was believed to have the potential to be a good daylight metric.

In this research, the following reviewed metrics (or its concepts) will be studied:

- Daylight factor, including point and average daylight factor calculated based on median external diffuse illuminance.
  The metric was studied in correlations with building user responses and compared with the new/alternative daylight metric. (Refer to Chapter 3, Chapter 6, Chapter 7).

- Daylight Autonomy[2], including point and special daylight autonomy.
  The metric was studied in correlations with building user responses and compared with the new/alternative daylight metric. (Refer to Chapter 6)

- MRSE
  MRSE was studies in real building and based on its concept a new metric, Mean Indirect Cubic Illuminance (MICI), was developed (refer to Chapter 3). The past studies of MRSE was also compared with findings of this study. (refer to Chapter 9).

- Cubic illuminance
  The concepts of cubic illuminance were used to develop the new metric MICI (refer to Chapter 3).

---

[2] The reason why Daylight Autonomy was selected among other CBDM metrics is given in Section 6.2.2

Chapter three: Evolution of MRSE into MICI

3.1 Chapter Introduction

The previous chapter reviewed the current daylight metrics, it was found that most of the current metrics only focus on the working plane. A few spatial lighting metrics from electrical lighting were discussed, and MRSE was believed to have the potential to be a good daylight metric.

Initially it was hoped that MRSE could be developed for use as a daylight metric. However, flaws of MRSE were quickly revealed through the preliminary study in real buildings. Hence A new metric - Mean Indirect Cubic Illuminance (MICI) was created based on the existing concepts of MRSE and cubic illuminance. This chapter explains how concepts of MICI were developed, introduces the calculation methods of MICI and studies the relationship between MICI and MRSE.

3.2 Criticism of MRSE

Whilst the concept of MRSE may appear promising, it also received criticism when it was introduced to the lighting community. Critics were concerned that without detailed information at the design stage MRSE may be hard to implement [63]. This is because lighting designers rarely have the luxury of designing with complete information such as surface finish, colour and texture, and without enough flexibility to cope with the potential changes as the building is going up Cuttle's method is not practical.

Boyce commented that he thinks MRSE is a "crude measure" of brightness perception. He agrees with Cuttle that visual performance has become much easier to overcome, however whether or not the perceived spatial brightness should be the primary focus of lighting design is questionable [63]. Raynham's criticism is that although the surface exitance is important to human perception of lightness, it cannot yet be treated as a "be-all and end-all" lighting design metric because MRSE carries no information about the light distribution and objects' appearance within the space [63]. Later on, Cuttle proposed Target/Ambient Illumination Ratio[3] (TAIR) as a supplementary tool to

---

[3] Cuttle proposed using MRSE to calculate TAIR, $\mathrm{TAIR} = \frac{\mathrm{E_{tgt}}}{\mathrm{MRSE}}$, where E_{tgt} is the illuminance of the target surface.

describe the light pattern or as Cuttle calls it, the Illuminance Hierarchy [8]. The MRSE/TAIR combination received positive responses from the lighting community. Mansfield commented [64] that he always felt Waldram's Studies in Interior Lighting paper provided a useful conceptual framework when considering the lighting of a space, and Cuttle's suggestion of using MRSE as an exploratory tool to define the adequacy of illumination is a good concept. He thought that unlike using the Brightness-Luminance relationship to define the apparent brightness of space, the MRSE approach avoids the "embarrassment of needing to define the adaptation level". Boyce has also become more convinced in this exitance based approach. In his paper Lighting Quality for All [65], Boyce discussed how good quality lighting might be made available to all and suggested four approaches that he thinks can bridging the gap between "indifferent" and "good" lighting. One of the approaches is to develop a new procedure for designing lighting, where he promoted Cuttle's MRSE/TAIR design method and encouraged the development of a suitable software.

Another approach for improving lighting quality mentioned by Boyce [65] was the increased use of daylight, as people love daylight and trend to consider spaces with extensive use of daylight attractive. Boyce also pointed out daylight, like any other light source, needs to be controlled so that visual and thermal discomfort can be avoided. The key of daylighting design is to create a bright and interesting visual environment, however Boyce did not elaborate on the design method of quantifying daylight. Perhaps one way of characterising daylight adequacy would also be the use of MRSE.

3.3 MRSE as a daylight metric?

Currently, most research about the MRSE were conducted under electric lighting and the possibility of implementing the MRSE concept in daylighting has not yet been investigated, although Cuttle did comment [7]:

> *"It has been convenient to examine the concept for electric lighting installations, the MRSE concept should be equally valid for daylight, and this opens up another long standing field of misapplied science."*

MRSE as a daylight metric has indeed quite a few nice properties. Firstly, it is a single number and is very easy to calculate to a first approximation using Sumpner's principle (Equation 20). All the components needed to calculate MRSE are just external illuminance on the window plane, window size/transmittance (for Φ) and room surface area (A_r)/reflectance (R). Meanwhile MRSE can also be accurately calculated by averaging exitance of all room surface (Equation 18). It can be a part of CBDM process, and perhaps a Median MRSE or Useful MRSE (similar to the UDI concept) could prove to be a useful parameter. Besides MRSE in daylight will have an additional meaning that MRSE essentially describes the general internal reflection of daylight. With self-luminous displays everywhere, the internal reflected light is arguably the more “useful” part of daylight in modern lighting scenarios (as it is less likely to cause noticeable screen glares or affect the visibility of computer screens).

In addition, MRSE may have the connection with biological effects of light. Given that intrinsically photosensitive retinal ganglion cells (ipRGCs) are distributed across the retina [3], a good candidate for driving the response is likely to be illuminance in the plane of the pupil. Moreover, as aversion of gaze is the natural reaction to a direct view of a light source, it is quite likely that the best metric to describe any possible response is indirect pupil plane illuminance. This then would suggest that MRSE might be a good way of describing the potential of a daylighting design to impact on people’s endocrine systems.

Whilst there are good reasons to believe that MRSE may be an improvement over the daylight metrics currently used, research and experiments need to be carried out in order to determine the true nature between MRSE and the building daylight adequacy. Any potential merit of adopting this new metric over current daylight metrics must be examined, evaluated and critically analysed.

The researcher believes that the most straightforward method to examine the effectiveness of any lighting metric is by the tests in real buildings. Hence case studies on real-life commercial buildings were conducted where the feasibility of MRSE as a daylight metric was investigated.

3.4 Complications in modern architectural environment

Major problems were found in the case studies when testing MRSE in real buildings. In the past when MRSE concepts were used, either when they were introduced by Cuttle [7] [8] or tested by Duff [55] [57] [56], it was always based on a very standard "box-like" room geometry. However, in real life buildings are rarely this simple. Modern office buildings tend to be structurally more complicated, and the open-plan office layout has become very popular worldwide. It was found out that the whole MRSE approach started to break down when the building geometry becomes open-plan and complicated.

Figure 3-1 shows an open office area, and it was an interior section of one studied case building. The building (refer to Section 4.2.1 for more detailed building information) was designed with numerous rooflights and atriums to maximise daylight accessibility. There were also some voids on the first floor forming "bridge-alike" areas as shown in the photo below.

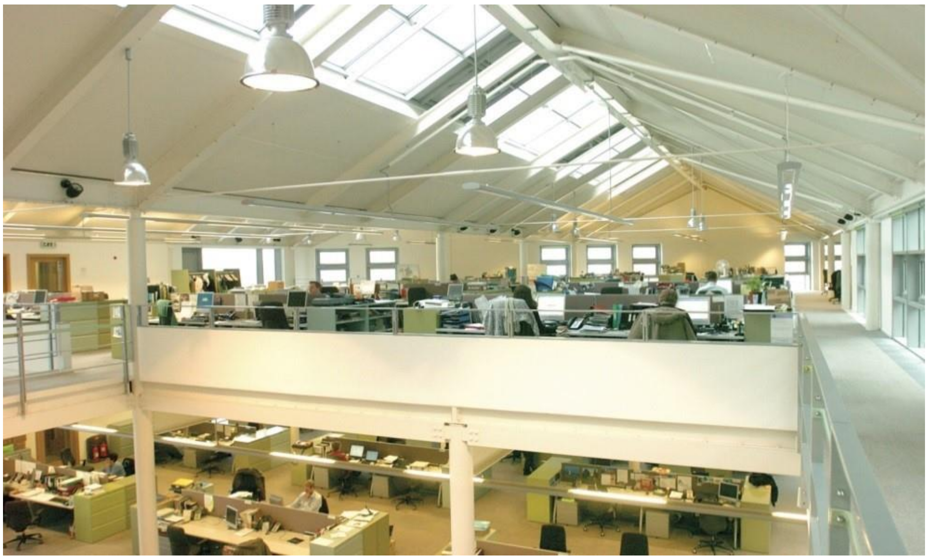


Figure 3-1: An open-plan office section in a case building

It was found to be impractical using MRSE to evaluate the daylighting of this bridge area. MRSE relies on room surfaces to calculate the exitant flux, however if looking at this area, not many "room surfaces" are present. Whilst the exitance from the floor, the balustrade/half wall and the roof surfaces can be calculated (marked as yellow in *Figure 3-2*), the reflected lights from the wall in the far back corner cannot. Also, it is practically impossible to calculate the flux "escape" to the ground floor due to the huge void opening on the 1st floor.

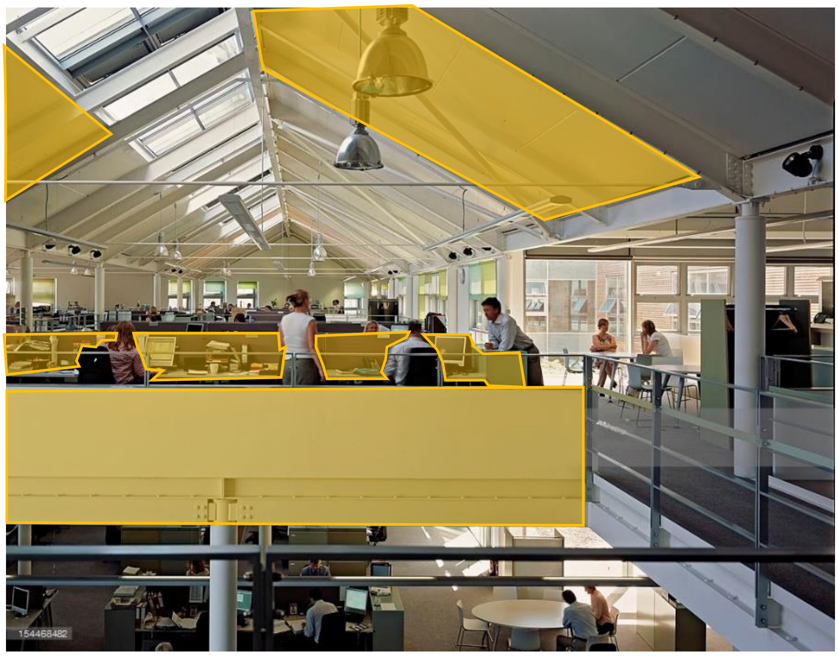


Figure 3-2: Major room surfaces (as highlighted in yellow) in the bridge area

MRSE often uses Sumpner's law [16], that is in any closed space the total amount of light being emitted must equal to the total amount of light been absorbed, and in the context of daylighting the amount of flux entering through the windows must equal to the amount been absorbed by the room surfaces. This allows MRSE to be easily calculated to a first approximation in both artificially lit or daylit environments. However, it also gives a limitation the MRSE approach that is the MRSE-evaluated area needs to be an enclosed space, and within the space MRSE cannot be subdivided to different sections.

Another simple example to demonstrate that MRSE could not work with complex room geometry is a "L" shaped room, and this was explained by Raynham et al [66]. Imagine a "L" shaped room and there is an observer standing at point P (as marked in *Figure 3-3* below).

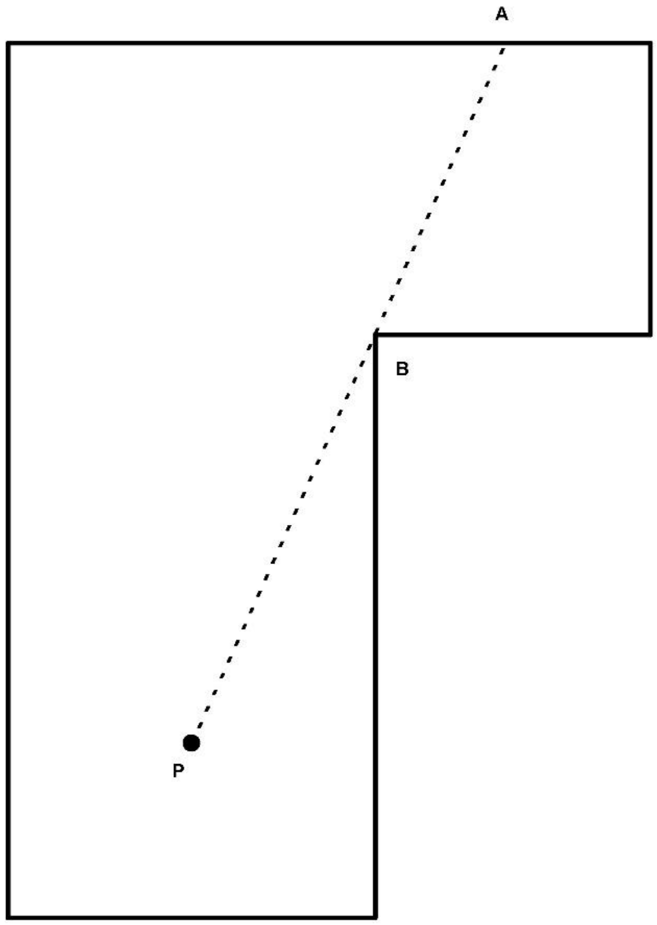


Figure 3-3: A L-shaped room with an observer standing at point P *[66]*

In this room an observer at point P cannot see the room surfaces between points A and B. Thus the surface exitance of the surfaces in this region will have no direct influence on the observer's perception of adequacy of illumination.

Additionally, MRSE evolved from studies where subjects were able to move through a room and assess the overall adequacy of the illumination, however for a person who works at a fixed position in a room may not be judging the overall effect of the illumination so much as the illumination at their work place. Consider a deep plan office that is daylit from windows in one wall. With the absence of artificial lighting, it is likely that the illuminance on the walls away from the windows will be less than one tenth of those close to the windows. Moreover, as any big furniture (such as bookshelves) in the room is likely to break up (at least to some extend) the space and hence disrupt any lightness constancy, it is possible to argue like Jay [67] that lightness constancy will not govern the perception of the space as a unified room and people close to the window may judge the space adequately lit and those at the back of the room may not.

The above problems of MRSE are, unfortunately, not uncommon in a modern daylit architecture. Therefore, it would be useful to have a new metric that could be more universally applied and at the same time had a similar relationship with the perceive adequacy of illuminance. MRSE is described by Duff et al [57] as "the measure of overall density of reflected (excluding direct) luminous flux within a space". It is thus possible to consider a metric that describes the density of inter reflected light at a point within the space, and by assessing the metric at a number of locations within the space derive a metric that describes the overall density of reflected lighting in the whole room or area.

3.5 Mean Indirect Cubic Illuminance

A good starting point for this is cubic illuminance. As introduced in Section 2.5.2 cubic illuminance specifies the spatial distribution of illumination by measuring the illuminances on six faces of a small cube centred at the reference point. In Cuttle's paper of cubic illumination [13], he also suggested a procedure for calculating cubic illuminance where illumination on each of the six faces ($E_{(i)}$) was divided into the direct illuminance contribution (E_{Direct}) and the indirect illuminance contribution ($E_{Indirect}$) (*Figure 3-4*).

$$E_{(i)} = E_{Direct(i)} + E_{Indirect(i)} \qquad \text{Equation 28}$$

Where i represents and includes all six faces of the cube (X+, X-, Y+, Y-, Z+, Z-).

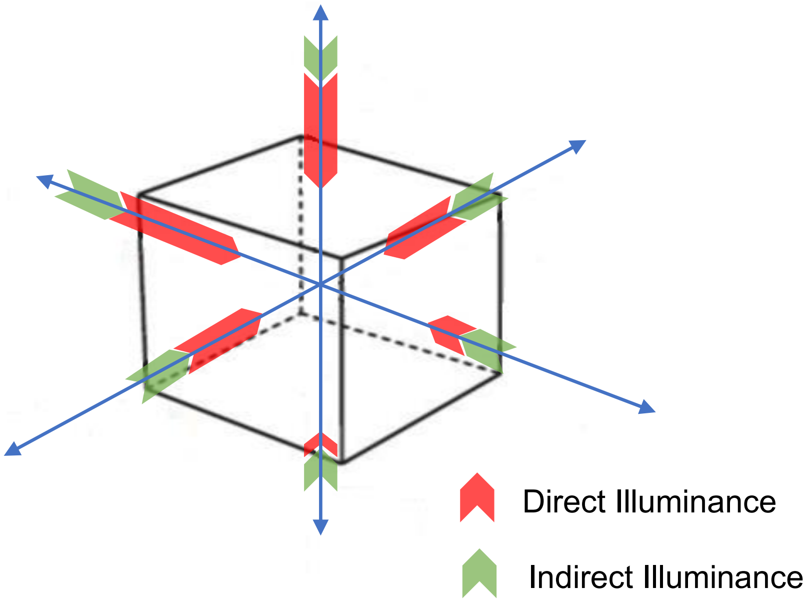


Figure 3-4: the direct and indirect illuminance components of cubic illuminance

For the direct illuminance component, it can be simply calculated using vector algebra (for the angle of incidence) and the inverse square cosine law[4]. As for the indirect illuminance, Cuttle suggested to MRSE as the approximate ambient indirect illuminance. Hence the equation for cubic illuminance (Equation 27) becomes:

$$E_{(i)} = E_{Direct(i)} + MRSE \qquad \text{Equation 29}$$

Now with the popularisation of computer simulation, the precise evaluation of the distribution of the inter-reflected flux within a space (namely the indirect illuminance component of the cubic illuminance) can be easily calculated (the calculation method is discussed in Section 3.5). Therefore, the use of Mean Indirect Cubic Illuminance (MICI) was proposed as a replacement of MRSE. This metric is the average of the six indirect illuminances received on the faces of a cube (*Figure 3-5*).

---

[4] The point to point formula: $\mathrm{E} = \frac{\mathrm{I}}{\mathrm{d}^2}\cos\theta$, where E is the illuminance of the reference point on a plane perpendicular to the light source; I is the luminous intensity of the light source; d is the distance between the reference point and light source; θ is the angle of incidence.

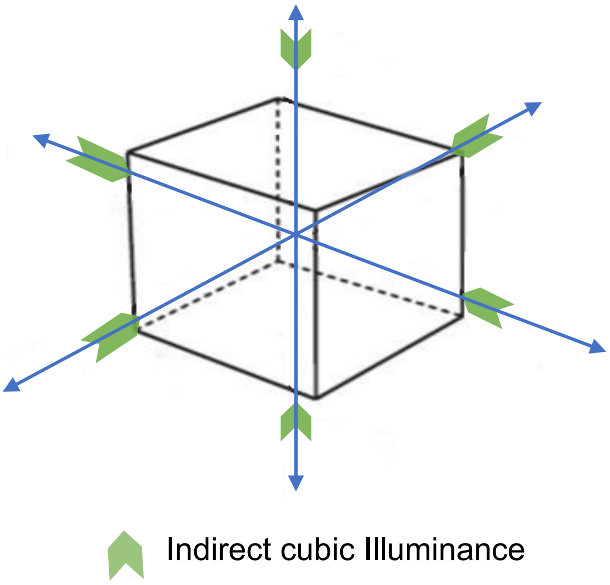


Figure 3-5: Mean indirect cubic illuminance

Unlike MRSE which emphasises room surfaces, MICI can be calculated for any given point in the volumn of space. Back to the example of the open-plan office (*Figure 3-1*), if multiple calculation points are assigned in this area, the MICI level at each point can be measured (Figure 3-6) and from this, an average value of MICI can be calculated to describe the overall inter-reflection whithin the office area.

Figure 3-6: calculating the average MICI of the space

3.6 The calculation method of MICI

The technique for calculating the indirect illuminance ($E_{Indirect(i)}$) using computer simulation is simply by running the calculation twice:

- The first run is with normal settings and the results are the total illuminance values ($E_{(i)}$).
- The second run is with the same settings except the reflectance of all indoor surfaces is set to be 0. The results of the second simulation will give the direct illuminance values ($E_{Direct(i)}$)

Hence the indirect illuminance equals:

$$E_{Indirect(i)} = E_{(i)} - E_{Direct(i)} \qquad \text{Equation 30}$$

Where i represents all six faces of cubic illuminance (+X, -X, +Y, -Y, +Z and -Z).

After the indirect illuminance values on all six faces of cubic illuminance were calculated, MICI can then be calculated by:

$$MICI = \bar{E}_{\mathrm{Indirect(i)}} \qquad \text{Equation 31}$$

Above calculation of MICI can be conducted in most lighting software (either with Radiosity or Ray-tracing). Post-processing of the calculated data may be needed to derive MICI from the raw illuminance results (using Equation 29 and Equation 30), and this can be done very simply in a spreadsheet.

3.7 The relationship between MRSE and MICI[5]

In the case when all the room surfaces have the same exitance it is possible to demonstrate that MICI at all points in the volume of the space will be the same as the MRSE of the room. It can be shown[6] that under a uniform luminance field the illuminance at point will be equal to π times the luminance. Given that the exitance of a Lambertian diffuser is also π times the luminance then MICI and MRSE will always be equal.

---

[5] Much of this section has been previously published in the article “A New Metric to Predict Perceived Adequacy of Illumination” [66].

[6] For example, see Section 3.2.1 of Daylighting by Hopkinson, Petherbridge & Longmore, Hinemann, 1969 [15].

The situation in real rooms is more complex and it is not possible to demonstrate the mathematical relationship between MICI and MRSE in a general mathematical sense. However, the authors hypothesised that the average MICI of all points in the volume of the space should be same as MRSE and to test this they calculated and compared the MRSE and MICI in a wide range of rooms for which MRSE is a valid measure

To test the relationship between MRSE and MICI, 10,000 separate rooms were considered. The length, width and height of the rooms were all set separately to random values in the range set out in *Table 3-1*. The values were based on room dimensions that are likely to be found in practice. All of the room surfaces were individually assigned a random luminance in the range 0 to 80 cd/m^2, this corresponds to exitances of up to just over 251 lumens per square metre. The luminance of each of the surface was uniform.

Room Dimension	Minimum Value [m]	Maximum Value [m]
Length	4	20
Width	2.5	16
Height	2.2	6

Table 3-1: Range of room dimensions

In each room a number of calculation points was selected such that the distance between any two points in any direction was less than 1m. The MRSE in each room was calculated from the areas of the 6 surfaces and the luminance of each of the surfaces and the result multiplied by π to convert the luminance into exitance. The indirect illuminance at each calculation point was calculated on each of the 6 faces of a nominal cube was calculated by subdividing the room surfaces into small patches with their maximum dimension less than one tenth of the distance of the calculation point to the surface. The areas were then treated as point sources with their intensity being calculated from the projected area of the surface toward the calculation point and the surface luminance. The six illuminance values were then averaged to create the mean indirect cubic illuminance for the point and then all of point values were averaged to create an average value for the whole room. Above calculations were conducted using a spreadsheet with EXCEL Visual Basic Tools.

The calculated values of MRSE and average MICI for each of the 10,000 rooms are plotted in *Figure 3-7*. This shows that MRSE is closely correlated with MICI with a R^2 value greater than 0.999.

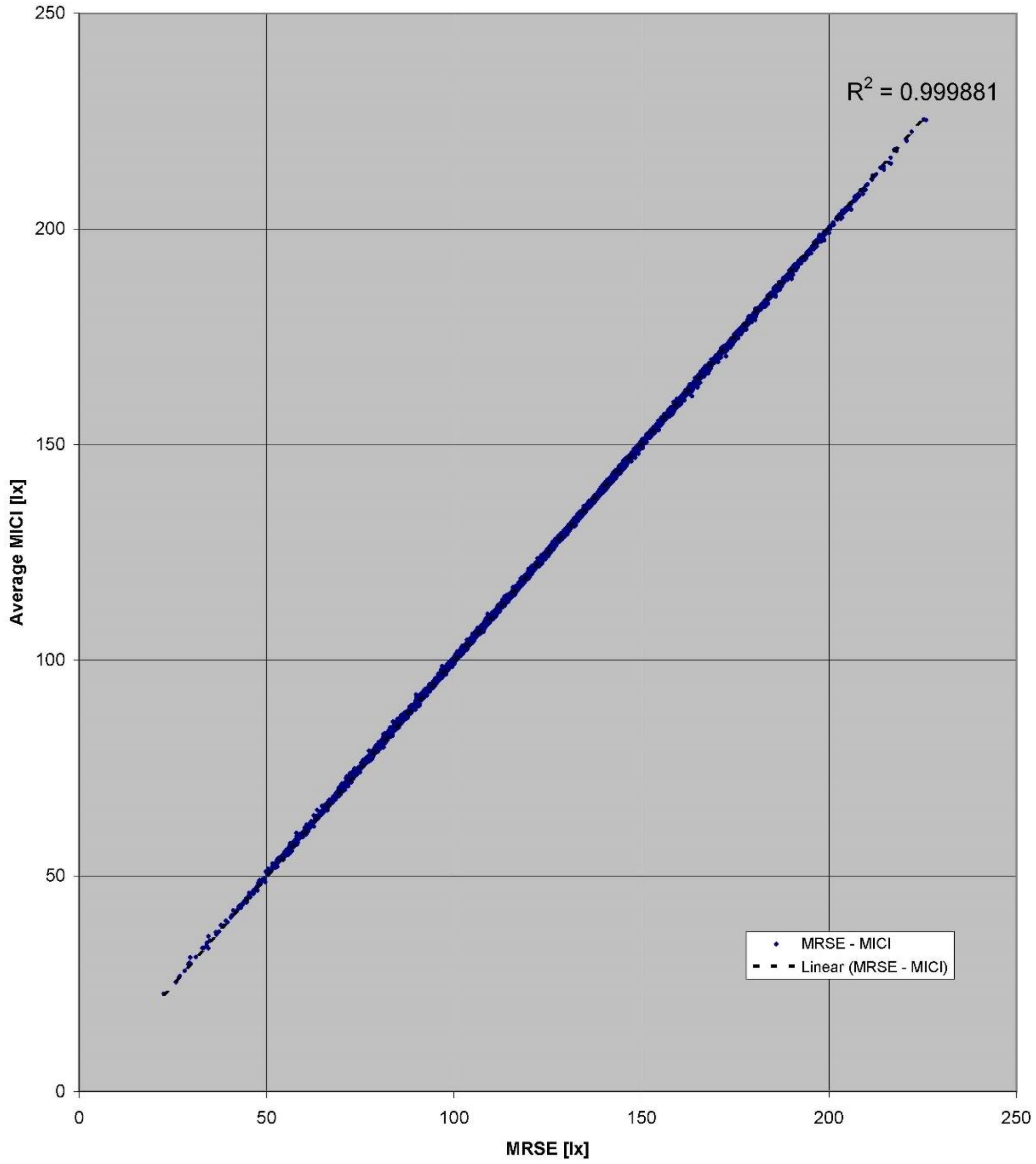


Figure 3-7: A plot of MRSE against MICI

The ratio of MRSE to MICI was calculated for each room and the average of all of the values was 0.999 indicating that MICI on average is very close to MRSE. The number of values in narrow ranges (±0.005) about a centre value were plotted (see *Figure 3-8*) and it is clear that distribution of results may be considered to be Gaussian.

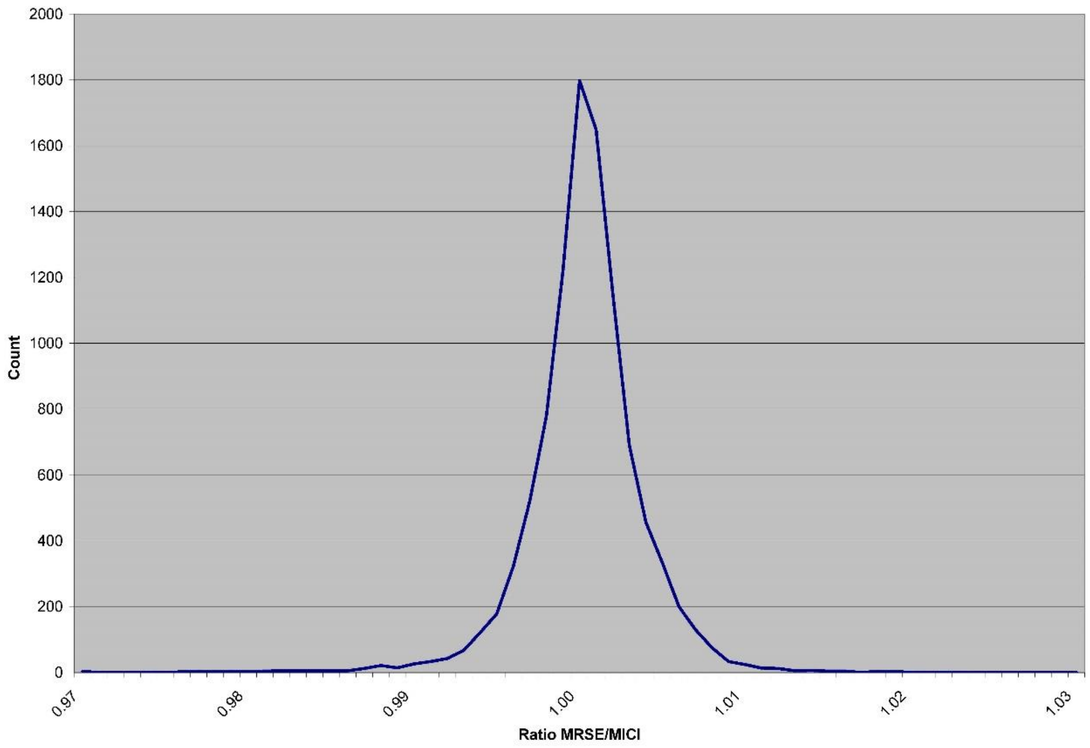


Figure 3-8: Distribution of values of MRSE/MICI

Given that the distribution is normal it was possible to calculate the standard deviation of the results and it was found to be 0.0035. Given that the average ratio of MRSE to MICI is close to 1 then using the language of CIE 198 [68] it would be possible to describe the MICI calculation predicting MRSE with an uncertainty of 0.35%.

Conceptually MRSE and MICI are different. MRSE describes the average inter-reflected flux density within a room and is independent of location within the room and view direction. MICI describes the inter-reflected flux density at a point in the room and thus is a function of position within the room but is independent of view direction. For a range of rooms, it has shown that the average value of MICI is the same as MRSE, however, MICI has the advantage that it can be computed in complex rooms, where not all of the room surfaces can be seen from all points in the room. Moreover, MICI may also be useful in a room where the lighting is very non-uniform (for example a daylit space).

Consider a room that is 10 m long and 5 m wide and 2.4 m high. In one of the short walls there is a 4m by 1m window with a transmittance of 0.7. The bottom of the window is 0.8m above the floor, the ceiling has a reflectance of 0.7 the walls 0.5 and the floor 0.2. Calculations were made for the room under an overcast sky that created an external illuminance of 14,100 lux. This value was chosen as it is the median external illuminance for London (see Section 2.4.1). From the calculated illuminance for each of the room surfaces it was found that the room had a MRSE value 80.7 lx. The results of the calculation of MICI at a height of 1.2 m above the floor are shown in *Figure 3-9*. Whilst the average of all values at 1.2 m above the floor is 77.5 lx the figure shows that there is a significant variation across the room. Whilst about one third of the room close to the window has MICI values in excess of 100 lx, the region of the room close to the rear wall has MICI values that are below 40 lx. This wide difference in MICI is likely to result in the rear part of the room being regarded as being too dark whilst the side of the room close to the window has adequate illumination.

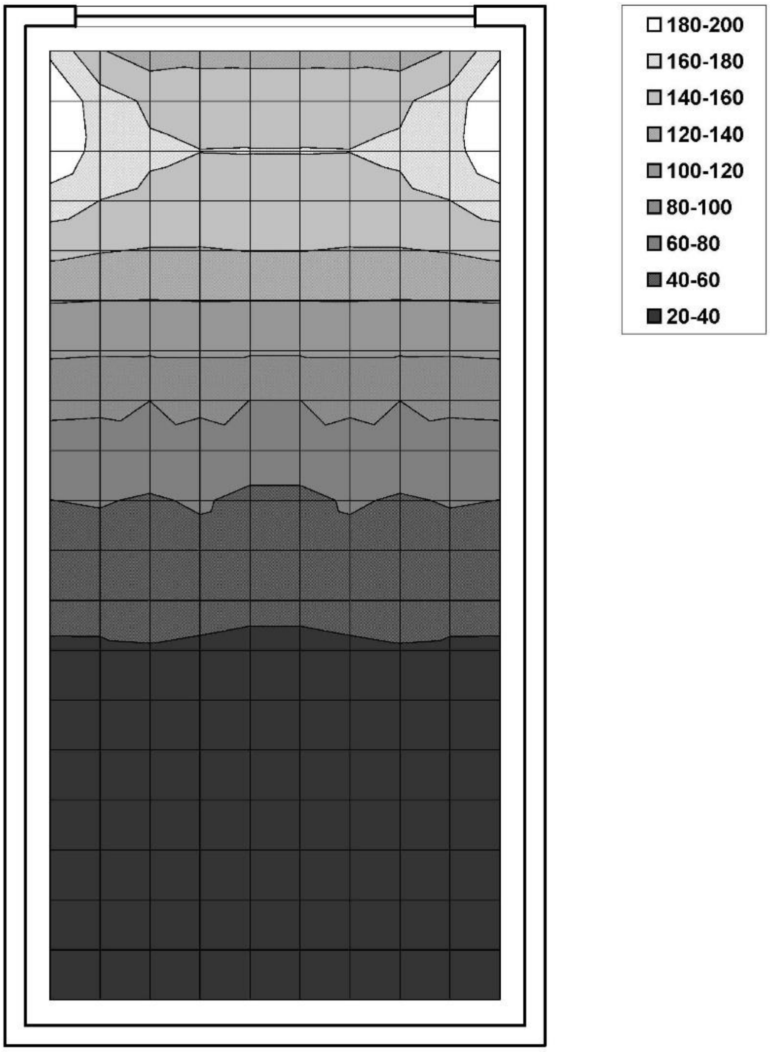


Figure 3-9: Plot of MICI in a daylit room with non-uniform lighting

This finding is no surprise and there is a test in BS 8206-2 for rooms that are lit by windows in only one wall to determine if the lighting is uniform. The test is given by the following formula:

$$\frac{L}{W}+\frac{L}{H} \leq \frac{2}{1-R_b} \qquad \text{Equation 32}$$

Where L is the depth of the room (m);

W is the width of the room (m);

H is the height of the room (m);

R_b is the area weighted average reflectance of the room surfaces.

The room clearly fails this test and its length would need to be reduced to 6.15m for it to pass the test. In this room the MRSE value of 80.7 lx would indicate that the room is likely to be regarded as being slightly under lit (will be further discussed in Section 6.2.2). However, would people working at different places in the room characterise their perception of the adequacy of illumination the same, or would people at the back of the space consider the room darker than those close to the window?

In summary, it has been shown that in a variety of regular rooms the average value of mean indirect cubic illuminance is very nearly equal to the mean room surface exitance. Thus it can be assumed that the perceived adequacy of illumination can also be predicted from MICI. The limitation of the study is that so far the connection between MRSE and PAI has only been established in uniformly lit spaces.

3.8 Chapter summary

This chapter investigated the possibly of implementing MRSE in daylighting, however the flaws of MRSE were soon revealed in the preliminary study of real buildings. The surface exitance concepts break down when the building geometry becomes complex. This was demonstrated in the examples of an open space office building and a L-shaped room.

A new metric, MICI, was then developed based on MRSE and cubic illuminance concepts. MICI has the ability to be calculated at any given point within the volume of space. A study was conducted to investigate the relationship between MICI and MRSE where the two metrics were calculated in 10,000 randomly generated six-plane rooms and the results were compared. It was found that the room average MICI is almost the same as MRSE for the room and therefore it is reasonable to believe that MICI, like MRSE, can also be used to predict the perceived adequacy of illumination.

MICI and MRSE were also tested in a simple daylit room (a six-plane room with a side window). Given the uneven distribution of daylighting, MICI is possibly an improvement over MRSE as a potential daylight metric as it is able to describe the varying conditions across the room.

It was also concluded that more studies are necessary to investigate the relationship between MICI and perceived adequacy of illumination in daylit spaces. Therefore, the focus of this PhD study was changed from MRSE to MICI. The aim of the rest of this study will be to investigate if there is any connection between MICI and PAI in daylit spaces, and if the correlation of perceived daylight adequacy is stronger than for existing daylight metrics.

Chapter four: Research objectives

4.1 Research overview

The aim of this study is to find out if the new metric MICI correlates to people's perception of daylight adequacy better than existing daylight metrics currently used in lighting design.

The research objective is:

> Compare the performance of various daylight metrics, including daylight factor, CBDM metrics, and MICI and assess which metric best correlates with the perception of daylight adequacy

Some potential benefits of this study are:

- To establish the most effective daylight metric for assessing daylight adequacy.
- To contribute to the knowledge of daylight design.
- To contribute to the knowledge of daylight calculations and simulations.

4.2 Research hypothesis

With the change of interest from working plane illuminance to the overall room appearance, perceived adequacy of illumination, visual comfort and visual communication are likely to play a more important role. Previous research on the metric MRSE indicated that it is correlated to perceptions of adequate illumination, however, it is not always possible or meaningful to use it as a metric for daylight. Hence the development of the metric MICI. As MICI is a metric derived from MRSE it is hypothesised that MICI will show a better connection with people's perception of adequate daylighting than other daylight related metrics.

Chapter five: Research methodology

5.1 Research methodology overview

The research method includes two parts: the post occupancy evaluation (POE) case studies and the controlled environment study.

POE case studies: The idea is to test daylight metrics through investigating their performance in a number of real-life buildings (refer to Chapter 6).

Controlled Environment study: As there are a range of factors that cannot be controlled in real world situations, controlled environment tests are necessary to fully explore the relationship between lighting metrics and human perception (refer to Chapter 7).

While the procedures will be explained in more detail in the following chapters of the specific studies (Section 6.2 and 7.2), this research methodology chapter gives an overview of the study method used in each study and the computer simulation method used to calculate the daylight metrics.

5.2 POE and BUS methodology

As an initial test of the validity of MICI it was tested in a series of existing buildings that had been surveyed for user satisfaction using the BUS method. The BUS method is a much used and proven tool for collecting user satisfaction data in buildings (see Section 6.2.1). For each of the buildings studied there was also sufficient information to create a lighting model of the internal spaces (see Section 6.2.2). This permitted the calculation of all of the necessary daylight metrics which could then be compared with the BUS responses on daylight. Statistical analysis and data management tools including Microsoft Excel and IBM SPSS were used to investigate the correlations between the datasets (see Section 6.3.1). The detailed study procedures were outlined in Section 6.2.3.

5.3 Controlled experiment

The controlled experiment was a follow up study to the BUS case studies where two office spaces were set up in a way that both spaces are similar in many ways such as room geometry, window view and furniture arrangement. By changing the room surface reflectance and the window transmittance, the two spaces differed in the amount of illuminance received on the working plane relative to the MICI values (see Section 7.2.1). In total 31 experiment subjects were taken to the controlled spaces and completed a questionnaire that was designed to centre around the same BUS question on the adequacy of natural lighting (see Section 7.2.3). The responses of the subjects were then compared with the daylight metrics which were either directly measured onsite or calculated via simulations based on the onsite measurements (see Section 7.2.2). Tools including Microsoft Excel and IBM SPSS were used to investigate the correlations between subject responses and different daylight metrics (see Section 7.4.1). The study procedures are outlined in Section 7.2.4 and details on the how experiment was conducted including the study dates/hours, weather conditions and the overall participant profile are given in Section 7.2.5.

5.4 Computer simulation

Since the early 90s computational simulation has played an increasingly important role in the daylighting design and nowadays it has become a very popular, if not the dominant, tool to evaluate the indoor daylighting (especially with the introduction of CBDM). As the calculations in this project depend on the software, it is worth to discussing some of the core mechanics/algorithms behind the computing tools for daylight simulation.

There are two popular computer graphics techniques for calculating light reflections and rendering images: Radiosity and Ray-tracing.

5.4.1 Radiosity

Radiosity is a finite element method for rendering scenes with diffuse surfaces [69]. This technique was originally developed for thermal transfer simulations, it subdivides all surfaces within the scene into a mesh of many smaller patches. For each pair of patches, a view factor is calculated and used to evaluate the flux transferred from between patches. The programme then calculates the direct illuminance for light sources onto each patch directly and then flux transfers are calculated to evaluate the indirect light on each patch (*Figure 5- 1*).

For daylight simulation, the radiosity method has constraints. Because of the diffuse bounce algorithm, it cannot correctly calculate specular elements in a daylit scene. Also, the radiosity approach always starts at the light sources and is a global illumination algorithm, which again make it not ideal for daylight simulation as the entire sky is quite complex and often with sophisticated descriptions. Moreover, the calculation complexity, and hence calculation time, for a model grows at the square of the number of elements in the scene, thus radiosity works best with simpler models. Popular lighting simulation programs that use radiosity methods include Relux [70], DIALux [71] and AGI32 [72].

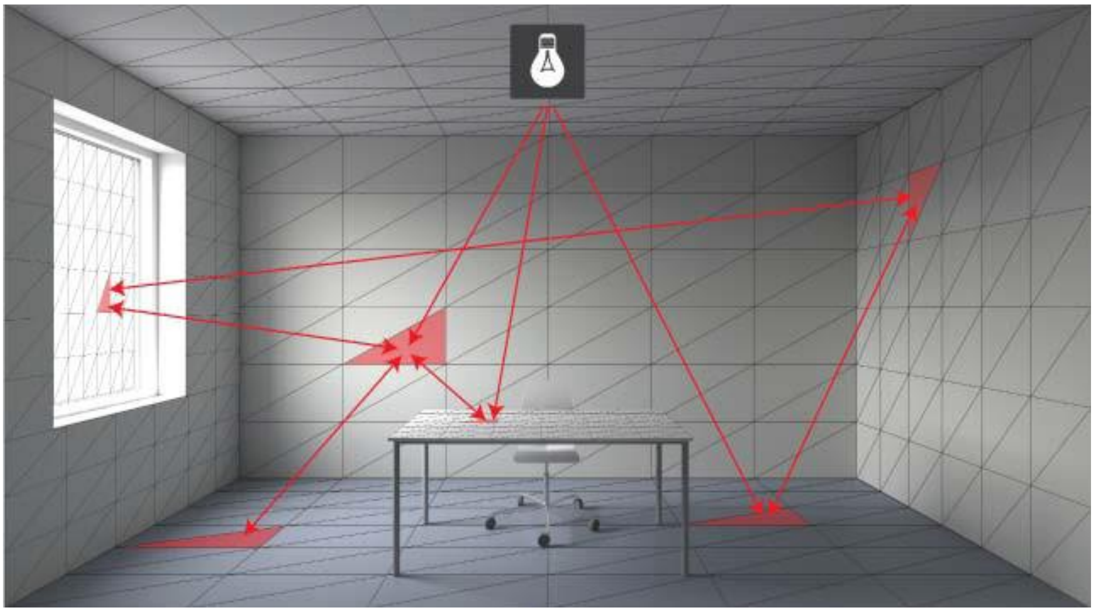


Figure 5- 1: Illustration of the radiosity calculation method (Figure by Iversen et al *[73]*)

5.4.2 Ray-tracing

Ray-tracing is a computer graphics technique [74]. By emitting and tracing a large number of rays in the lighting scene, it allows accurate modelling of the inter-reflection. Rays can be emitted either from the light source and traced forwards, or from a viewpoint and traced backwards. For daylight calculations, backward ray-tracing is preferable as it only calculates the rays from the calculation point. In simple terms ray-tracing works by emitting a large number of rays from the reference point, the computer then follows each ray until it has bounced certain times in the space (*Figure 5- 2*). If a ray did not find a light source after a pre-set number of ambience bounces, the computer will discard this ray. But if a ray successfully found a light source, then the computer will calculate the light contribution from this ray. In the end of the simulation, the computer adds up the contributions from all the effective rays to give the light level of the reference point.

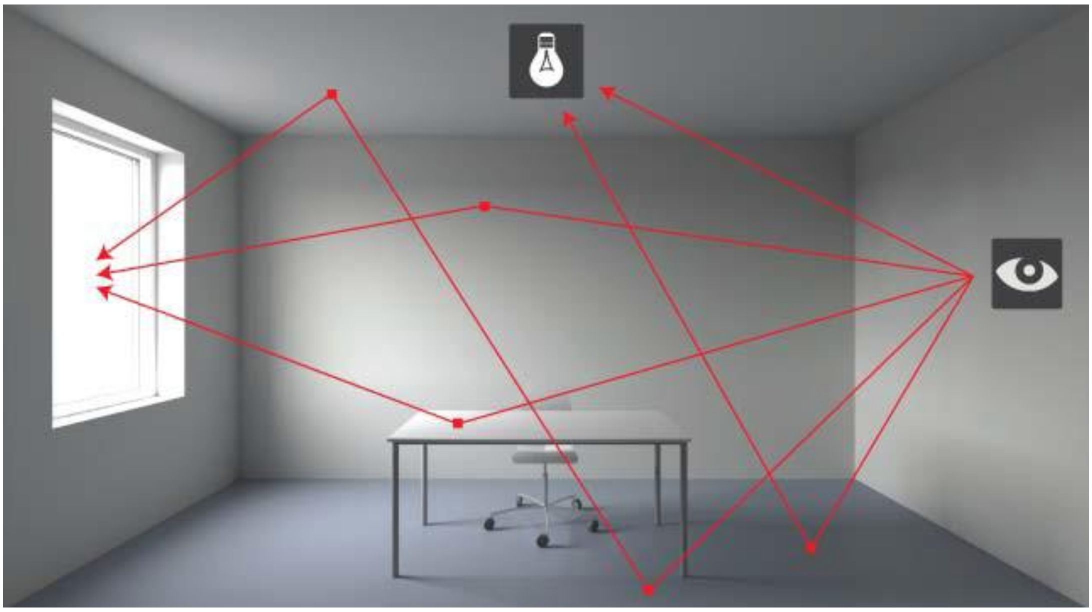


Figure 5- 2: Illustration of the backward ray-tracing calculation method (Figure by Iversen et al *[73]*)

Compared with other lighting modelling techniques (such as Radiosity), ray-tracing is often considered more efficient and accurate. Programs that use ray-tracing technique include Radiance [75] and DAYSIM [76].

5.4.3 Hybrid Techniques

Almost all of the popular lighting programmes employ both ray-tracing and radiosity. For example, DIALux does the bulk of its lighting calculations using radiosity but uses some ray tracing to make the images it creates loom more realistic. Also, Radiance uses some radiosity based pre calculations to speed up simulation processes.

5.4.4 Software used in the study

For this PhD study, lighting simulation software including Radiance and DAYSIM were used for the calculation of daylight metrics.

Radiance is a thoroughly validated ray-tracing tool and can deliver results with very high accuracy. It was developed from 1980s primarily by Greg Ward Larson and was initially released on the UNIX systems. After 2002 the software was released under an Open Source license that allows distribution, and since then it has been ported to many other operating systems including Linux, OS X and Windows. A study conducted by Roy [77] concluded that over the years RADIANCE has become “the most generally useful software package for architectural lighting simulation” and was widely “served as the underlying simulation engine” for many other packages (including DAYSIM and DIVA, the daylighting simulators developed by Christoph Reinhart).

Radiance was used in both the POE case studies and the controlled experiment study. The Radiance settings used in the studies were given in Section 6.2.2 and 7.2.2

DAYSIM is another a validated ray-tracing tool developed by Christoph Reinhart. It is based on Radiance and primarily for modelling the annual amount of daylight in and around buildings [76]. Simulation outputs include various CBDM metrics (DA, UDI and ASE) as well as traditional average daylight factors. Additionally, raw calculated data (such as the hourly illuminances) are stored in a temperate folder and can be extracted for further analyses. DAYSIM does not integrate electrical lighting for its calculation and it is designed specifically for daylighting analyses.

DAYSIM was used in the POE case studies and the controlled experiment study. The CBDM simulation settings used in both studies were given Section 6.2.2 and 7.2.2.

Chapter six: POE case studies

6.1 Study introduction

One way to test a metric is through the examination of its applicability to real life practice. To understand more about the relationship of daylight conditions with occupant perceptions, two buildings and one tenancy were selected for the study of the relationship of perceptions with MICI and other daylight metrics for assessing daylight adequacy.

This chapter explains in detail how the POE case studies were conducted, including the study methodology, procedures and results. Analyses and discussions were given at the end of the chapter.

6.2 Study methodology

6.2.1 BUS survey and the building selections

The three buildings in which the case studies were carried out had all been part of a longitudinal study of building performance by Bunn [78]. Measurement of occupant satisfaction relied upon the Building Use Studies (BUS) occupant satisfaction survey.

BUS survey is a self-completion questionnaire developed in the mid 1980's. It was continuously refined and has been used in a number of POE programmes including the UK government funded PROBE building investigation project [79], the Low Carbon Building Programme [80] and the Innovate UK (former Technology Strategy Board) funded Building Performance Evaluation Programme [81]. The robustness and reliability of BUS responses have been tested and reported in previous research [82] [83] [84], and in general the BUS survey can be considered to be a widely used and accepted POE method across the industry and provides a rich database of post-occupancy building information.

The questionnaire of the BUS survey contains 45 questions seeking views on a wide range of building aspects from the thermal comfort, acoustics, lighting to work productivity etc. There are a total of 5 questions covering the daylighting and artificial lighting of the building. Respondents are first asked to rate whether lighting overall is unsatisfactory or satisfactory, on a 7-point scale. Two subsequent questions poll perceptions on whether natural light and artificial light is too dim or two bright, and two more on whether there is too much or no glare from daylighting and artificial lighting. The section is introduced by the statement:

> ***“Lighting*** *- How would you describe the quality of lighting in your normal work area? The question refers to conditions all year round.”*

Then the following block of questions are given:

Lighting Overall	Unsatisfactory	1	2	3	4	5	6	7	Satisfactory
Natural light	Too Little	1	2	3	4	5	6	7	Too Much
Glare from sun and sky	None	1	2	3	4	5	6	7	Too Much
Artificial light	Too Little	1	2	3	4	5	6	7	Too Much
Glare from lights	None	1	2	3	4	5	6	7	Too Much

As well as the tick boxes, a space for comments is also provided at the end of the section. In this study, only the results of the question: **Natural light** are reported and analysed.

The buildings selected for this study include:

Building 1: Constructed in 1991, building 1 is a 17,565 m^2, deep-plan office over three storeys. The wholly open-plan building was remodelled into separate tenancies in 2008, reducing the floor depths from 120 m to around 27 m (max). The three office floors are penetrated by three, 14 m diameter circular atriums topped by triodetic domes with motorised sail blinds. The office remodelling heavily restricted exposure of daylight from the atriums to the office spaces. The building's envelope on the first two floors is formed of a double-skin facade, with the outer weather screen of clear glass and an inner skin of double-glazed sash windows of grey-tinted glass with a claimed light transmission of 27%. The two lower floors have coffered concrete ceilings with a floor-to-rib height of 3.62 m. The buildings occupants were surveyed using the BUS survey in 1995 and 2016. BUS survey data from one 1865 m^2 tenancy on the south-facing first floor in 2016 was used in the lighting analysis. 98 subjects filled in the BUS questionnaire, and this represents about 75% of the population of building users. However, due to partial information about the subject’s location and incomplete forms it was only possible to use the data from 68 subjects.

Building 2: Constructed in 2004, building 2 is a 7350 m^2 two-storey, deep-plan building on a trapezoidal footprint. The wholly open-plan building was constructed on a north-south axis with the longest facade facing south. The envelope is a mixture of aluminium curtain walling, with a covered walkway and heavy brise soleil on the south elevation. Smaller areas of fixed glazing are set into brick walls of the remaining elevations. The pitched roof is regularly punctuated with mostly north-facing rooflights. There are two large glazed courtyards and nine internal lightwells that break up the second floor mezzanine. Internal finishes are mostly of white painted plaster. The floor to ceiling heights vary between 2.5 m to 5.4 m. The building's occupants were surveyed twice using the BUS survey: in 2006 and in 2015. The lighting assessments carried out used 2015 data from departments with the highest response rates and known relationships to the physical structure. 361 subjects filled in the BUS questionnaire, and this represents about 66% of the population of building users. However, due to partial information about the subject’s location and incomplete forms it was only possible to use the data from 146 subjects.

Building 3: Constructed in 2005, building 3 is a 4852 $m^{2,}$ narrow-plan, two-storey building on a cruciform footprint. The building has a mix of open-plan and cellular offices and a narrow atrium along the East-west axis. The building is naturally lit via conventional windows and some motorised clerestory windows. Floor-to-ceiling heights vary from 2.9 m to over 5.0 m for the pitched-roof spaces. The building occupants were surveyed twice using BUS in 2007 and 2015. The 2015 data was used for the lighting assessments, disaggregated by large tenancy. 118 subjects filled in the BUS questionnaire, and this represents about 80% of the population of building users. However, due to partial information about the subject’s location and incomplete forms it was only possible to use the data from 94 subjects.

To ensure that the results of the case studies were robust it was necessary that the buildings and tenancy chosen for the study had delivered large occupant survey samples. Large samples and high response rates as this gives confidence that the surveys had good spatial coverage and are demographically representative. Table 6-1 shows a summary of the key building information and survey sample size of the three selected sites.

	1 Single Tenancy	2 Building	3 Building
Location	Edinburgh, UK	Swindon, UK	Durham, UK
Constructed	1991	2004	2005
Floor area (gross) m^2	1865*	7350	4852
Floor levels	1*	2	2
Artificial Lighting System	Suspended fluorescent/compact fluorescent downlights		
Occupant survey date	01/06/2016	01/05/2015	01/06/2015
Number of responses for which analysis was possible	64	146	94

* The tenancy surveyed occupied just part of the total building area and only one of the 3 floors in the building.

Table 6- 1: Details of the building and effective sample size for the three selected sites

6.2.2 The computer simulation of daylighting

To investigate the relationship between the indoor daylight availability with occupant responses and find out which daylight metric(s) best correlates with the building users' perception. Three metrics were calculated using computer simulation for each of three case buildings, including MICI (the newly proposed daylight metric for this study), daylight factor (the current dominating daylight metric) and daylight autonomy[7] (a popular CBDM metric).

---

[7] The reason this study chose DA over UDI as a representative of the CBDM metrics (to compare with other daylight metric) is because on the BUS questionnaire respondents were asked to rate the natural lighting on a scale from "too little" to "too much" which will not be reflected by the UDI value by its nature (As discussed in Section 2.3.4, UDI only reports the time percentage of the illuminance within the "useful" range).

Because the BUS survey was conducted before this study and the daylight question referred to the conditions all year around, there is no point in calculating the daylight metrics based on the daylight condition on a specific date. Therefore, it was decided to calculate MICI and daylight factor under the CIE standard overcast sky. For the MICI calculation, the indoor illuminance values were based on an external illuminance of the annual median diffuse horizontal illuminance ($E_{v,d,med}$) value, which was calculated from the IWEC weather file [85] of the nearest weather station. The locations of the weather stations and the $E_{v,d,med}$ values are given in Table 6- 2. The same weather files were also used for the daylight autonomy calculations.

Site	Weather Station Location	$E_{v,d,med}$ [lx]
1: Single Tenancy	Leuchars	14,000
2: Building	London (Gatwick Airport)	14,100
3: Building	Finningley	14,900

Table 6- 2: Weather station locations and $E_{v,d,med}$ values used for the simulations

The simulations were carried out using RADIANCE. As already introduced in Section 5.4.4 RADIANCE is a thoroughly validated ray-tracing tool with high accuracy [75] [86]. As it is a highly flexible and sophisticated software, the accuracy of its calculation is controlled by many simulation parameters. A short preliminary study (refer to Annex One for more detailed study results) was carried out to determine the settings to apply in the RADIANCE software to ensure that the simulated results had sufficient accuracy. This was done by comparison of the results with extremely high accuracy settings that took a very long time to calculate the results and then finding parameter value that gave results within 2% of those results but in a shorter time. The parameter settings used are given in Table 6- 3: RADIANCE parameters used for the daylight calculations

.

RADIANCE parameter	Set value
Ambient Bounces (-ab)	8
Ambient Super-samples (-as)	256
Ambient Accuracy (-aa)	0.1
Specular Threshold (-st)	0.15
Direct Sampling (-ds)	0.2
Direct Pretest density (-dp)	512
Direct Threshold (-dt)	0.05
Limit Weight (-lw)	0.004
Ambient Division (-ad)	1500
Ambient Resolution (-ar)	300
Specular Jitters (-sj)	1
Direct Jitters (-dj)	0
Direct Relays (-dr)	3
Direct Certainty (-dc)	0.75
Limit Reflection (-lr)	12

Table 6- 3: RADIANCE parameters used for the daylight calculations

For the daylight autonomy calculations, subprograms of DAYSIM (a validated, RADIANCE-based daylighting analysis tool [76]) were used to (1) convert weather data (for the locations listed in Table 6- 2: Weather station locations and $Ev_{,d,med}$ values used for the simulations

) into hourly stepped DAYSIM weather files and (2) generate daylight coefficients (as discussed in Section 2.3.3) for calculating the illuminances for all considered time steps of the year. Because DAYSIM uses RADIANCE as the calculation engine, it has similar RADIANCE parameter settings. In this study, all the RADIANCE parameters used in DAYSIM were the same as listed in Table 6- 3. For the DAYSIM and CBDM specific settings, they are given in Table 6- 4.

DAYSIM-specific CBDM settings	
Calculation time-step	Every 1 hour
Weather file converting option	Direct normal irradiance + diffuse horizontal irradiance
Daylight coefficient format	DDS format[8] with shadow testing

Table 6- 4: DAYSIM-specific CBDM settings used for the calculations

6.2.3 General study procedure

The general procedures for the case studies were as follow:

Collecting the BUS data

As already mentioned, this study used existing BUS dataset acquired from a third party with permission for academic use. The buildings choice was based on its sample size (ideally a large sample size with more than 50 subjects), building type (office buildings) and the time that the BUS survey was conducted (ideally close to the time of this study).

Acquiring building information

Once the case building was selected and the BUS dataset was acquired, the actual building information was then needed for the daylight modelling and metric calculation. To ensure high accuracy, detailed building construction drawings were requested from the architects or the current building management team. Site visits were conducted to retrieve building details such as surface finish materials, desk layout/arrangement, on-site daylight measurement (for the validation of the calculations) and any significant post-occupant building changes (differing from the architectural drawings).

Conducting the daylight simulation

After all the necessary building information was acquired, computer simulations were conducted. A 3D building model was built in AutoCAD 3D [87] then converted into

---

[8] The Dynamic Daylight Simulation (DDS) model is an improved daylight coefficient model (based on past models) developed by Bourgeois, Reinhart and Ward [104].

RADIANCE geometry format. All the surface properties were defined in the RADIANCE source file (.rad) and the sky model (used for MICI and daylight factor calculations) was generated using RADIANCE's gensky command [88]. The Calculation grids were created based on the desk locations (Building 1) or building zones (Building 2 & Building 3) and the daylight calculations were carried out on them. All the RADIANCE/DAYSIM settings were as suggested in Table 6- 3 and Table 6- 4. The calculation results were absolute illuminance values at each reference point on the given calculation grid. The raw illuminance data were then imported to an EXCEL spreadsheet for further processing and analysis.

Calculating the daylight metrics

Because the outputs of both RADIANCE and DAYSIM are illuminance values, post calculation was required in order to obtain daylight factor, daylight autonomy (DA) and MICI results. All the post calculations were conducted in EXCEL. Daylight factors were calculated using Equation 1 and MICI values were calculated by averaging the indirect illuminance component of all the six faces of cubic illuminance (refer to Section 3.5 for the calculation method). For DA calculation the building occupied hours of all three buildings were defined as from 9am to 6pm in this study, and the illuminance values within this period were extracted to work out the percentage of the hours that was over 300 lux (Point DA) or the percentage of the space that achieved 300 lux for at least 50% of the occupied hours (spatial DA). A validation check was performed to test the accuracy of the daylight simulation for all buildings, where the calculated results were compared with on-site illuminance measurements.

Analysing and concluding the study results

Evaluations were made looking at both different zones within each building and across buildings where responses were grouped (refer to Section 6.4.2 and 6.4.3 for the detailed analysis). Statistical analyses were conducted using SPSS to investigate the correlations between the calculated daylight metrics and the BUS responses.

The IBM Statistical Package for the Social Sciences (SPSS) [89] is a widely used software package for statistical analysis in social science. It provides researchers with a comprehensive statistical toolset including various statistical functions, text analytics and visualization tools. The version of SPSS used in this study was IBM SPSS Statistics V25.

Lastly, conclusions were dawn after a thoroughly review of the results from all building cases.

6.3 Study results

6.3.1 Building 1

In this study the single tenancy Building 1 provided a seating plan, so it was possible to locate exactly where in the building the respondents (who had given their names on the survey) sat. Only 64 out of the total 98 respondents fully completed the lighting questions and also gave their desk location. Figure 6- 1 below shows the rating of the “natural lighting” with these respondents’ desk locations.

Figure 6- 2 shows the average MICI calculated on plane heights of 0.4m, 0.8m, 1.2m and 1.6m at the centre of each desk. Figure 6- 3 and Figure 6- 4 show respectively the point daylight factor and point daylight autonomy (percentage of the occupied hours that achieved >300 lux) calculated on the working plane height (0.8m) at the centre of each desk.

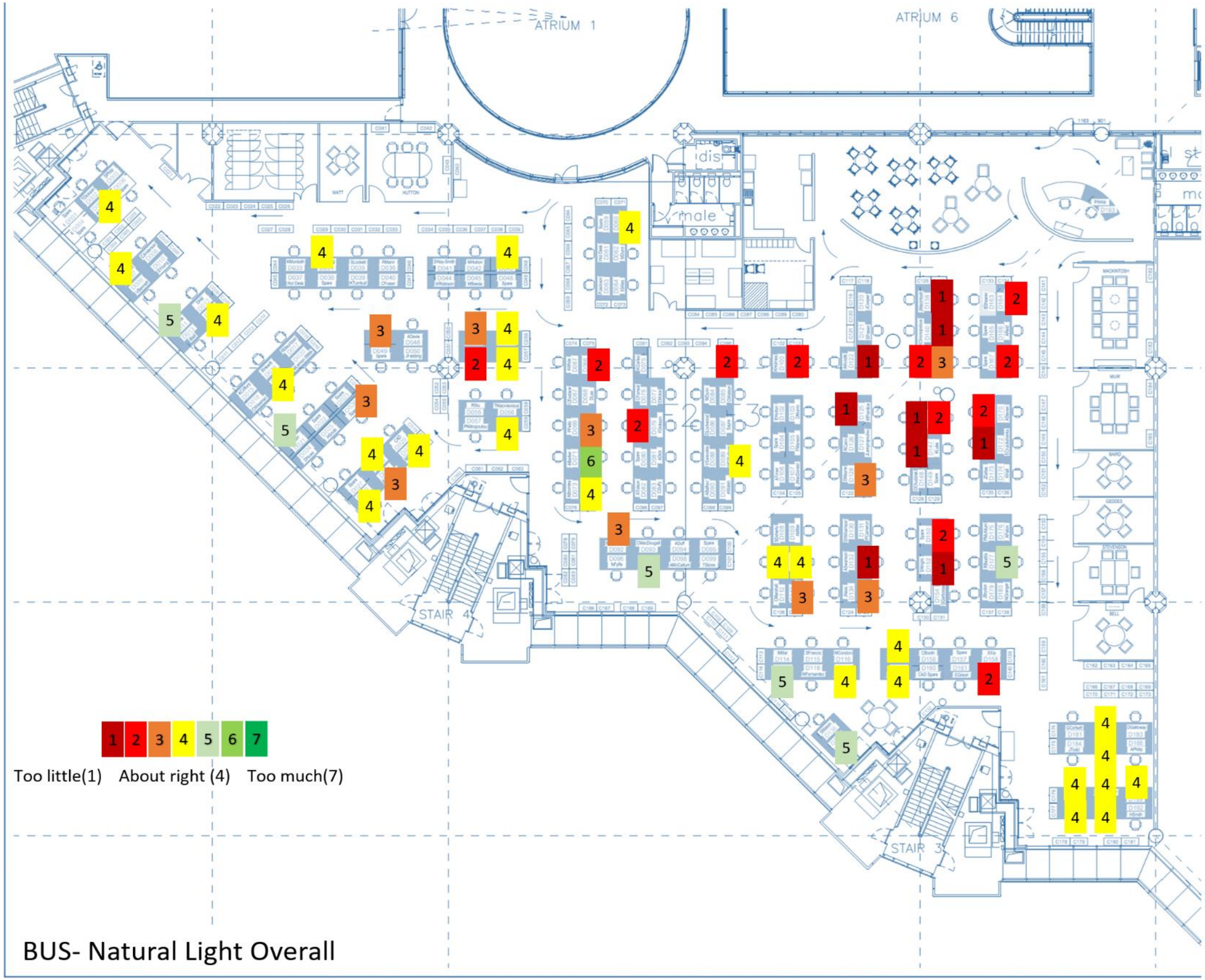


Figure 6- 1: BUS responses of the question: natural lighting in Building 1

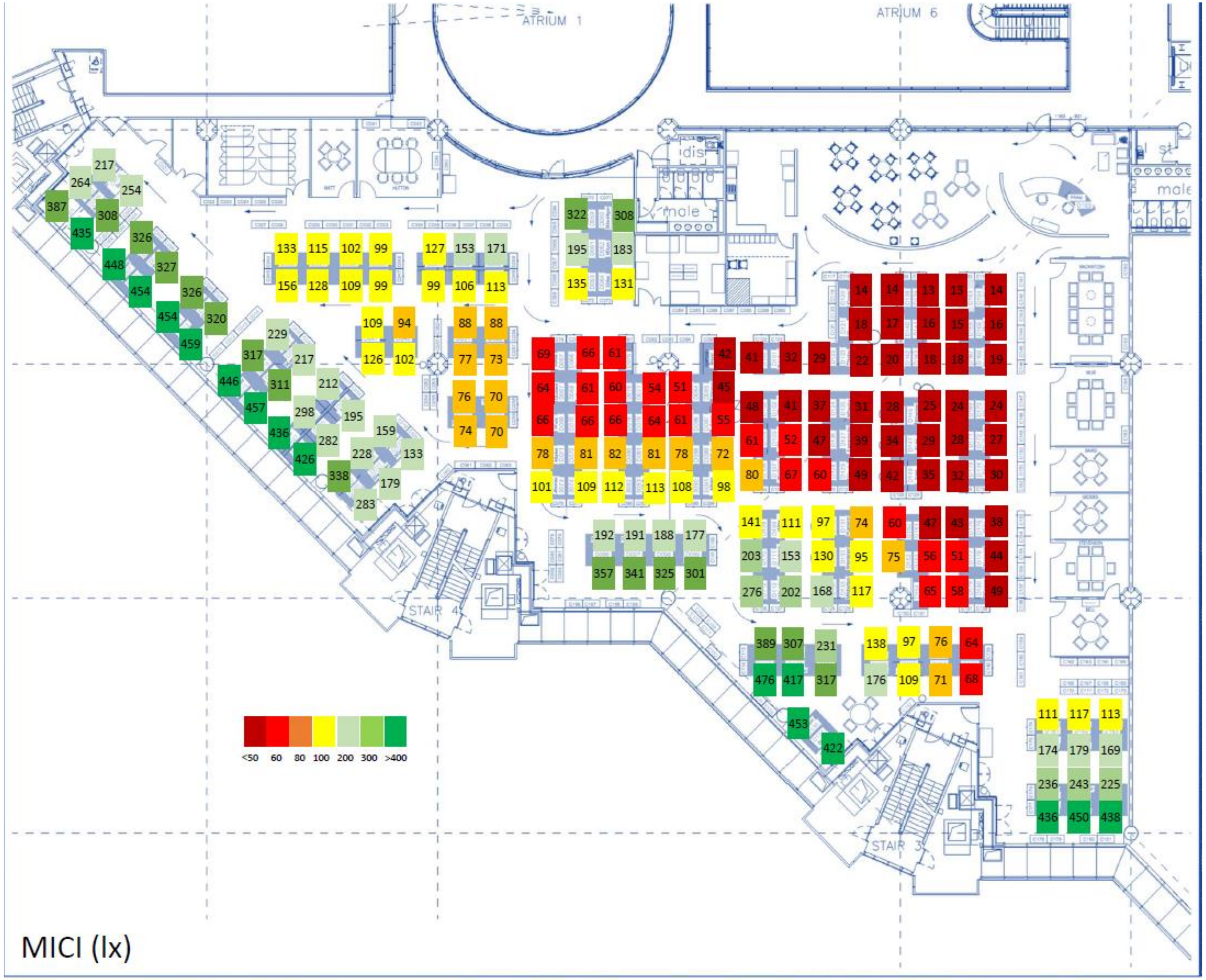


Figure 6- 2: Average MICI calculated on plane heights of 0.4m, 0.8m, 1.2m and 1.6m at centre of each desk

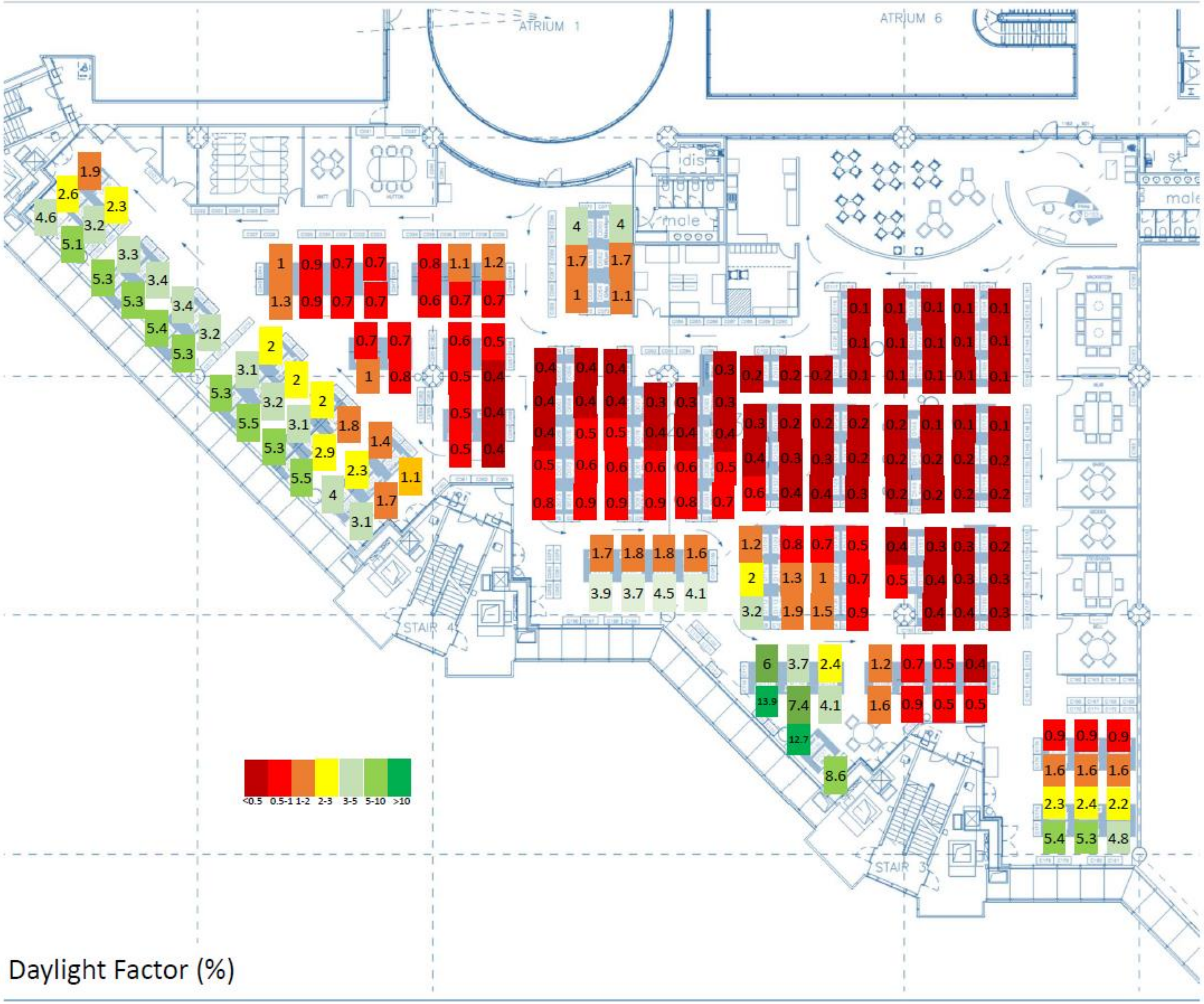


Figure 6- 3: Point daylight factor calculated at the centre of each desk (plane height: 0.8m)

Figure 6- 4: Point daylight autonomy (>300 lx) calculated at the centre of each desk (plane height: 0.8m)

For the validation of the calculation results of Building 1, the calculated illuminance values of a few reference points (at working plane height - 0.8m) were compared with the recorded values from on-site measurements. Table 6- 5 gives the illuminance values from both the calculated results and on-site measurements. Note that the calculation was conducted under a CIE overcast sky with an external horizontal illuminance of 14000 lx. The time when the on-site measurements were recorded was at noon (lunch break) and the weather condition was moderately overcast (with an external illuminance very close to 14000 lx[9]). All electrical lighting was turned off during the measurement.

	P1	P2	P3	P4	P5
Calculated illuminance value [lx]	343	84	448	14	336
On-site illuminance reading [lx]	369	90	462	15	350

Table 6- 5: A comparison of the calculated results with the on-site illuminance measurements in Building 1

From Table 6- 5, the calculation error from the computer simulation was less than 10%. The locations of the measurement points (P1-P5) are given in Figure 6- 5.

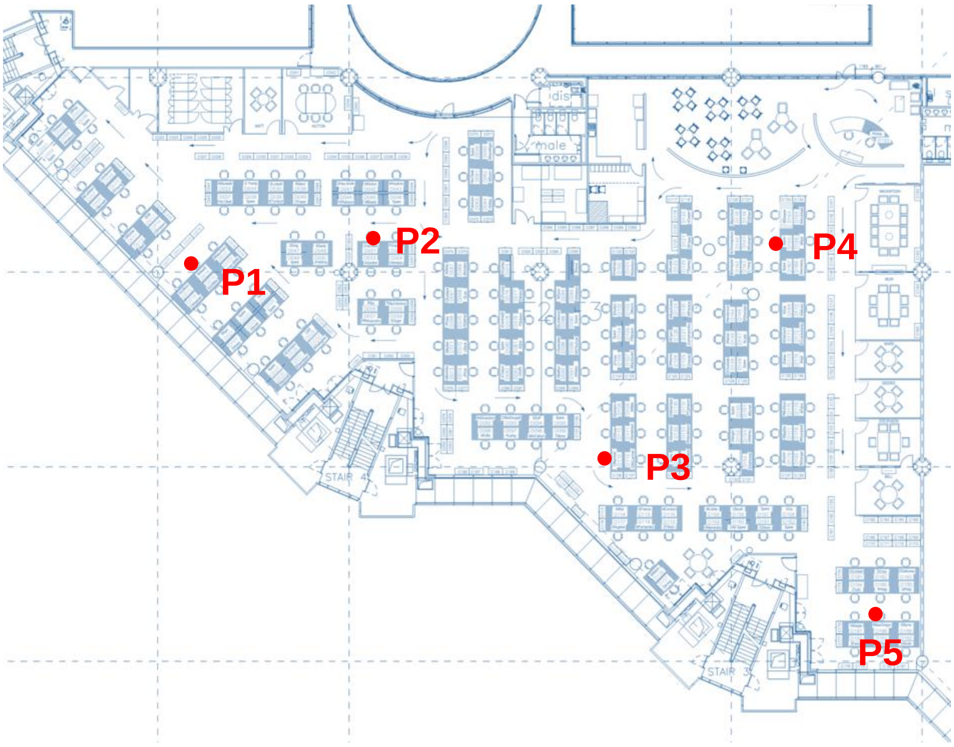


Figure 6- 5: The locations of the measurement points (Building 1)

---

[9] Measured three times at the roof of the building, and average value is around 14300 lx

6.3.2 Building 2

Unlike Building 1, the BUS survey results of Building 2 did not give the respondents' seating plan. It was only possible to locate subjects by the department that they worked and thus it was only possible to locate subjects to general areas within the building (and for this reason average daylight factor, spatial daylight autonomy and average MICI were calculated as the daylight metrics).

The office spaces in the building 2 were allocated to 7 different departments (represented by A-G), and the approximate building areas for each department are shown in Figure 6- 6 and Figure 6- 7.

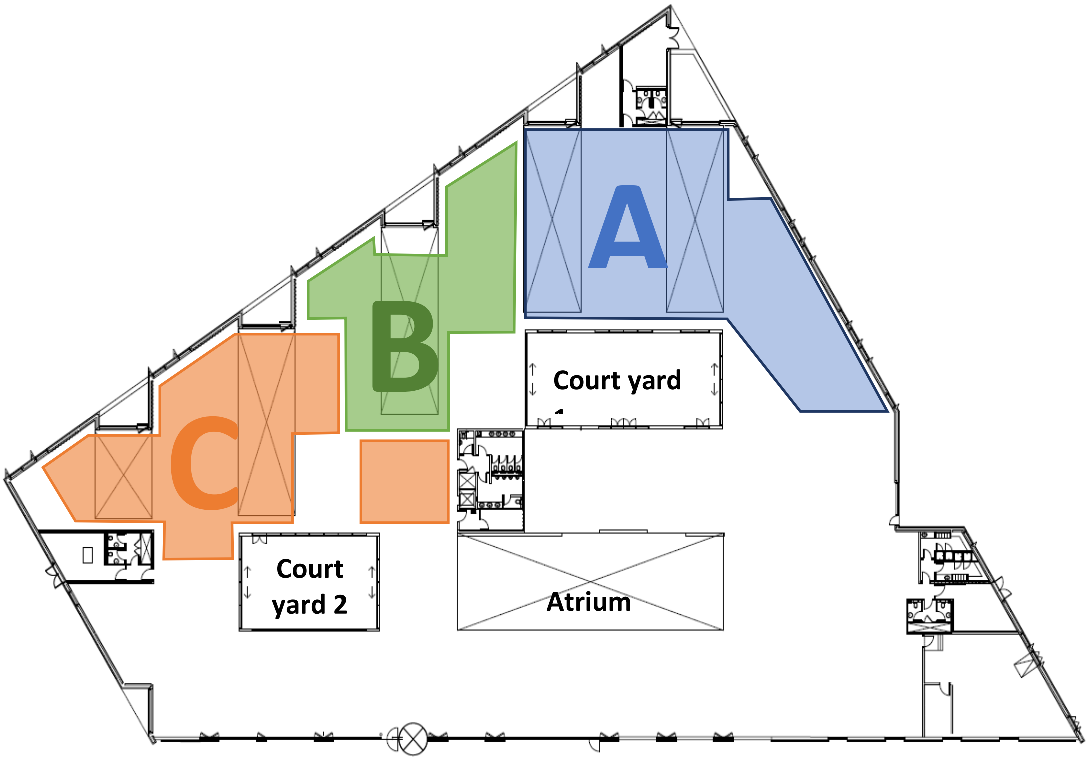


Figure 6- 6: The ground floor plan of Building 2 and the department locations

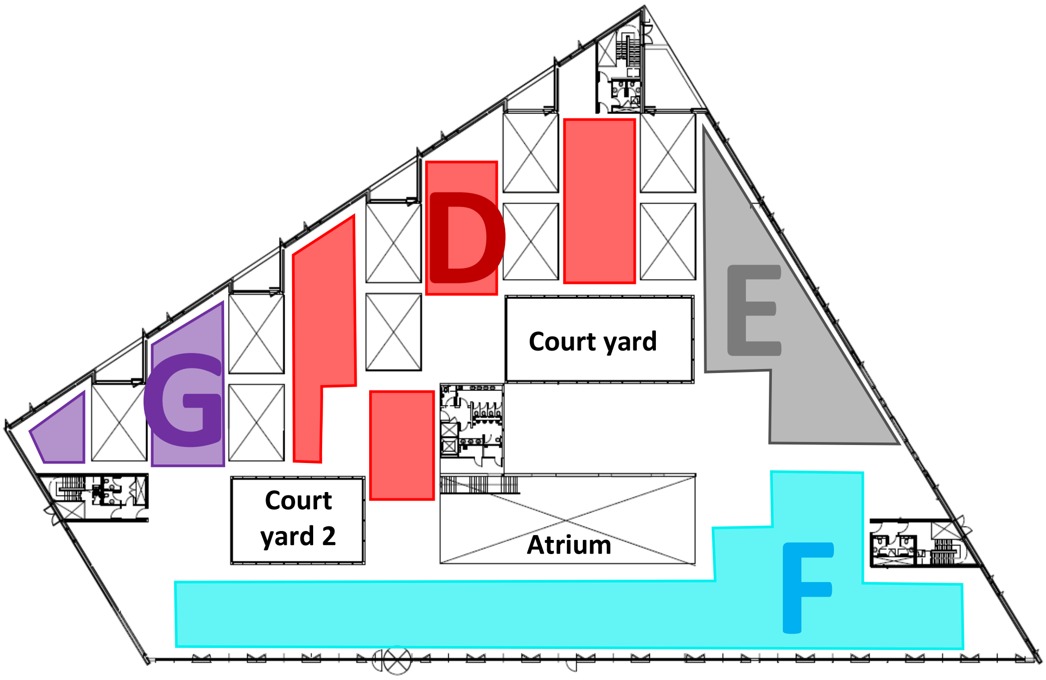


Figure 6- 7: The first floor plan of Building 2 and the department locations

The BUS responses were sorted by the respondent’s work department. Only 146 out of the total 361 respondents fully completed lighting questions and gave their department information (responses with no rating given for the question: **natural lighting** or not given department information were discarded). Table 6- 6 gives the sample size of effective responses of each department.

Department	A	B	C	D	E	F	G
Number of effective responses	38	12	35	17	8	27	9

Table 6- 6: Effective sample size of each department in Building 2

Figure 6- 8 shows the distribution of the BUS responses for the question: **natural lighting** by each department.

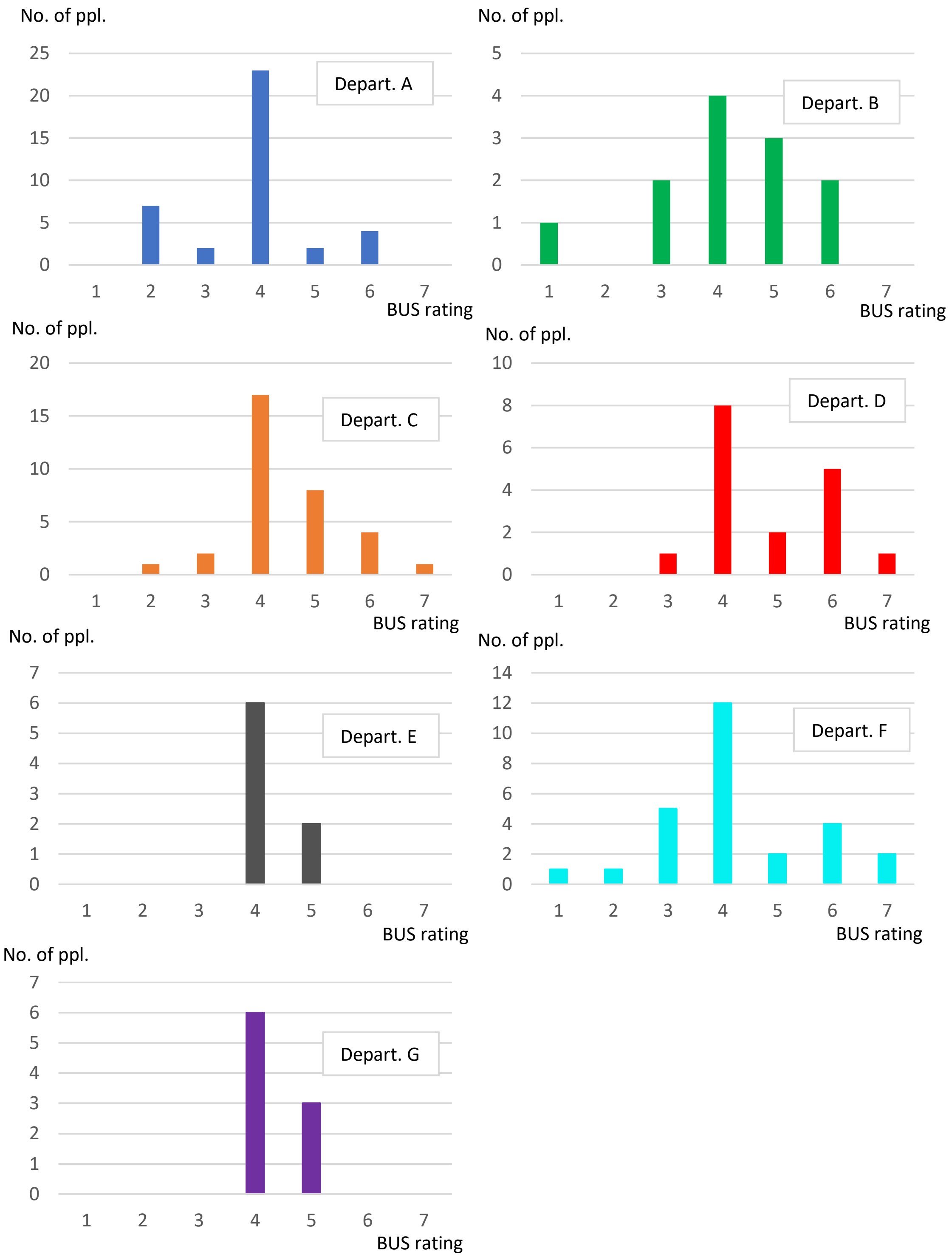


Figure 6- 8: Results of BUS responses by respondent’s department in Building 2 (Questions: **natural lighting**)

For daylight simulation results, Table 6- 7 gives a summary of the average daylight factor, spatial daylight autonomy (sDA) and the average MICI for the areas of each department.

Department	Avg. BUS rating	Avg. DF	sDA	Avg. MICI
A	3.84	0.7%	22.7%	76 lx
B	4.16	1.6%	36.9%	136 lx
C	4.45	1.7%	19.2%	165 lx
D	4.82	4.6%	80.5%	302 lx
E	4.25	3.4%	51.3%	232 lx
F	4.22	3%	92.7%	240 lx
G	4.33	3.2%	52.6%	233 lx

Table 6- 7: Summary of the daylight parameters for areas of different departments in Building 2

For the calculation validation of Building 2, the calculated illuminance values of a few reference points (at working plane height - 0.8m) were compared with the recorded values from on-site measurements. Table 6- 8 gives the illuminance values from both the calculated results and on-site measurements. Note that the calculation was conducted under a CIE overcast sky with an external horizontal illuminance of 14100 lx. The weather condition at the time when the measurements were taken was moderately overcast with an external horizontal illuminance of 20600 lx. The measured results in Table 6- 8 have been scaled to give values that would have been obtained under a sky of 14100 lx external illuminance. All electrical lighting was turned off during the measurement.

	P1	P2	P3	P4	P5
Calculated illuminance value [lx]	629	433	1040	564	433
On-site illuminance reading* [lx]	580	455	920	512	405

* These values have been scaled based on the external illuminance

Table 6- 8: A comparison of the calculated results with the on-site illuminance measurements in Building 2

From Table 6- 8, the calculation error from the computer simulation was less than 10%. The locations of the measurement points (P1-P5) are given in Figure 6- 9 below. The locations were randomly selected across the entire building.

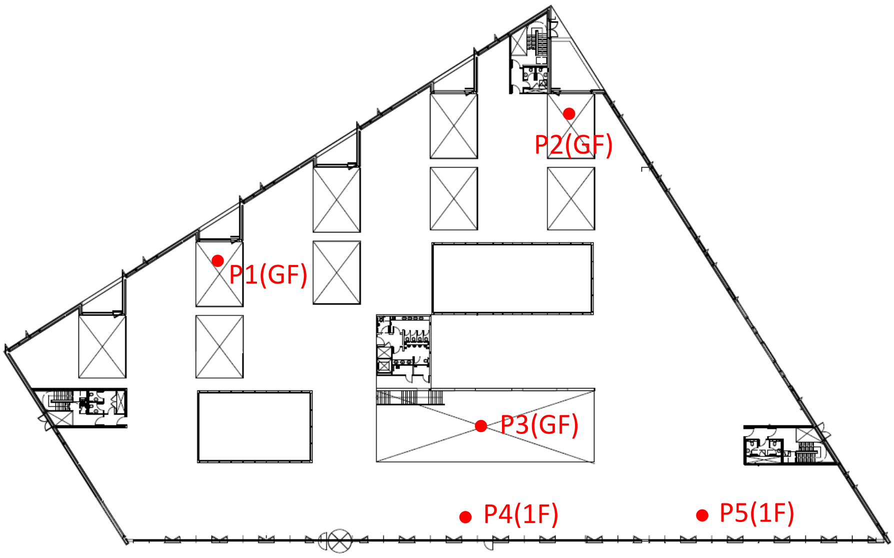


Figure 6- 9: The locations of the measurement points (Building 2)

6.3.3 Building 3

The BUS survey results of Building 3 were also not provided with a respondents' desk plan. Therefore, it was only possible to locate the subjects by their general department areas (This is the reason why average daylight factor, spatial daylight autonomy and average MICI were calculated as the daylight metrics for Building 3). The office spaces in Building 3 were allocated to 9 different departments (represented by A-I), and the approximate building areas for each department are shown in Figure 6- 10 and Figure 6- 11.

The BUS responses were also sorted by the respondent's work department. 94 out of the total 118 respondents fully completed lighting questions and gave their department information. Table 6- 9 gives the sample size of effective responses in each department.

Department	A	B	C	D	E	F	G	H	I
Number of effective responses	17	16	11	20	4	9	4	8	5

Table 6- 9: Effective sample size of each department in Building 3

Figure 6- 12 shows the distribution of the BUS responses for the question: **natural lighting** by each department.

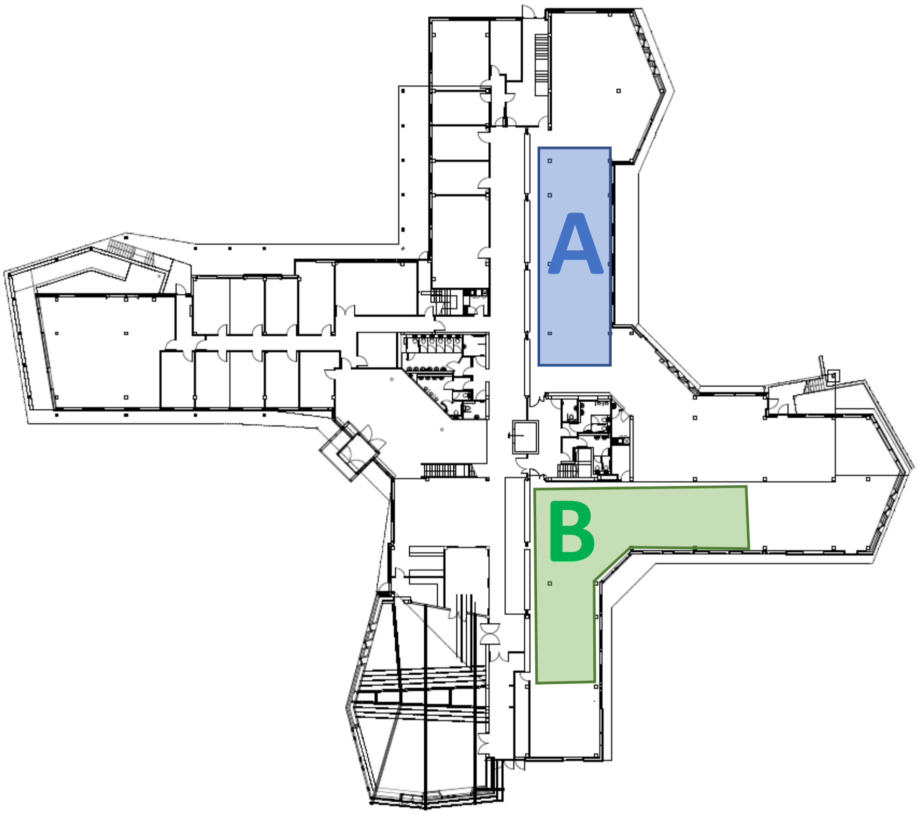


Figure 6- 10: The ground floor plan of Building 3 and the department locations

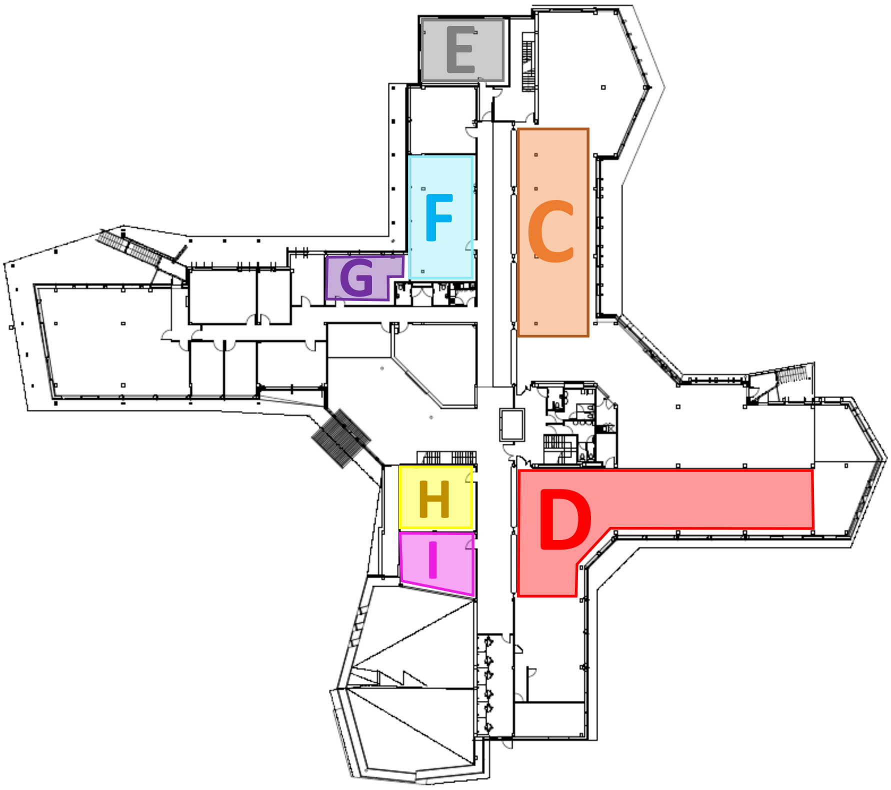


Figure 6- 11: The first floor plan of Building 3 and its department locations

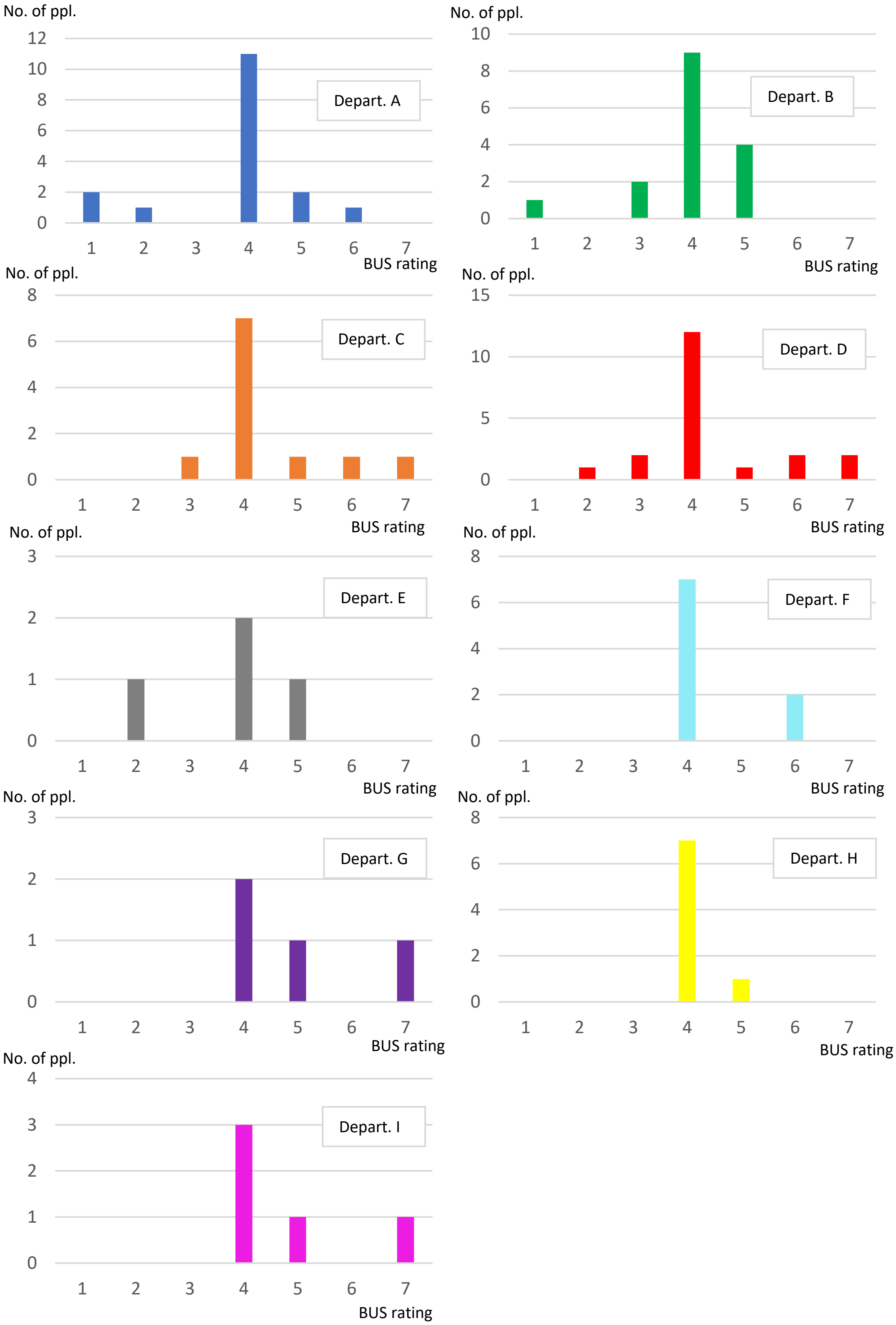


Figure 6- 12: Results of BUS responses by respondent's department in Building 2 (Questions: **natural lighting**)

For daylight simulation results, Table 6- 10 gives a summary of the average daylight factor, spatial daylight autonomy (sDA) and the average MICI for the areas of each department.

Organization	Avg. BUS rating	Avg. DF	sDA	Avg. MICI
A	3.8	3.3%	91.9%	309 lx
B	3.9	2.7%	70.3%	246 lx
C	4.5	2.1%	26.8%	329 lx
D	4.4	2.3%	67.7%	385 lx
E	4.4	3.9%	91.4%	329 lx
F	4.4	3.4%	92.6%	351 lx
G	5	7.8%	96.4%	460 lx
H	4.1	3.1%	85.4%	338 lx
I	4.8	2.5%	97.2%	405 lx

Table 6- 10: Summary of the daylight parameters for the area of different departments in Building 3

For the calculation validation of Building 3, the calculated illuminance values of a few reference points (at working plane height - 0.8m) were compared with the recorded values from on-site measurements. Table 6- 11 gives the illuminance values from both the calculated results and on-site measurements. Note that the calculation was conducted under a CIE overcast sky with an external horizontal illuminance of 14900 lx. The weather condition at the time when the measurements were taken was overcast with a very light rain with an external horizontal illuminance of 19700 lx. The measured results in Table 6- 11 have been scaled to give values that would have been obtained under a sky with external illuminance of 14900 lx. All electrical lighting was turned off during the measurement.

	P1	P2	P3	P4	P5	P6	P7
Calculated illuminance value [lx]	423	664	334	432	450	551	834
On-site illuminance reading* [lx]	450	662	358	456	479	586	851

*These values have been scaled based on the external illuminance

Table 6- 11: A comparison of the calculated results with the on-site illuminance measurements in Building 3

From Table 6- 11, the calculation error from the computer simulation was less than 10%. The locations of the measurement points (P1-P7) are given in Figure 6- 13. The locations were randomly selected across the building.

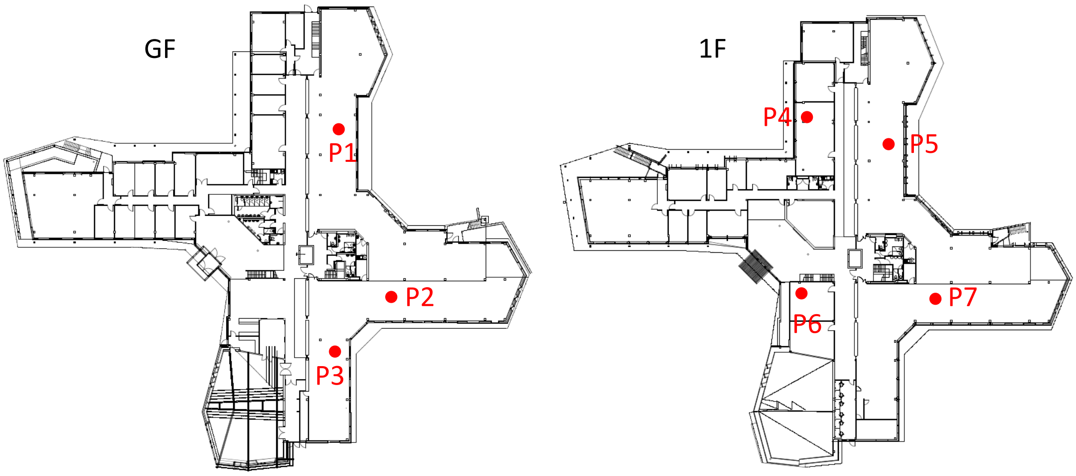


Figure 6- 13: The locations of the measurement points (Building 3)

6.4 Results analysis

6.4.1 On the data analysis methods

To investigate which of the daylight metrics, MICI, daylight factor or daylight autonomy, best reflected the building users' responses from the BUS survey, correlation analyses were conducted.

All the calculated metrics were plotted against the BUS response of the question: **natural lighting** in EXCEL where some basic analyses were conducted (such as the linear regression analyse). Then the data were further analysed in IBM SPSS software by running more detailed statistic tests.

The distribution of the data was investigated in SPSS using various statistical and graphical methods, including measures of central tendency, skewness/kurtosis, frequency histograms, box and whisker plots. It was found that all the data of all the case studies were not normally distributed, therefore non-parametric statistical tests were applied for all the correlation analyses.

Considering the non-parametric nature of the data, Kendall’s Tau was selected for the correlation tests. The variation of Kendall’s Tau coefficient used in SPSS is Tau-b. Values of Tau-b range from -1 (100% negative association) to 1 (100% positive association), and a value of 0 means the variables have no association. Two-tailed significance values (p) were also reported for the statistical significance in all the Kendall’s Tau correlation tests, and for this study a correlation would be considered significant if the significance value was smaller than 0.05.

6.4.2 Correlations between the calculated metrics and BUS responses in the case buildings

Because of the provided seating plan, the various daylight metrics calculated at the respondents’ desk location (as shown in Figure 6- 2, Figure 6- 3 and Figure 6- 4) can be linked with the individual BUS responses of the question: **Natural light** (as shown in Figure 6- 1). Figure 6- 14, Figure 6- 15 and Figure 6- 16 show the scatter plots of the BUS responses against the daylight factor, daylight autonomy and MICI (average of MICI values at 0.4m, 0.8m, 1.2m and 1.4m at centre of the desk) respectively. The plots also show a linear trend line together with the fitting coefficient R^2.

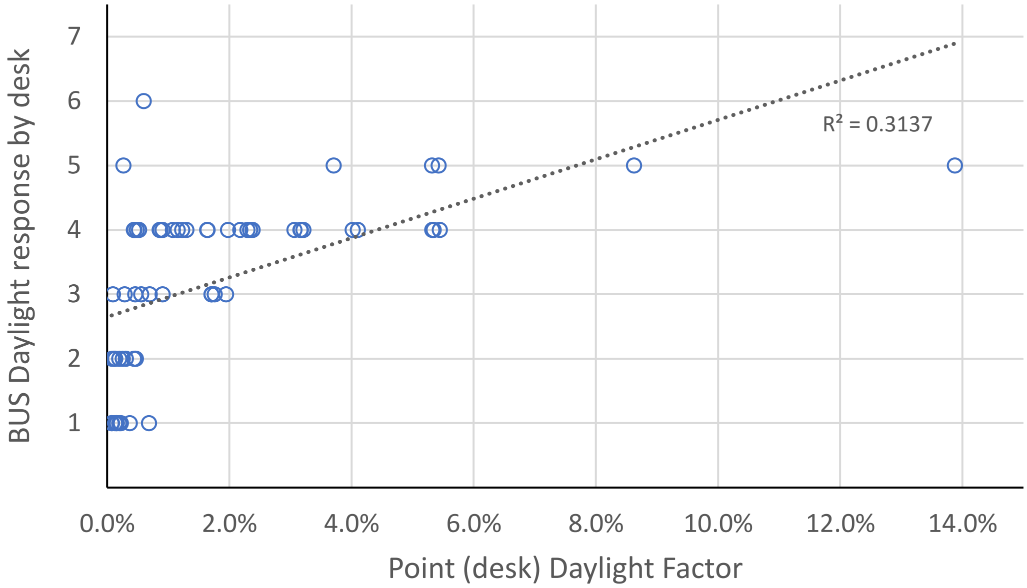


Figure 6- 14: point daylight factor against the BUS responses of natural lighting in Building 1

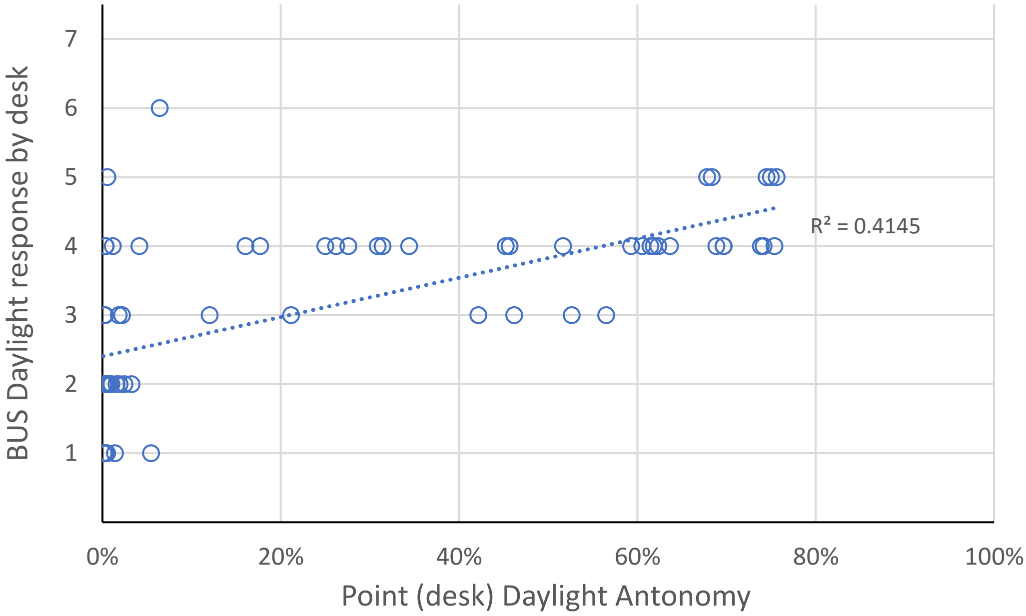


Figure 6- 15: Point daylight autonomy (>300lx) against the BUS responses of natural lighting in Building 1

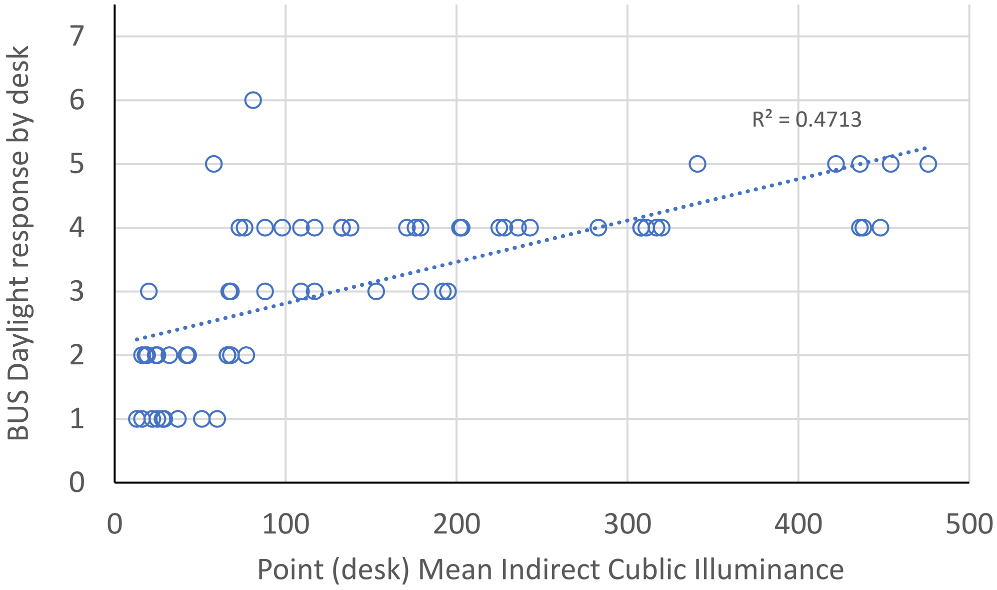


Figure 6- 16: Point (desk) MICI against the BUS responses of natural lighting in Building 1

Similarly, Table 6-12 shows the average daylight metrics for the zones in Buildings 2 and Building 3 against the BUS survey responses. Note that because subjects' desk locations are unknown in these buildings, their individual BUS scores are only able to be compared with the average daylight parameters of the building zones in which their working department was located.

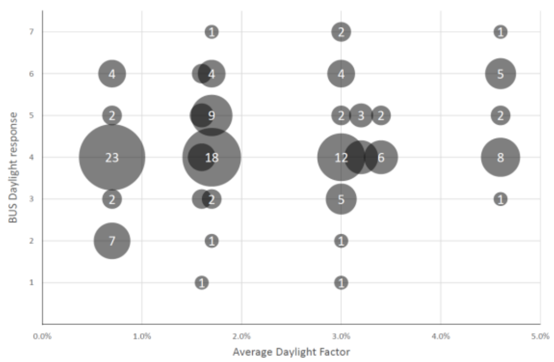
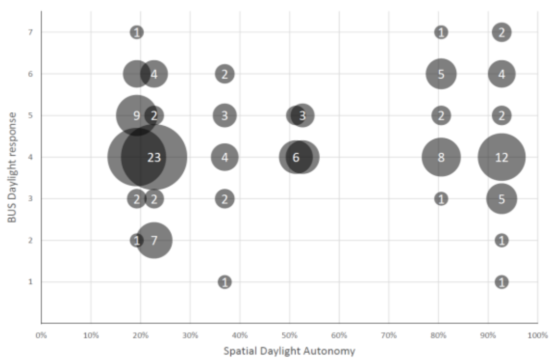
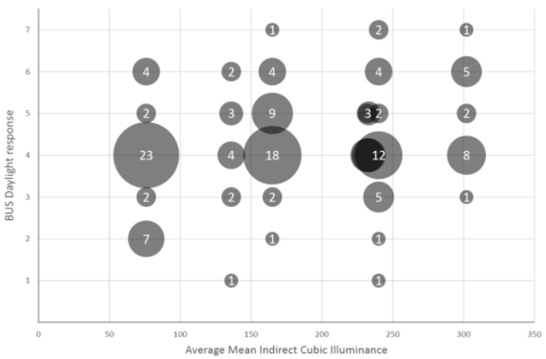
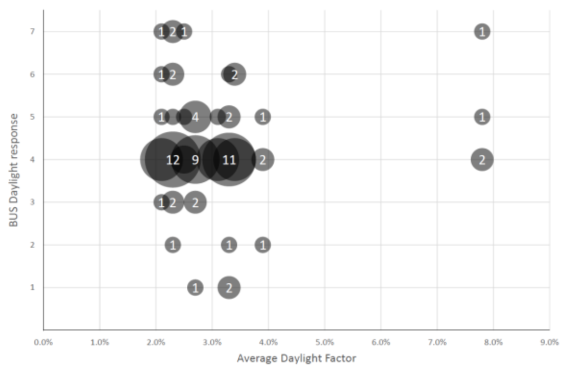
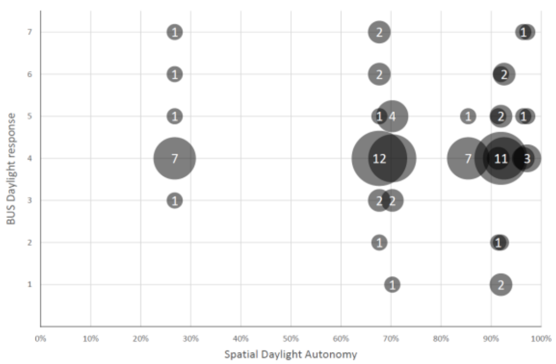
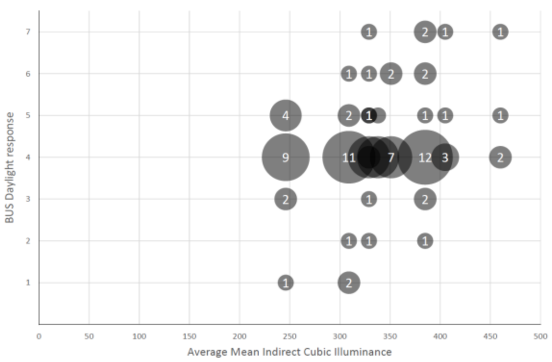
	Average Daylight Factor	Spatial Daylight Autonomy	Average Mean Indirect Cubic Illuminance
Building 2			
Building 3			

Table 6-12: All BUS responses to the question of **natural lighting** against average daylight metrics for the 7 zones in Building 2 and the 9 zones in Building 3

Table 6- 13 describes the results of the correlation analysis using the Kendall rank correlation coefficient (t) to describe the relationship between building user survey responses to the question about natural light and the three daylight metrics, and p is the significance value.

	t	**p**	**t**	**p**	**t**	**p**
Individual BUS Daylight scores by desk for:	**Point Daylight Factor**		**Point Daylight Autonomy**		**Point Mean Indirect Cubic Illuminance**	
Building 1	0.608	0.000*	0.579	0.000*	0.643	0.000*
Average BUS Daylight scores for zones in:	**Average Daylight Factor**		**Spatial Daylight Autonomy**		**Average Mean Indirect Cubic Illuminance**	
Building 2	0.16	0.018*	0.01	0.927	0.15	0.028*
Building 3	-0.02	0.832	0.04	0.646	0.14	0.097
	Median Daylight Factor		**Median point Daylight Autonomy**		**Median Mean Indirect Cubic Illuminance**	
Building 2	0.12	0.085	0.11	0.106	0.13	0.061
Building 3	0.03	0.726	-0.04	0.646	0.12	0.161

*Samples are correlated (alpha = 0.05)

Table 6- 13: Kendall's Tau correlation coefficients (t) describing the relationship between Building User Survey Response to the question of **natural lighting** (1 Too Dim - 7 Too Bright) and Daylight Metrics explored in this study. Underline denotes highest correlation coefficient for each site.

In Building 1, desk locations of 65 subjects were known therefore point measurements of Daylight Factor (DF), Daylight Autonomy (DA) and Mean Indirect Cubic Illuminance (MICI) were correlated with survey responses by desk. All samples for Building 1 are correlated, the marginally strongest association achieved with MICI.

For Building 2 and Building 3, all responses reported in the building zones were compared with daylight metrics of average DF, Spatial DA (50% of occupied hours, > 300 lx) and average MICI of those zones. Average MICI and average DF are correlated with the daylight responses in Building 2, however the other four samples are not. In Building 3 analysis demonstrates that although not correlated, the association between daylight responses and average MICI (p=0.097), appears stronger than that of Spatial DA (p=0.646) and average DF (p=0.832).

The analysis was also conducted using medians rather than means of the values in the zones, to reduce the effect of extreme values on the results analysed. Point Daylight Autonomy (percentage of the occupied hours that achieved >300 lux) was used to calculate the median values for Daylight Autonomy. Whilst none of the six samples are correlated, the highest t values are achieved with median MICI, when compared to median DA and median DF. This suggests that when correlated to users' perceptions in the three buildings tested, MICI performs at least as well as other accepted daylight metrics and could therefore be considered valid.

To further analyse the results of Building 2 and Building 3, the average BUS **natural lighting** score of each zone were also compared with the average lighting parameter of each zone. The results are shown in Table 6- 14. Cross the two buildings, the zone-average MICI reported a significant association with the zone-average BUS response (t=0.373, p=0.047), whereas the other two metrics did not suggest such correlation.

	t	p	Sample size
Average daylight factor	0.271	0.148	16
Spatial daylight autonomy	0.16	0.391	16
Average MICI	0.373	0.047	16

Table 6- 14: Kendall's Tau correlation coefficients (t) describing the relationship between the average BUS **natural lighting** scores (of each building zone) and the average daylight parameters (of each building zone) in Building 2 and Building 3

6.4.3 Correlations between the daylight metrics

Daylight metrics are likely to related to each other in a given building. This is because they all depend on the amount of daylight getting into a space and the light reflecting properties of the space. A correlation analysis was also conducted to investigate the relationships between different daylight metrics in the three case study buildings.

Table 6- 15 shows the correlation between different daylight metrics using Kendall’s Tau correlation coefficient (t). The average daylight metric values of different zones in Building 2 and Building 3 were grouped together for the analysis. The results suggested that in all the case study buildings significant correlations exist between MCI and other daylight metrics. The only exception is for the median daylight autonomy in Building 2 & 3, which did not show a significant association with the median MICI.

	t	p	**t**	**p**
Average Mean Indirect Cubic Illuminance	**Average Daylight Factor**		**Spatial Daylight Autonomy**	
Building 2 & 3	0.605	0.013*	0.723	0.02*
Median Mean Indirect Cubic Illuminance	**Median Daylight Factor**		**Median point Daylight Autonomy**	
Building 2 & 3	0.383	0.038*	0.283	0.126
Point Mean Indirect Cubic Illuminance	**Point Daylight Factor**		**Point Daylight Autonomy**	
Building 1	0.892	<0.001*	0.815	<0.001*

*Samples are correlated (alpha = 0.05)

Table 6- 15: Relationships between different daylight metrics described by Kendall’s Tau correlation coefficients (t). Underline denotes highest correlation coefficient among different metrics.

6.5 Discussions and conclusions of the POE case studies

This POE study tested the performance of different daylight metrics on three selected office buildings, and the new metric MICI was found to be at least as good as the current metrics (daylight factor and daylight autonomy). In Buildings 2 and Building 3, the correlations of three daylight metrics to the building users’ responses are all quite poor with mostly no correlation, and the only exceptions were achieved by the mean DF and mean MICI in Building 2 (although both correlations are very low, t=0.16 and 0.15 respectively). This may be because in Building 2 and Building 3, the user responses were collected in a way that did not permit the identification of their desk locations and it was only possible to localise them to a general area based on their working departments. Some zones consisted of a quite large occupied area, therefore predicting all building users' perception by one average value is likely to be unreliable. However, when the exact desk locations are known as in Building 1, all the daylight metrics perform well. This provides evidence that all three daylight metrics were quite useful in predicting building users' perceptions of daylight. In addition, it was found that in most studies on the three different building sites, the highest correction coefficients between daylight metrics and users' responses were achieved by MICI (with only one exception in Building 2, where the average DF shows a very marginal better correlation over MICI), this further indicates MICI's potential as a good daylight metric. Moreover, if the average of the users' responses in each of zones in Building 2 and Building 3 are considered, then it was found that MICI correlates the best with user's responses.

In general terms all of the daylight metrics used in this study are a function of how much daylight comes through the windows into the buildings and how much light is inter-reflected inside the buildings. Whilst the three buildings used in this study were all very different in style, Building 1 being very deep plan, Building 2 being deep plan with a series of atria and skylights and Building 3 being shallow plan, it is that case than within in a given building there were a lot of common features, such as internal finishes, and this means the various daylight metrics are going to give values that are correlated to each other. This has been shown in Table 6- 15, and it is a limitation to this study. Across buildings it is likely that the correlation will be less pronounced and in a cross building correlation analysis MICI was the metric that best correlated with the building users' responses (see Table 6- 14). However, as the results are inconclusive further investigation will be needed to see how well each of the metrics of daylight perform in conditions engineered to ensure that the metrics are less correlated.

6.6 Chapter summary

This chapter presented the work of a POE study on the relationship between daylight metrics and user responses over three selected office buildings. In two of the buildings it was not possible to locate exactly where the respondent to the BUS survey was sitting and this made it hard to relate the subjects' responses to the actual daylight conditions. In the one case the where location information was available the best metric was found to be MICI followed by daylight factor and then daylight autonomy. In all buildings significant correlation between all of the tested daylight metrics was found.

Overall, it could be concluded that MICI at least performed as well as the other metrics. However, due to the correlation between the various daylight metrics it was not possible to conclude the new metric was significantly different to the old metrics. Thus, a study in a controlled environment, where MICI and the other metrics were quite different, was required.

Chapter seven: Controlled experiment

7.1 Study introduction

7.1.1 Testing lighting metrics in a controlled environment

In the previous POE case studies chapter, comparisons of daylight metrics with user responses have shown that the new metric MICI is at least as good as older metrics such as daylight factor at predicting user response to daylight availability in a building. However, within the buildings studied, constancies in geometries and surface reflectance values lead to relationships between the various daylight parameters. Therefore, to fully test which daylight parameter best corresponds to user response a controlled experiment was necessary to compare spaces where MICI and other metrics of daylight were not correlated.

This chapter explains how the controlled environment study was conducted, covering the detailed study methodology, study procedures and all the study results. Analyses and discussion of the study results were given at the end of the chapter.

7.1.2 On setting up the experiment

The aim of this experiment was to compare user's perceptions of two spaces that are similar in many ways but differ in the amount of daylight received by the working plane relative to their MICI values. The idea was to set up two similar spaces (same geometry, furniture arrangement) in an open plane office that had been divided using high partitions (with a height of 2.55m) located in an office block in central London (51.53 N, 0.138 W). The daylight flux entering each space was controlled a thin transparent window film applied to one of the experiment space's glazing to reduce the flux entering. The inter-reflected light was adjusted by painting the inside of one of the spaces (the same space with window film applied) white. The whole experiment was carried over a period of two weeks and thus across various external daylight conditions. As the experimental variables, the daylight parameters (namely the working plane illuminances and MICI) of two experiment spaces were then compared with the subjects' responses.

Other extraneous variables whose effects might influence the results of the experiment needed to be controlled. Firstly, the direct sunlight is a constantly changing and hard to control element. To avoid the dynamic nature of sunlight and control the indoor lighting conditions better, this experiment was conducted during periods of the day when direct sunlight did not enter the room.

The second factor could have impacted the experiment result was view, as it is also an important aspect of daylighting. Research [90] [91] [92] has found that the window view can have a considerable effect on the perceived workplace quality. Therefore, ideally the experiment spaces should be quite close and have the same orientation so that they share similar outside views.

Another factor that might have an impact on the experiment result was room aesthetics. Although extra efforts were put into the setup to ensure that both experiment spaces had the identical room geometry and furniture/room object arrangement, one of the spaces would need to be painted white to alter the light inter-reflection and hence making the appearance of the two spaces inevitably different in regards to the surface finishes. To address this concern, careful calculation/simulation was conducted to determine which surfaces were necessary to be painted, and room appearance related questions were included in the questionnaire to discover if the two spaces were perceived differently in terms of room aesthetics.

7.2 Experiment methodology

7.2.1 Room set-up

The experiment location was chosen in an abandoned[10] faculty building in central London. It was a 4-storey former warehouse building and had been used by UCL as the home of Bartlett School of Architecture. The lower two floors were used as workshops and laboratory rooms, and the upper two storeys were mostly open plan office spaces.

On the top floor of the building, there were two arrays of office cells (placed on the two sides of the open floor area) divided by wooden partitions. The cells had been

---

[10] As the experiment took place, the building was emptied and scheduled to be demolished because of the expansion of the nearby Euston train station.

used by faculty staff and PhD students and were attached to each other. Inside the cells (*Figure 7- 1*), the furniture arrangements were nearly identical (mirrored, see *Figure 7- 5*), with a long desk plate fixed onto one side of the partition wall and layers of bookshelf plates fixed onto the other side. Opposite the cell entrance was a large single-glazed window (with translucent window roller blinds). Hanging from the ceiling there were arrays of pendent plasterboard panels (vertically placed), and on the floor there was a dark grey carpet flooring. Apart from daylighting, the cells were also illuminated by artificial lights (fluorescent tubes) which were turned off during the experiment.

Figure 7- 1: Office cell in the faculty building

The size of office cells is enough for the ordinary use of two people, and the detailed dimensions of the cell are shown in *Figure 7- 2*, *Figure 7- 3* and *Figure 7- 4*.

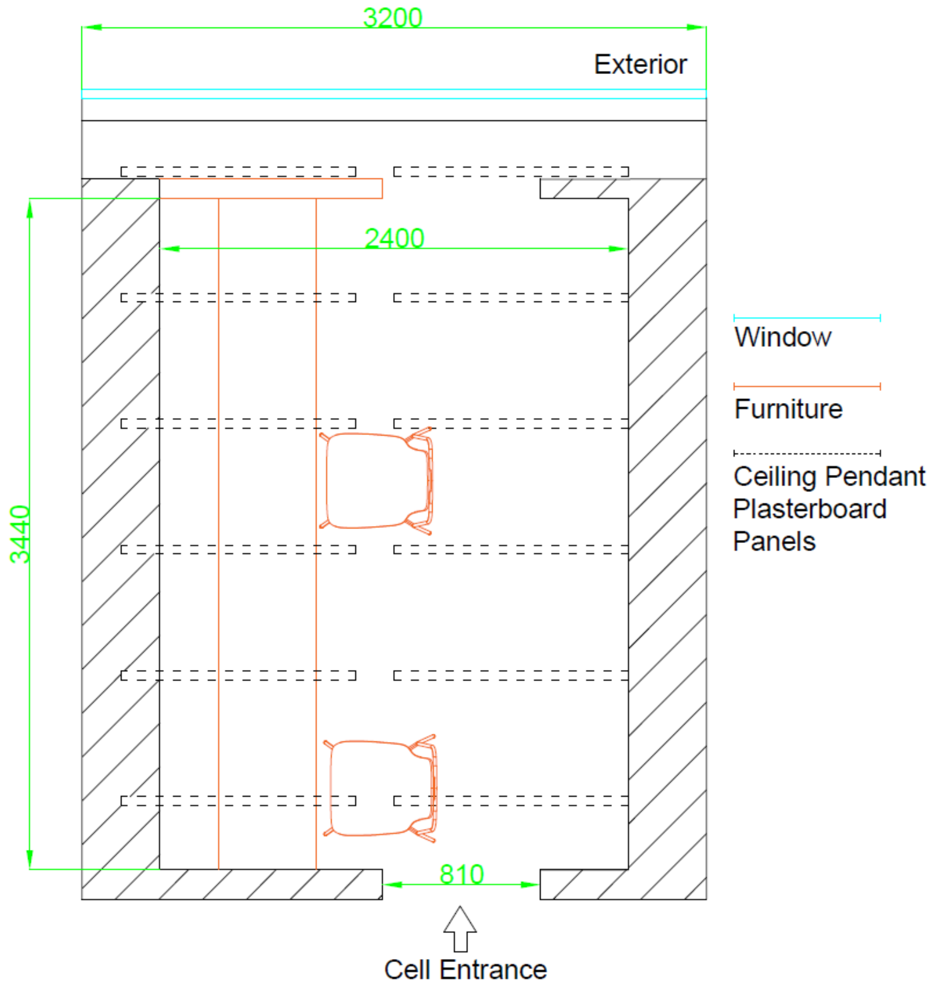


Figure 7- 2: Plan drawing of the office cell

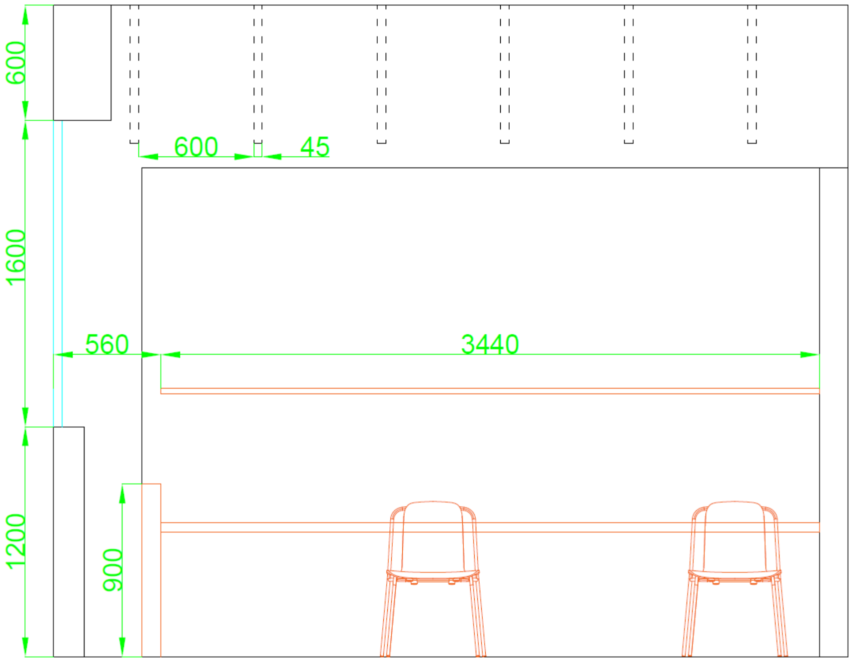


Figure 7- 3: Section drawing of the office cell

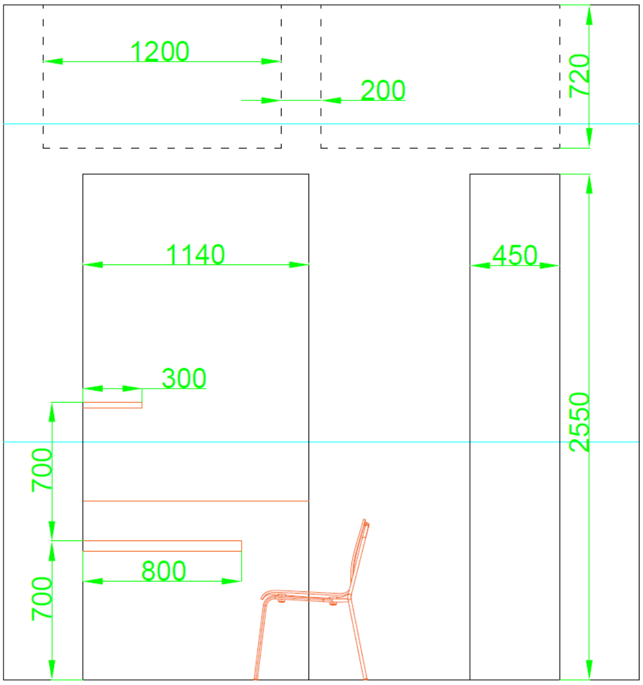


Figure 7- 4: Front drawing of the office cell

Two adjacent cells in middle of the east facing row were selected for this experiment (*Figure 7- 5*).

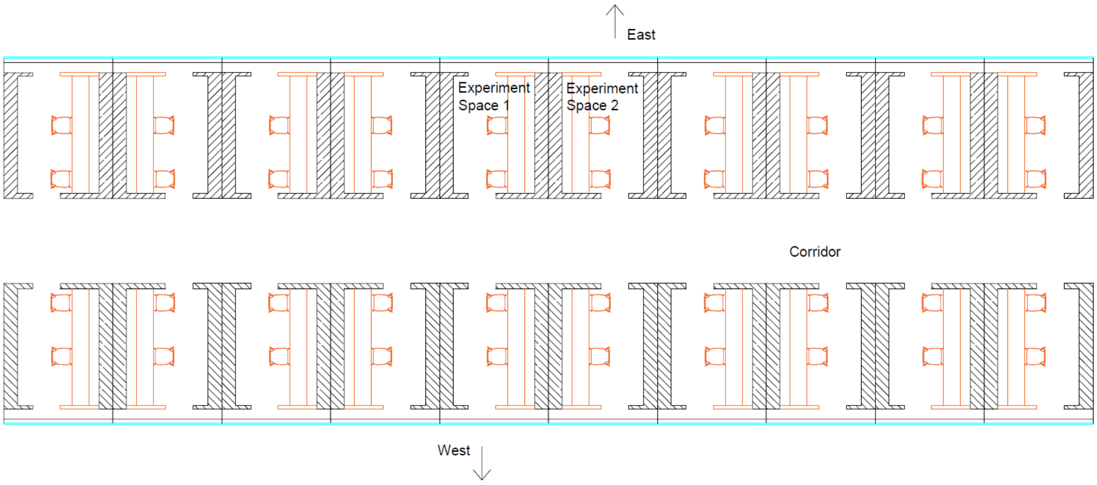


Figure 7- 5: Selection of the experiment spaces and their orientation

Because of the location proximity, the views from the two selected cells were nearly identical. *Figure 7- 6* below shows photos taken inside from both office cells during the refurbishment (for the experiment).

Figure 7- 6: Views from experiment space 1 (left) and experiment space 2 (right)

There are no major external obstructions for both cells, with only few high-rise buildings at distance in excess of 600 meters.

The reflectance values of the existing room surfaces were shown in *Table 7- 1* (measured with an illuminance meter and a luminance camera):

Wooden partition	0.34
Ceiling	0.6
Carpet floor	0.12
Plasterboard panels	0.74
Desk & bookshelf surface	0.68

Table 7- 1: Reflectance values of the existing room surfaces

A transparent (with a blue tint) window film was originally on windows, which was then removed in both spaces for the experiment. After having been cleaned the clear glass had a measured transmittance of approximately 0.7.

As briefly discussed in Section 7.1.2, the plan was to regulate the incoming daylight flux by applying transparent window films to the glazing and control the inter-reflections by changing the room surface reflectance, so that the two experiment spaces had different MICI in the volume of the space relative to the illuminances over the desks.

To estimate how much light should be blocked by the added window film and what the new reflectance values should be for room surfaces, a digital model of the experiment space was built, and RADIANCE was used to test different options (*Figure 7- 7*).

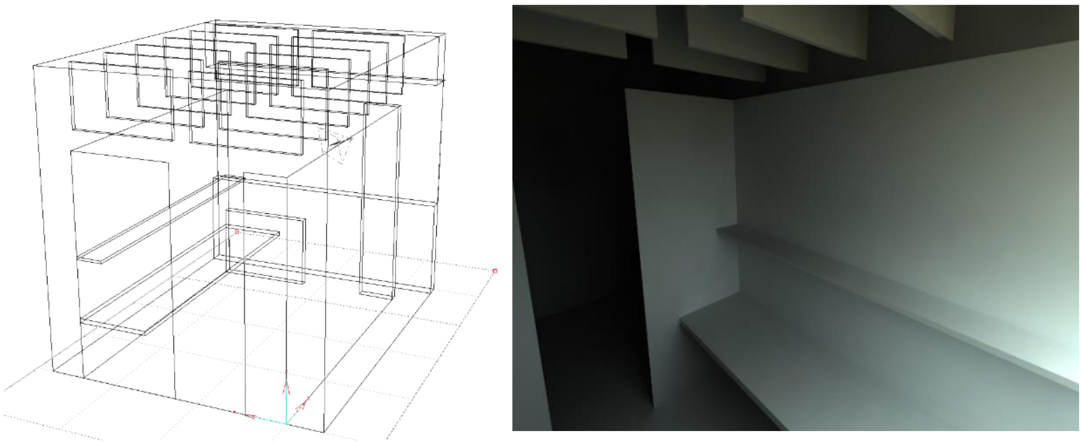


Figure 7- 7: : 3D model of the experiment space in Autodesk (left) and a RADIANCE render of the space (right)

The simulation tests were set under the CIE Standard Overcast Sky with an external horizontal illuminance of 14100 lx. With the existing window transmittance (0.7) and room surface reflectance (as listed in *Table 7- 1*), the illuminance at the desk centre (the approximate sitting position of the experiment subject) was 587 lx and the MICI value at the centre of the room was 128 lx.

To validate the accuracy of this RADIANCE model, on-site illuminance measurements of the experiment spaces were conducted during an overcast day. The measured results were then compared with the simulated data (*Table 7- 2*), and it was found that the errors between the simulated results to the measured values were within 10%.

	Vertical window illuminance (at the centre of the window)	Working plane illuminance at the desk centre	Working plane illuminance near the window	Working plane illuminance near the entrance
Measured result	1830 lx	588 lx	1882 lx	124 lx
Simulated result	1730 lx	587 lx	1794 lx	116 lx

Table 7- 2: Validation of the RADIANCE model: the measured results vs simulated results

After the tests of different combination of surface reflectance/window transmittance it was found that in order to achieve a considerably different MICI value (with a difference of >50%) while keeping the work plane illuminance at a relatively consistent level, the surface reflectance of the wooden partition needed to be increased to at least 0.8 (this high reflectance also meant that fewer surfaces needed to be painted) and in addition 10% of the incoming flux needed to be blocked by the window. *Table 7- 3* shows the simulated results after the changes of surface properties.

	Original	Partition reflectance increase to 0.8; window transmittance reduced to 0.6
Working plane illuminance (centre of the desk)	587 lx	632 lx
MICI (centre of the room)	128 lx	255 lx

Table 7- 3: Simulated results of the daylight parameters before/after surface changes

To alter the glazing transmittance, a transparent clear window film was carefully applied to the internal side of the window surface (*Figure 7- 8*). The film itself has a transmittance of 0.9, which reduces the overall transmittance of the window from 0.7 to approximately 0.6. This change of glazing transmittance was only made for the "light space" (Experiment Space 2 shown in *Figure 7- 5*), and the window film was not applied to the glazing in the "dark space" (Experiment Space 1 shown in *Figure 7- 5*).

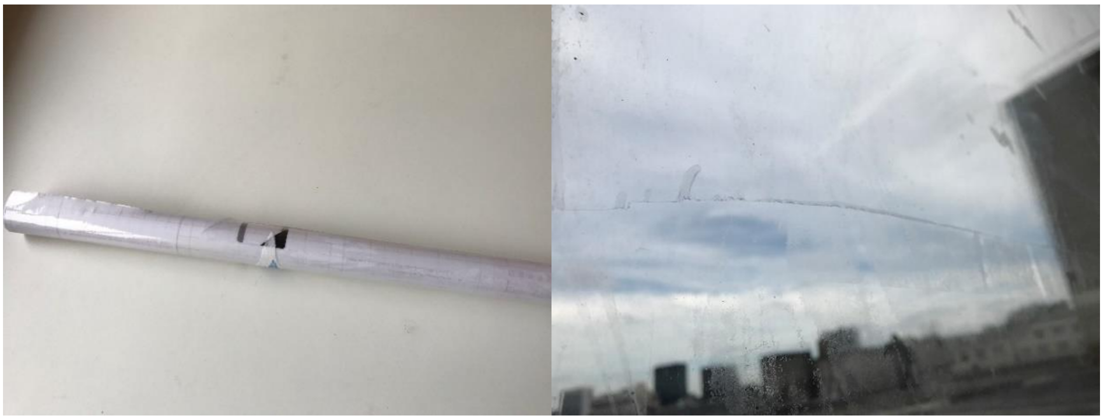


Figure 7- 8: Transparent window film (left) and a close look at the window glazing with the film applied (right)

The film became less noticeable when standing further away from the window, and from the experiment’s sitting position the applied window film was hardly noticeable (*Figure 7- 9*).

Figure 7- 9: The window film became less noticeable from further away

A white gloss wood & metal paint was applied to some of the room surfaces. Considering the workload and feasibility the ceiling was not painted, and the carpet flooring also remained unchanged. The painted surfaces include:

- All wooden partitions
- Bookshelf panel (both sides)
- Desk panel

Only the selected surfaces in the “light space” were painted, and the corresponding surfaces in the “dark space” remained unchanged. All painted surfaces received two coats of paint to ensure a uniform colour coverage. The reflectance of the painted surfaces was measured and found to be approximately 0.88. *Figure 7- 10* shows the surfaces with painting in progress.

Figure 7- 10: Surface refurblishement in progress

Two chairs (black cotton fabric/black coated steel frame) were placed in each experiment space. One was for the study subject positioned at near the centre of the desk (1.8m away from the window), and the other was for the researcher positioned near the entrance (1.7m away from the subject’s sitting position). The reasons behind this sitting arrangement were that (a) the participant sitting in the middle of the room can have a relatively better sense of the whole space and (b) the researcher sitting at the corner can serve as a facial communication reference for facial modelling at the back of the room.

To make the experiment spaces look more like real ordinary workplaces and also to serve as references for observation, some decorations were added to both spaces. These extra decorations/objects include:

- Two pairs paintings separated and placed in each space (picked from a collection of architecture students’ design work, the paired paintings had the same theme/style and looked very much alike)
- Some “normal to find” objects on the bookshelf table, including a screwdriver, a hard hat, and two toy figures. Identical items were placed in both spaces.

- A pile of books and some hard copy documents placed on the desktop around the participant’s sitting position. All books/documents and the way they were placed on the desk was identical in both spaces.
- A laptop placed on the desktop at the participant’s sitting location. The same laptop was used for both spaces (when the session was finished in the first space, the laptop was then taken to the other space)
- A framed certificate, a notebook, a porcelain mug, an illuminance meter and some documents placed on the desktop around the researcher’s sitting position. All the objects were identical in both spaces.

Figure 7- 11 shows the location of all room objects in a plan view.

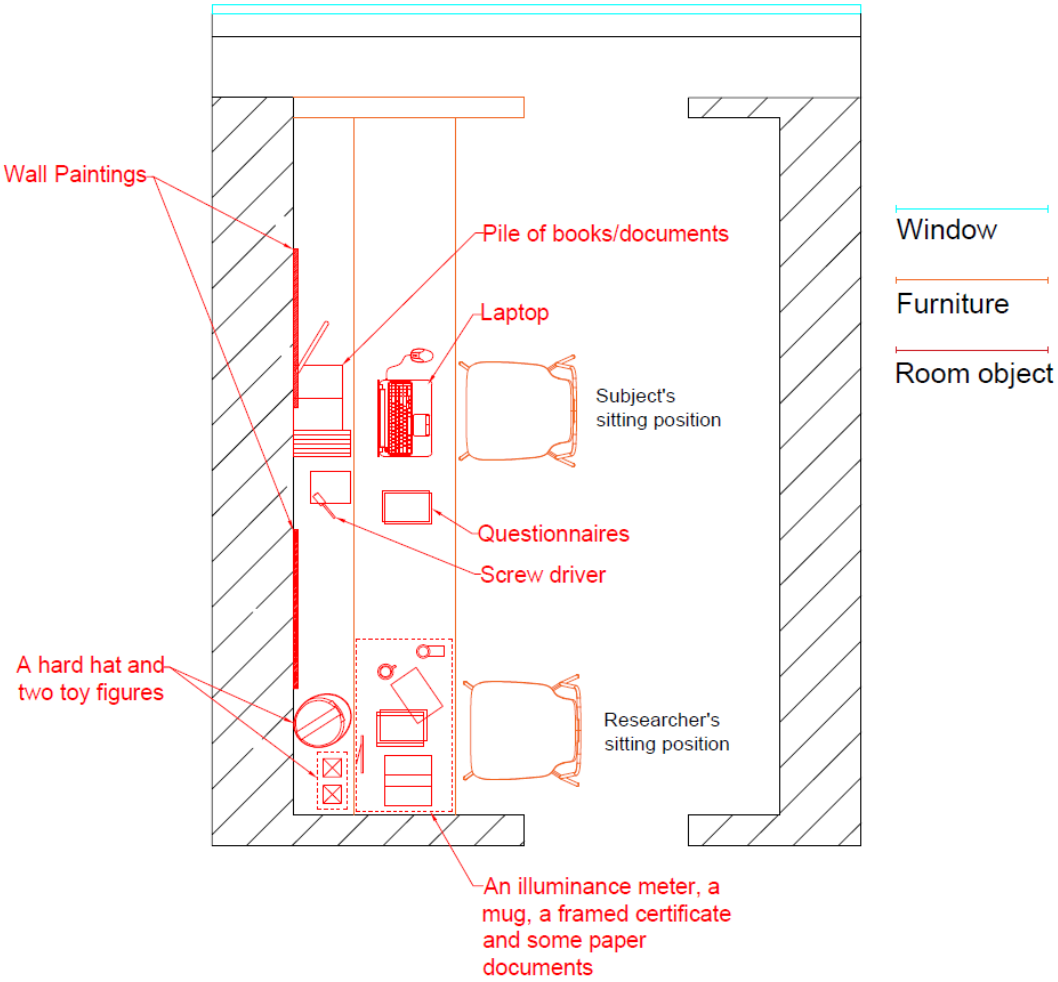


Figure 7- 11: Room objects and their locations (in a plan view)

Photos of the two experiment spaces were taken after the refurbishment. *Figure 7-12* shows the completed experiment setup of both “dark space” (left side in *Figure 7-12*) and “light space” (right side in *Figure 7- 12*) from different camera angles.

Figure 7- 12: The completed experiment setup of “dark space” (left) and “light space” (right)

7.2.2 Indoor daylighting measurements and calculations

7.2.2.1 Measurements of room surface illuminances:

To quantitatively analyse the indoor daylighting, illuminance measurements were taken during every experiment session. An illuminance meter (KONICA MINOLTA – T10) was used to record the luminous flux incident on various room surfaces, as listed below:

- Vertical illuminance at the centre of the window (interior side) – P1
- Horizontal illuminances across the working plane, measured at:
  - (a) the sitting area of the study participant – P6
  - (b) near the window – P2
  - (c) near the room entrance- P3
- Horizontal illuminance on the floor, measured at the centre of the room – P4
- Vertical illuminance on the centre of the partition wall – P5

Figure 7- 13 below indicates the locations (P1-6) where the indoor illuminances were measured.

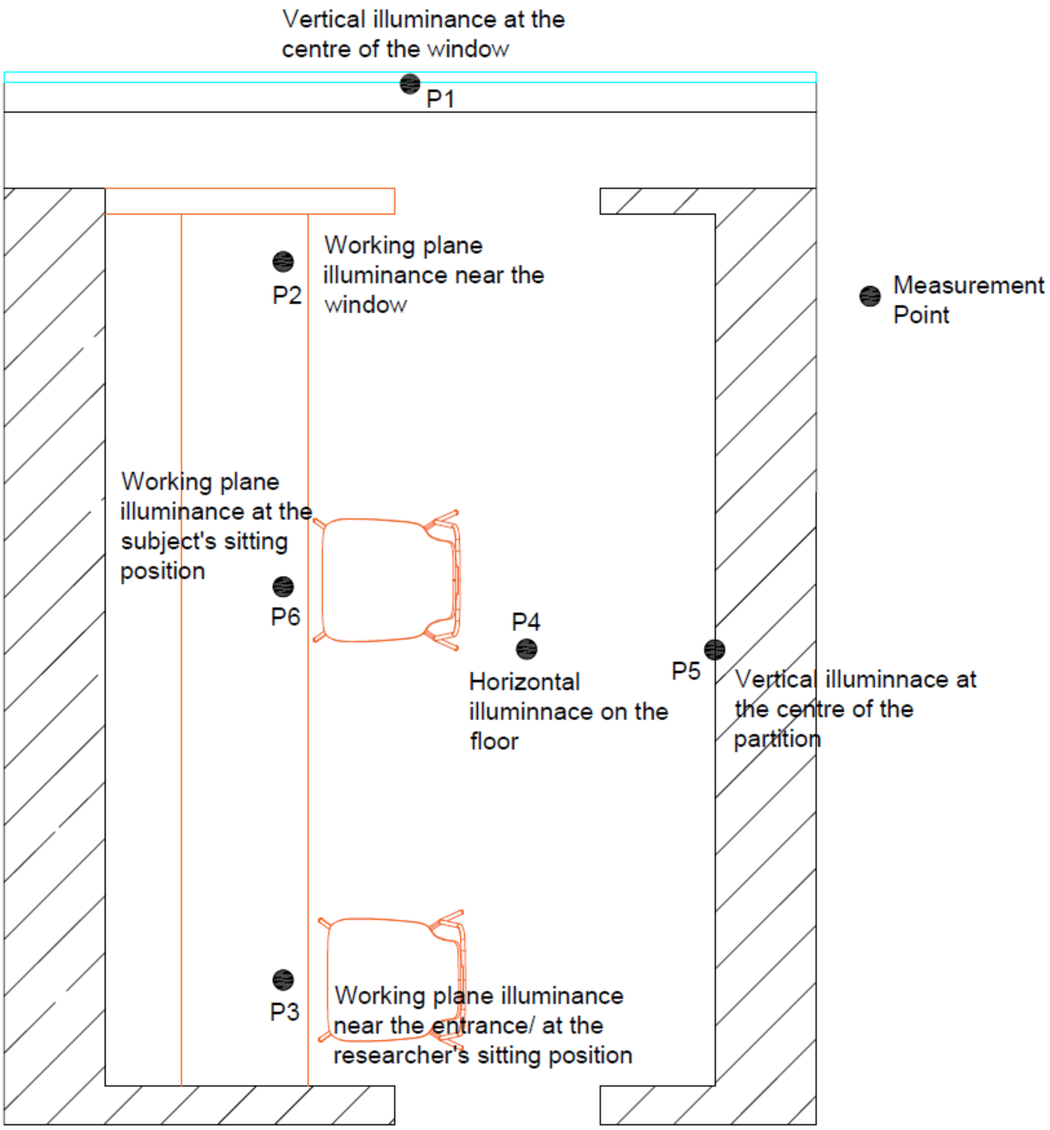


Figure 7- 13: The locations of the indoor illuminance measurements

7.2.2.2 Calculation of working plane illuminance

Since the majority of traditional daylight metrics are based on the horizontal working plane illuminance, this study compared the point and average working plane illuminance with the new metric MICI.

For the Point Working Plane Illuminance (E_P), it was measured directly at the sitting position of the study participants (measurement reading P6):

$$E_P = P_6 \qquad \text{Equation 33}$$

And for the Average Working Plane Illuminance (E_{Avg}), it was calculated by averaging the three measurement readings cross the whole desk (near the window/centre/near the entrance):

$$E_{Avg} = (P_2 + P_6 + P_3)/3 \qquad \text{Equation 34}$$

7.2.2.3 MICI calculation

Because MICI describes the indoor inter-reflected light flow and only considers the indirect component of illuminance, its direct measurement is practically very hard to achieve (this will be further discussed in Section 10.2). It was thus decided to use computer simulation to help in the assessment of MICI levels for the experiment spaces.

The experiment was conducted under various real weather conditions, however, there was no facility to capture the direct normal/horizontal irradiance/illuminance or the diffused horizontal irradiance/illuminance. The only measurements were the illuminance readings from the six indoor points (including one vertical illuminance reading measured at the centre of the window). Therefore, recreating the experiment scenes with real-time weather information was not possible for this study.

MICI is a function of the incoming flux, the room geometry and surface reflectance. The experiment sessions were only conducted in the afternoons to ensure the absence of the direct sunlight, therefore one significant factor that might greatly impact the indoor light flow was eliminated. Despite the differences in the distribution of sky luminance for different weather conditions, the sky flux entering the window can be considered relatively consistent in terms of its distribution. This, combined with the simple “box-like” geometry of the experiment spaces, made it reasonable to expect that the indoor average MICI value around the object’s sitting position was a function of the flux entering the window in each of the experimental spaces.

To test this theory radiance models of the two experiment spaces were put through a trial of Climate-Based Daylight Modelling (CBDM). The CBDM method was the same as used in the POE case studies (the same software and settings, refer to Table 6- 3 and Table 6- 4 in Section 6.2.2). The Radiance model of the experiment space was already established and validated in Section 7.2.1 of this chapter. The weather file used was The International Weather for Energy Calculation (IWEC) - 037760 for London Gatwick [93] (the closest weather data available). Eight points (on two planes of different heights) surrounding the subjects' sitting area were picked for calculating the average MICI, and inside this area is where the subject's head was positioned during the experiment (for detailed locations refer to *Figure 7- 14*). In addition, a calculation point was added at the centre of the window (the same position as the illuminance measurement point – P1) for estimating the total flux entering the window.

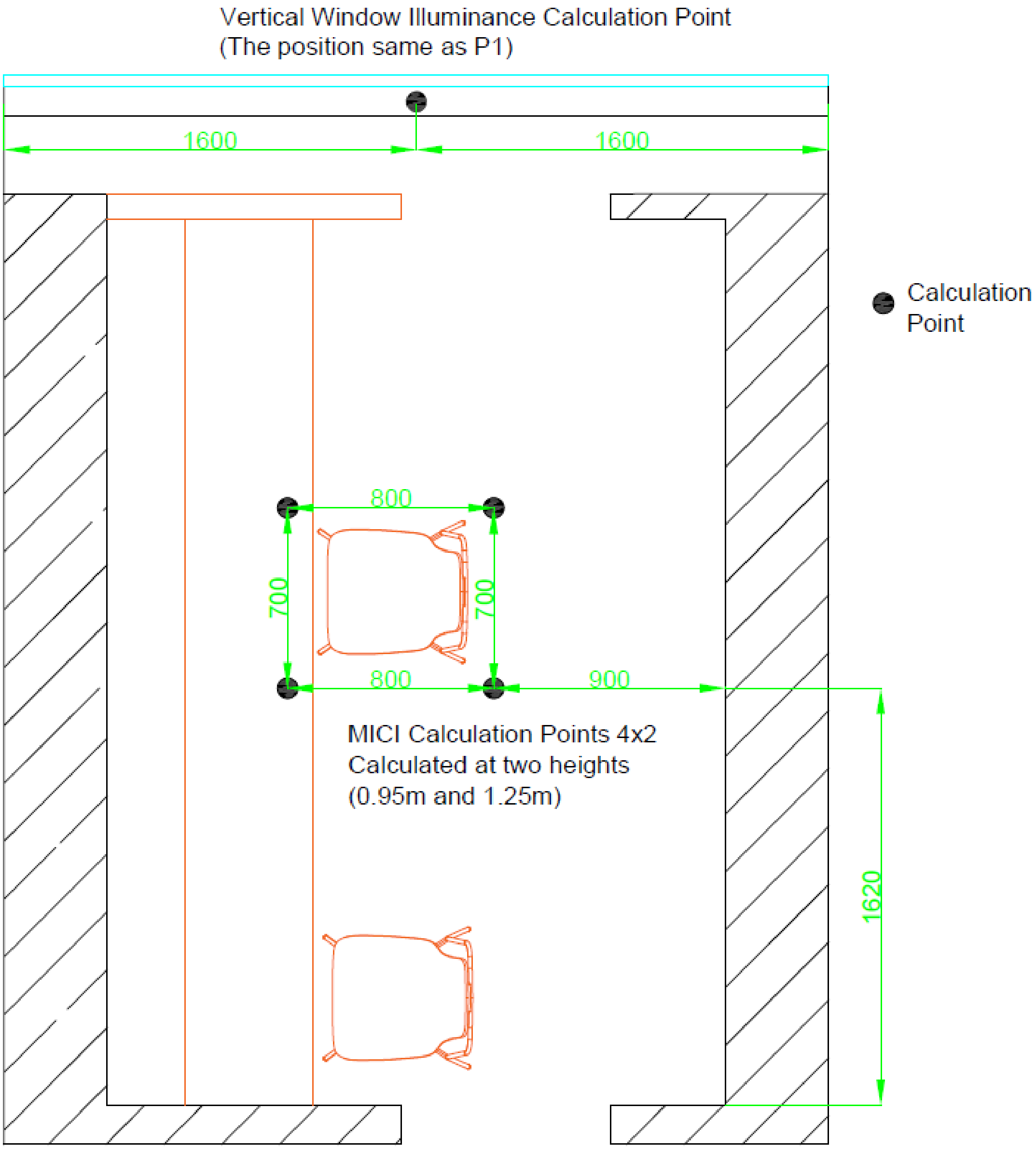


Figure 7- 14: Locations of calculation points for the CBDM simulation

The CBDM calculation was conducted for a whole year but only the hourly results for the time window between 13:00-16:00 (when the experiment sessions actually took place) were extracted for analysis. The calculated hourly average MICI values were then compared with the hourly corresponding window vertical illuminance values. *Figure 7- 15* below shows a plot of the average MICI against the vertical window illuminance for both the dark and light spaces.

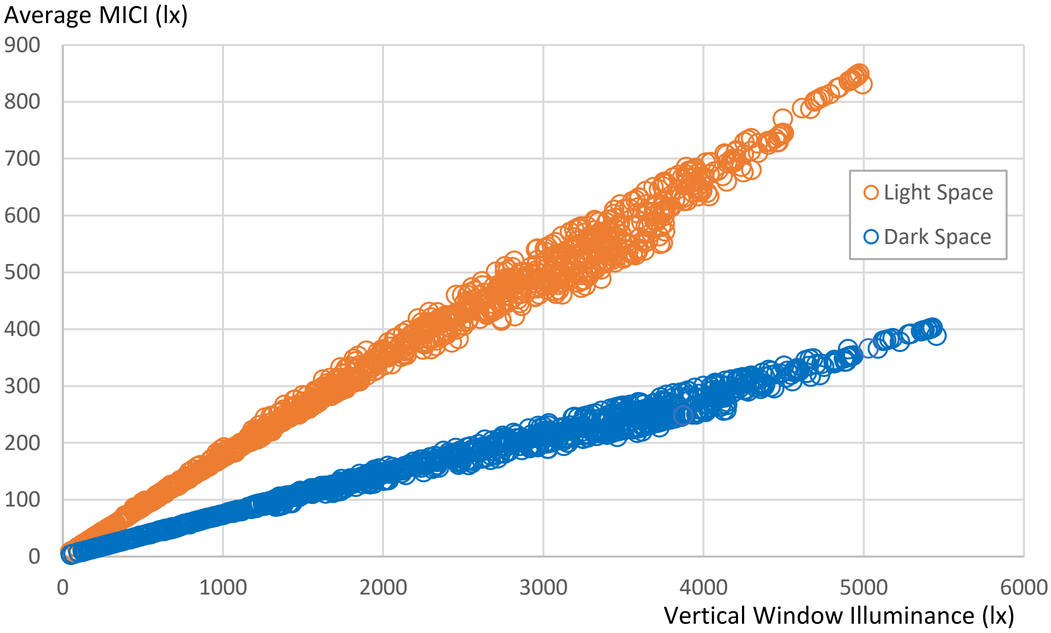


Figure 7- 15: Average MICI against the vertical window illuminance under CBDM (hourly results from 13:00-16:00 of an entire year) for the experiment spaces

Figure 7- 16 shows the average MICI against the window vertical illuminance of only 11th - 26th July (in the afternoon 13:00-16:00).

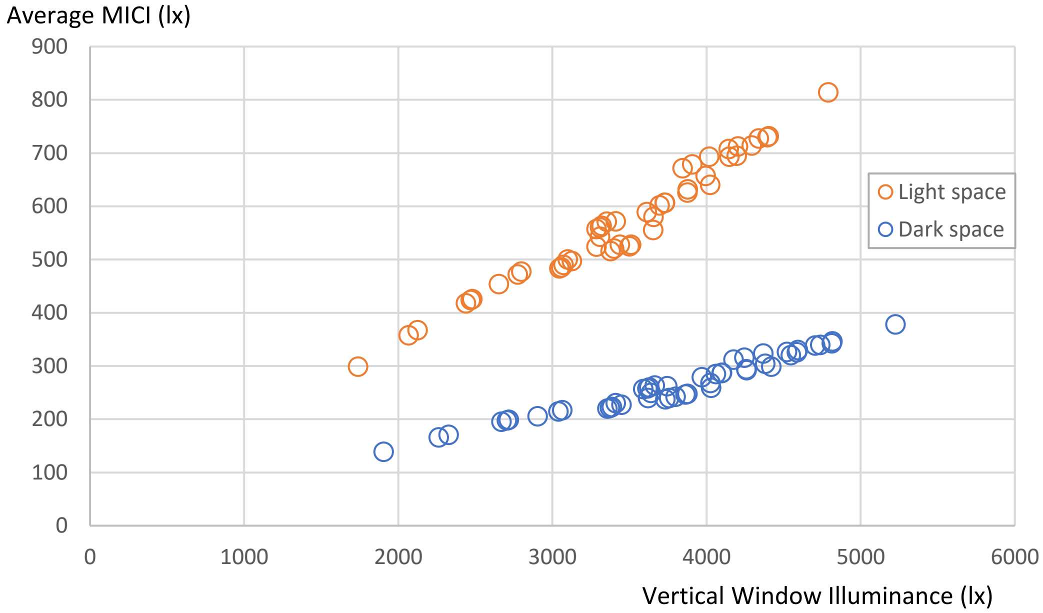


Figure 7- 16: Average MICI against the vertical window illuminance under CBDM (hourly results from 13:00-16:00 during 11th-26th July) for the experiment spaces

As a comparison, *Figure 7- 17* below shows the point working plane illuminance at the study subject’s sitting position against the vertical window illuminance in both experiment spaces (separated by colour) under the same CBDM test (hourly results from 13:00-16:00) for the whole year.

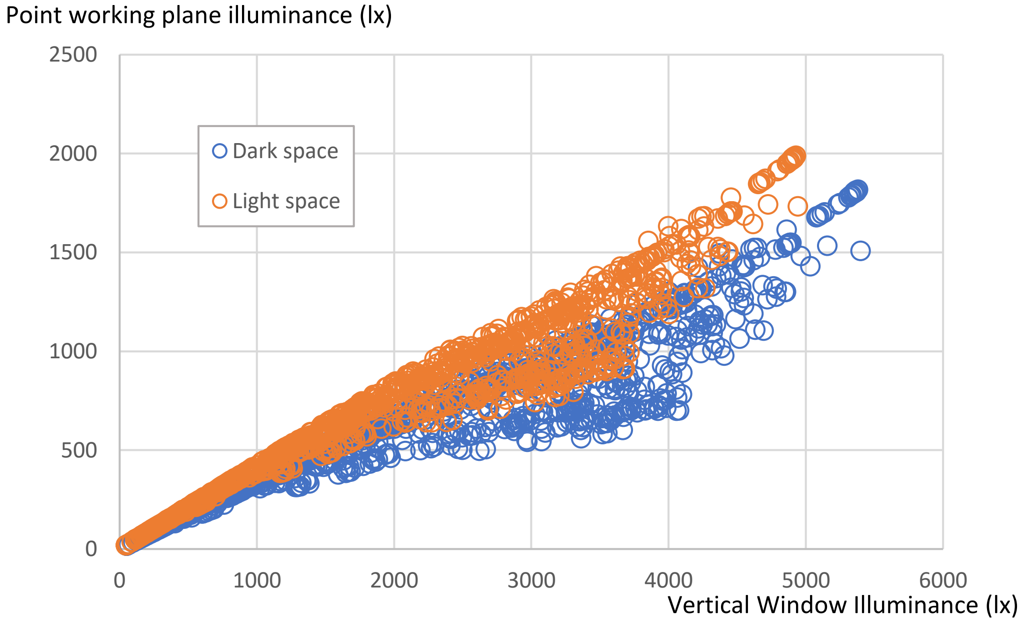


Figure 7- 17: Point working plane illuminance (at subject’s sitting position) against the vertical window illuminance under the CBDM test (hourly results from 13:00-16:00 of an entire year) for both experiment spaces

Figure 7- 18 shows the point working plane illuminance against the window vertical illuminance of only 11th -26th July (afternoon 13:00-16:00) for both experiment spaces.

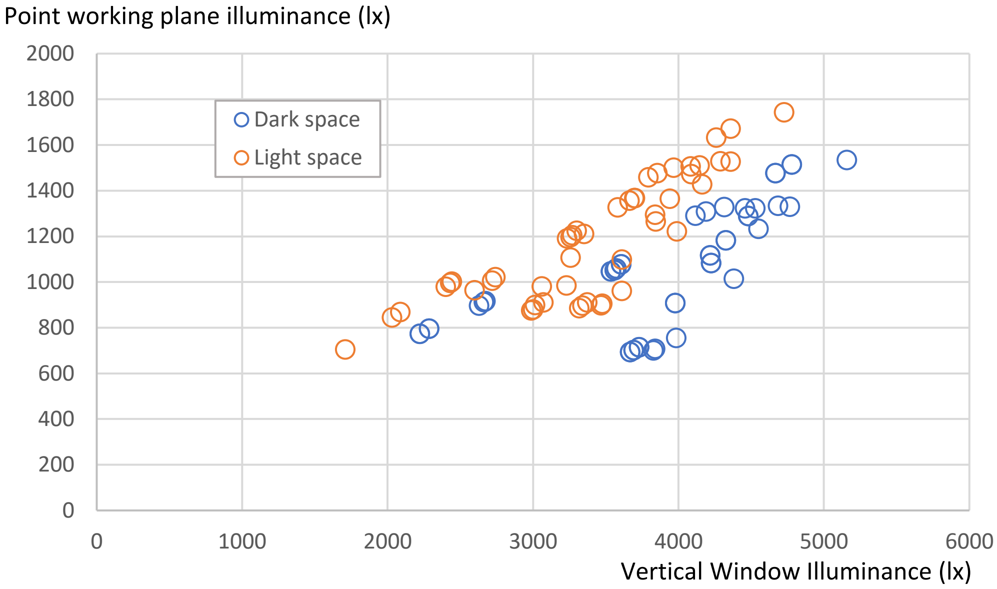


Figure 7- 18: Point working plane illuminance (at subject's sitting position) against the vertical window illuminance under the CBDM test (hourly results from 13:00-16:00 during 11th-26th July) for both experiment spaces

Figure 7- 17 and *Figure 7- 18* suggest that the window illuminance is a poor predictor of the working plan illuminance. Unlike MICI the changes of the sky luminance distribution due to different weather conditions will have a more significant impact on the working plane illuminances.

In analysing the data of the whole year for the time window 13:00 to 16:00 the mean ratio of the average MICI to the vertical window illuminance for the "dark space" was 7.19%, with a standard deviation of 0.0036 (meaning that the standard error due to different weather was only 5.09%). The mean ratio (between the average MICI and the window vertical illuminance) for the "light space" was 17.2% and the standard deviation of the mean is 0.0087 (standard error: 5.07%).

If only focusing on dates when the experiment took place (11th – 26th July), the mean ratio (average MICI and vertical window illuminance) for the "dark space" became 6.97% with a standard deviation of 0.0032 (standard error: 4.59%). For the "light space" the mean ratio was 16.48% with a standard deviation value of 0.0067 (standard error: 4.06%).

Table 7- 4 below gives a summary of the average MICI to the vertical window illuminance ratios:

Simulation time/Location		Mean ratio of average MICI (8 points) to the window vertical illuminance (R)	Standard deviation ($s_{\bar{x}}$)	Standard error ($\sigma_{\bar{x}}$)
13:00 – 16:00; the whole year	dark space	0.07189	0.00366	5.089%
	light space	0.17199	0.00872	5.067%
13:00 – 16:00; 11th – 26th July	dark space	**0.06970***	0.00320	4.592%
	light space	**0.16481***	0.00669	4.057%

* the ratio used to calculate the average MICI of the experiment spaces for this study

Table 7- 4: Summary of the CBDM test results

To further verify the MICI to window illuminance ratio, a manual calculation was conducted using Hopkinson's split flux method (discussed in Section 2.2.2). The calculated coefficient for calculating the average inter-reflected component of the illumination from the vertical window illuminance was 0.0596 for the "dark space" and 0.1618 for "light space". The calculation method is given in the Annex Two.

With a confidence level of 95%, it was therefore safe to conclude that the average MICI value around the object's sitting area is on scale with the vertical window illuminance for both experiment spaces. Hence for this study it was decided to calculate the average MICI of the subject's sitting area using the measured vertical window illuminance readings for the time that the experiment took place and the MICI to vertical window illuminance ratio as calculated in *Table 7- 4*. To test MICI in the most onerous way and better reflect the weather conditions during the experiment period, the average MICI to window vertical illuminance ratio used in the calculation was the one derived from the CBDM test for 13:00-16:00 during 11th to 26th of July, which is 0.06970 for the "dark space" and 0.16481 for the "light space".

Hence the average MICI at subject's desk was calculated by:

$$Avergae\ MICI = E_{P1} \cdot R \qquad \text{Equation 35}$$

Where $\mathrm{E_{P1}}$ is the vertical illuminance measured at position P1;

R is the ratio of average MICI to the window vertical illuminance (different for each experiment space), and it is given in *Table 7- 4*.

7.2.3 Questionnaire design

The design of the questionnaire was inspired by the BUS survey (introduced in Section 6.2.1). It used the same semantic differential scale of 1-7 asking subjects to rate the questions. The whole survey was developed centring around the question "what do you think of the daylighting in this room?".

The questionnaire consisted of 4 parts. The first part was just a brief introduction to the experiment, giving general instructions (on how to complete the questionnaire) and covering basic ethics (to make sure the participation is voluntary and anonymous). The information about the participants' gender and age range were also collected at this stage.

Before answering the second part of the questionnaire, the subjects were asked to sit down, take a good look around of the entire room, the view out and perform any office task they like (for instance reading books, web browsing using the computer, chatting with the researcher). The whole process took about 5 minutes, and then the subjects were instructed to complete the 2nd part of the questionnaire. This section covers the question "what do you think of the appearance of the room?", where the subjects needed to rate the room on aspects of "room decoration", "window view" and "how comfortable the room is as a working environment". In addition, subjects were encouraged to leave comments about their overall impression of the space. A list of adjectives[11] was also given to the subjects and they were free to tick out any word(s) that described their impressions.

---

[11] All the adjectives provided to the subjects to describe the room appearance were the same used in past research [105] [101] [106]

The purpose of this section was to get some understanding of the subject' impression of the room. Although the experiment spaces were initially used as offices, they have been completely emptied and gone through some surface changes. As an extraneous variable for the experiment, the aesthetic appearances of the rooms needed to be considered as similar as possible to each other. Subjects' feedback in this section was used to determine if the impacts from these variables (such as window views and room decorations) have been effectively minimised.

The third part of the questionnaire was essentially Rea's numerical comparison test [94]. The questionnaire included four pages of "stimulus sheets". These sheets each contained two sets of number list, one reference list and one response list. Each list had 54 rows in total and within each row numbers were spread as wide as possible. Numbers in the reference set were 5 digits long, all randomly generated using Excel Visual Basic Application (VBA) tools, the response set were mostly identical to the reference set except for few rows that the corresponding number had one different digit. These differences were also generated using an algorithm developed in EXCEL VBA, and their occurrences were random with a five percent chance of any given number pair being different. During the experiment, subjects were asked to "quickly and accurately" compare all pairs of numbers on the four sheets and mark out any differences on the response list. The time that each subject took to complete this test was recorded and their accuracy rates were calculated when the whole experiment was completed (no performance feedback was provided to the subjects during the experiment).

Adding Rea's task performance test to the experiment provided all subjects with a relatively intensive task to complete and extended the length of time they stayed in each room. It helped immerse subjects in the environment and fully adapt themselves to the room lighting before answering the questions on the next/final part of the questionnaire.

The last part of the questionnaire was the most important, as subjects' feedback on the room lighting were collected in this section. It began with the question "What do you think of the lighting in this whole room?", under which aspects of lighting were further divided into (under the following sequence):

- Uniformity
- Glare
- Visibility of objects in the room
- Visibility of computer screen
- Facial communication
- Daylighting
- The overall rating for the lighting

Subjects were instructed to rate all these specific lighting questions on a scale from 1 to 7, and some short explanative words were given at the bottom of the scales to indicate what exactly the two ends of the scale (number 1 and 7) stand for. For these questions it should be pointed out that the rating scales were reversed between questions. For instance, under question “Visibility of objects in the room” scale value 1 stands for “Clear/easy” and 7 stands for “Obscure/difficult”, whereas for the next question “Visibility of computer screen” value 1 becomes “Obscure/difficult” and 7 becomes “Clear/easy”. The purpose of this design was a precaution to reduce the possibility of the subjects becoming lazy towards the end of the experiment and starting to tick a constant rating value without much thinking. The researcher informed all study participants of this scale reversing design at the very beginning of each experiment.

The last question was “What do you think of this room as a (daily 9-5) workplace?”, and it was also rated on a 1-7 scale with 1 being “Dislike” and 7 being “Like”. After the question, space was also given for any further comment regarding the subject’s opinion of the space as a daily workplace.

A complete set of the questionnaire is given in Annex Three.

7.2.4 Experimental procedures

The experiment was designed for one participant per session, and each session used exactly the same tests conducted in both “light space” and “dark space”. The order in which spaces were firstly tested was randomised. That is, some sessions started with the “light space” and some sessions started with the “dark space”. Every session took approximately 40 minutes to complete, and the procedure was as follows:

Table 7- 5 gives a summary of all the experiment steps. Note that the time for each step stated in *Table 7- 5* is the accumulated minutes.

1	2	3	4	5	6	7	8
Experiment preparation	Starting experiment	Room appearance appraisal	Task performance test	Completing questionnaire	Changing experiment space	Repeat of steps 3 to 5	Completing experiment
N/A	0-3 min	3-8 min	8-15 min	15-20 min	20-23 min	23-40 min	N/A

Table 7- 5: Summary of the experiment steps

(1) Preparing for the experiment

The researcher set up the experiment spaces prior to the arrival of study participants. Then the light levels in both cells were checked. The cells were designed to meet a desired lighting condition, that is with relatively similar working plane illuminance but different MICI). The readings of the horizontal illuminances on the desks should be relatively close (with a margin of less than 100 lux) in the two experimental spaces.

The room arrangement also needed to be checked. All objects (as references of observation) placed in the two rooms needed to be in the correct position, and the desktop items including all books, papers and the laptop needed to be identical. The screen brightness of the laptop was set to the same level (Windows 10 Display Setting: automatic mode - off, screen brightness - 100%, night light mode - off).

(2) Starting the experiment

Upon arrival, the subject was directly taken into one of the experiment spaces (without seeing the other experiment space). After the subject was comfortably seated, the researcher would ask the subject to look around the room freely, then gave out the questionnaire and talked through some of the key points that needed attention during the experiment (such as the reversed scales on the questionnaire). Then the subject would read and complete the first part of the questionnaire (experiment introduction, study ethics checks & gender/age information).

At this stage the researcher would record the illuminance levels of the space (as explained in Section 5.2.2.1) and then sat at the designated position (as shown in Figure 7- 11) and remained in the same position for the rest of the experiment (so as not to disrupt the indoor daylight distribution and also to serve as a reference for facial modelling).

(3) Room appearance appraisal – space 1

Before starting the second part of the questionnaire, the researcher asked the subject to perform the office task of their choice. It could be very basic office task such as reading one of the books placed on the desk, using the laptop (checking emails/web-browsing/reviewing documents et cetera), writing/scribbling on the paper, chatting/communicating with the researcher or even multi-tasking.

After around 5 minutes of trying out different office tasks and being fully immersed in the created environment, the subject was then instructed to complete the second part of the questionnaire.

(4) Task performance test – space 1

After completing the second part of the questionnaire, three pages of the task performance “stimulus sheets” were then given to the subject. It was a timed test, and the researcher was responsible for setting up the timer. During the test, the researcher stayed quiet and did not disrupt the subject. The subject was expected to complete the test in his/her own pace but been told in a “quickly and accurately” manner. Normally this test took 4-7 minutes.

(5) Completing the questionnaire – space 1

The last part of the questionnaire was quite straightforward. At this stage, the subject was expected to have fully adapted to the lighting and have a good grasp of the indoor daylighting to give confident opinions. The subject would follow the instructions on the questionnaire and finish all the remaining survey questions. This normally took 3-5 minutes.

(6) Changing the experiment space

When the subject finished the questionnaire, the researcher would collect the documents and then took the subject to the next experiment space. Like in Stage (2) the subject was asked to sit and freely look around the room while the researcher was giving out another copy of the questionnaire (identical to the one completed in the previous experiment space) and taking the illuminance measurements.

(7) Repeating the same tests – space 2

This stage mirrors Stage (3) to (5) but take place in the second experimental space. Both the researcher and the subject accordingly repeated the same tasks as conducted in the Stage (3), (4) and (5).

(8) Completing the experiment/preparing for the next session

The researcher collected all the documents and informed the subject that the experiment had been completed. When the subject left, the researcher then cleaned up and reset the desk space preparing for the next session.

7.2.5 Conducting the experiment

The experiments were conducted between the 11th to 26th of July 2017, and sessions were only conducted in the afternoon from 13:00 to 16:00 (to avoid direct sunlight). Various weather conditions occurred during the experiment days and the experiment spaces were illuminated by clear, intermediate and completely overcast skies (*Figure 7- 19*).

Figure 7- 19: Different weather conditions during the experiment

In total 31 people participated the experiment, among them 20 were females and 11 were males. 24 participants were in the age group of 18-25 years old, 6 participants were 25-40 years old and 1 participant was 40-60 years old. Participants were mostly undergraduate/master students with various backgrounds including architecture, product design, engineering et cetera.

7.3 Experiment results

7.3.1 Questionnaire feedback

After the completion of the experiment sessions, all questionnaire data were transferred to a spreadsheet. Note for simplicity the score scales used in the analysis were always with the worst condition being given the value of 1 and the best condition being given a value of 7. As the direction of the scales on the questionnaire had been randomised this meant that some of the recorded responses were reversed prior to analysis.

7.3.1.1 Questionnaire - room appearance

Figure 7- 20, *Figure 7- 21* and *Figure 7- 22* show the participants' responses over the different aspects of the room appearance (Question: "What do you think of the appearance of this room?" - decoration, window view & comfort as workplace).

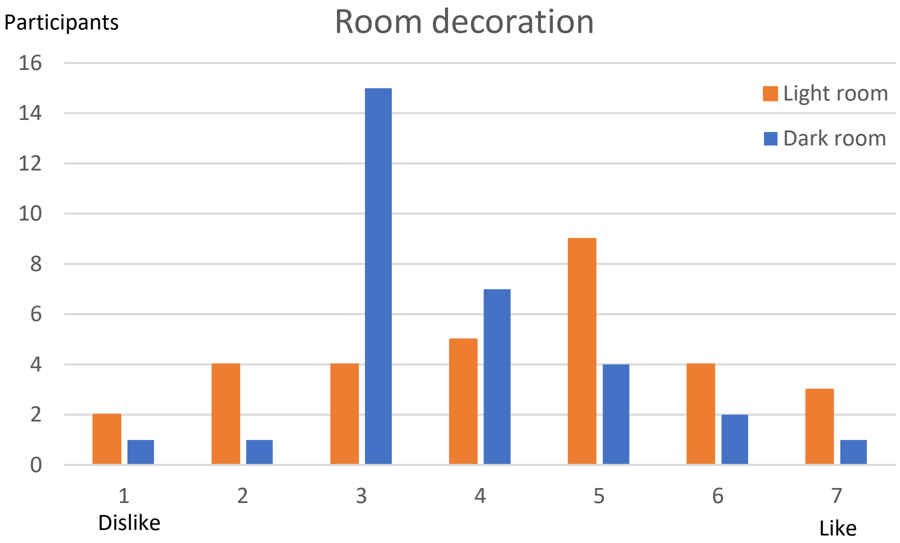


Figure 7- 20: Participants’ ratings over the room decoration

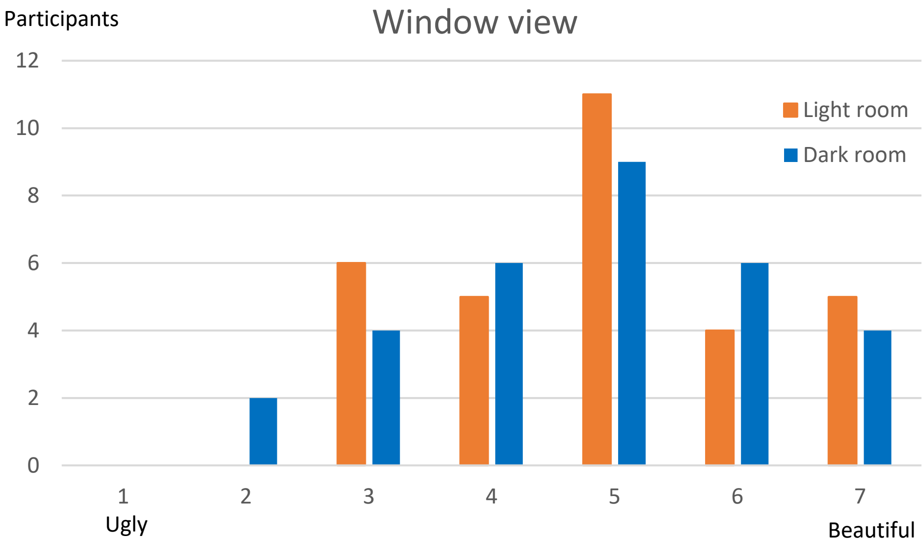


Figure 7- 21: Participants’ ratings over the two rooms’ view out

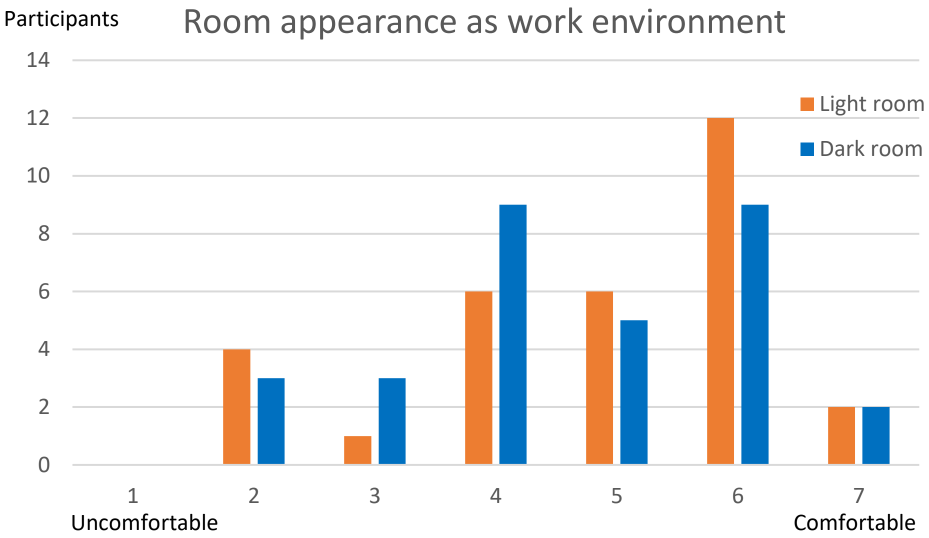


Figure 7- 22: Participants’ ratings over comfortability of the room as a workplace

Looking at each participant’s rating of the two spaces (*Figure 7- 23*), 7 subjects (23%) thought that the decoration of the two experiment spaces were identical (having given the same rating); 11 subjects (35%) thought that the room decorations were closely similar (ratings with difference of only 1 point); 9 subjects (29%) thought that the room decorations were to some degree similar (ratings with difference of 2 scale points); 4 subjects (13%) thought that the room decorations were quite different (ratings with difference of 3 or more scale points).

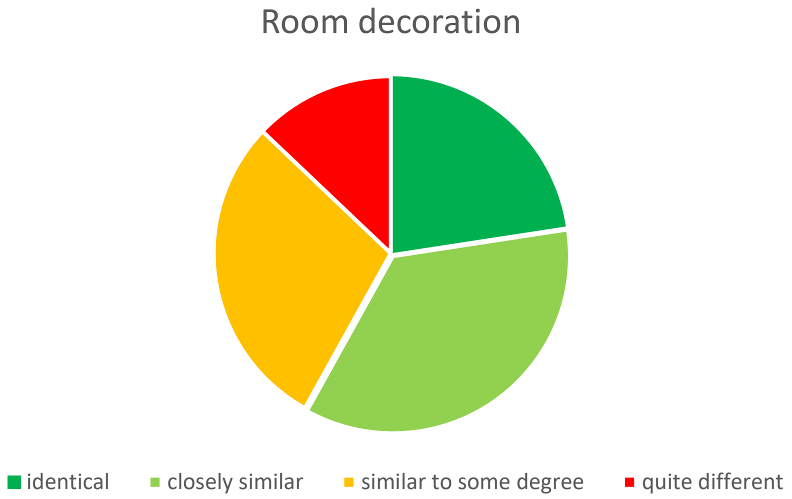


Figure 7- 23: Comparing each subject’s rating of the room decoration of the two spaces

In terms of the window view (*Figure 7- 24*), 24 subjects (78%) thought that the view outside from the two rooms were identical (have given the same rating); 5 subjects (16%) thought that views were closely similar (different by only 1 rating scale); 2 subjects (6%) thought that views were to some degree similar (ratings with difference of 2 scale points); no subject gave view ratings with 3 or more scale points of difference.

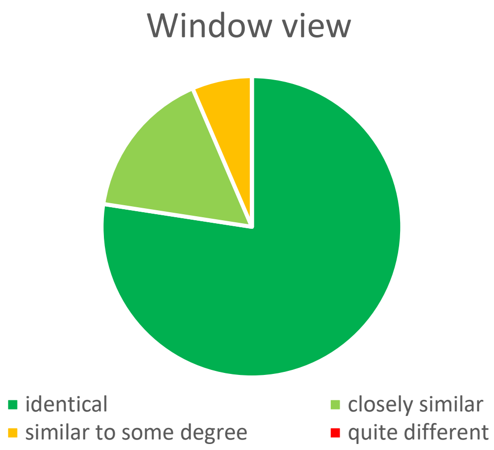


Figure 7- 24: Comparing each subject's rating of the window view of the two spaces

For "considering the room appearances as working environment" (*Figure 7- 25*), 12 subjects (39%) thought that the two experiment spaces' appearances were equally comfortable (had given the same rating); 8 subjects (26%) thought that the two spaces were closely similar (different by only 1 rating scale); 4 subjects (13%) thought that the two spaces were too some degree similar (ratings with difference of 2 scale points); 7 subjects (22%) thought that the two spaces were quite different (ratings with difference of 3 or more scale points).

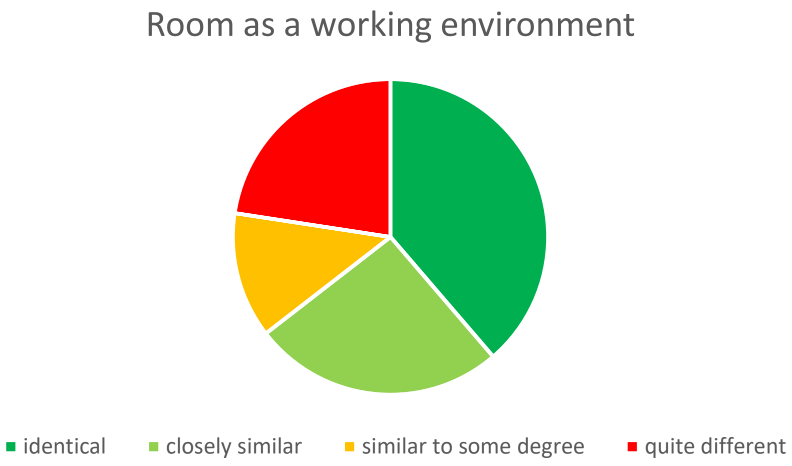


Figure 7- 25: Comparing each subject's rating of "room as a working environment" of the two spaces

A key word analysis was conducted for the subjects’ comments of the general room appearance (either their own or picked form the “list of adjectives”). The most frequently appearing words and the number of times they have appeared for the “light space” and the “dark space” were given in *Table 7- 6*.

For the “light space”	
Frequently appearing key word:	Number of subjects who mentioned/ticked this key word
“Bright”	22
“Simple”	11
“Spacious”	10
“Uniform”	10
For the “dark space”	
Frequently appearing key word:	Number of subjects who mentioned/ticked this key word
“dim/gloomy”	12
“comfortable”	8
“Simple”	6
“Enclosed”	6
“Non-uniform”	6

Table 7- 6: The key words from subjects’ comments (for the question: “Any impression of the room?”)

7.3.1.2 Questionnaire – task performance test

Rea’s numerical comparison test was given to the subjects so that they all carried a similar set of visual tasks in the visual environment of the simulated offices. All subjects were able to complete this task in a period of 3 to 5 minutes. The results of the task were not analysed in detail as it was not the objective of this experiment to check visual performance. The only noticeable finding was that subjects were quicker at doing the test in the second room (whichever experiment space that is tested latter).

7.3.1.3 Questionnaire – lighting in the space

For the question “What do you think of the lighting in this whole room?”, *Figure 7- 26* to *Figure 7- 33* shows the subjects’ responses on different aspects of the lighting for the two experimental spaces.

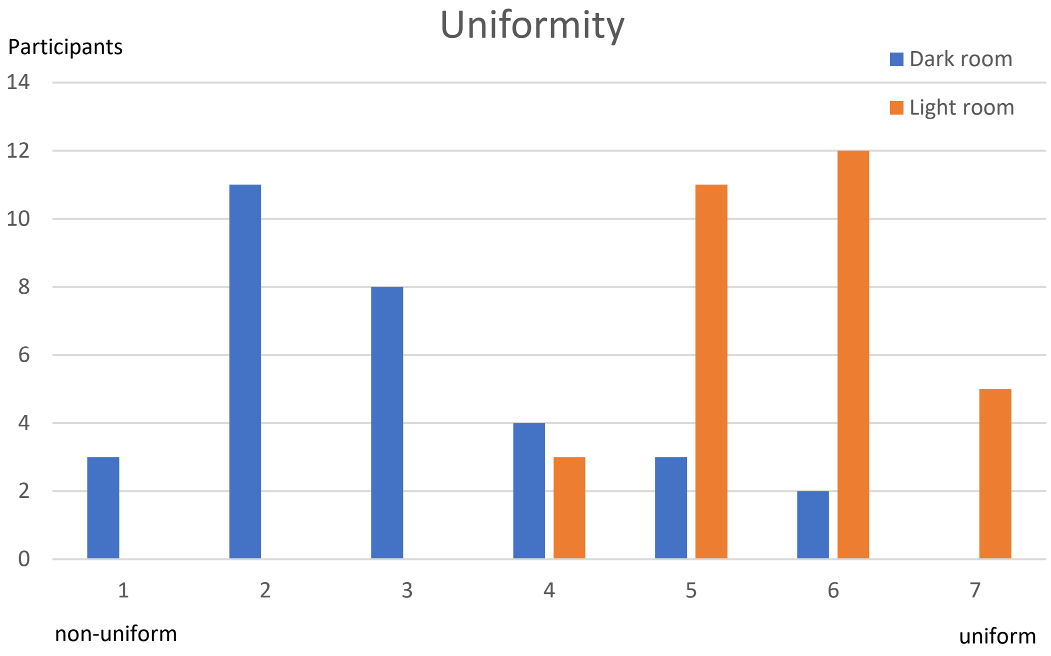


Figure 7- 26: Subject responses on the lighting uniformity

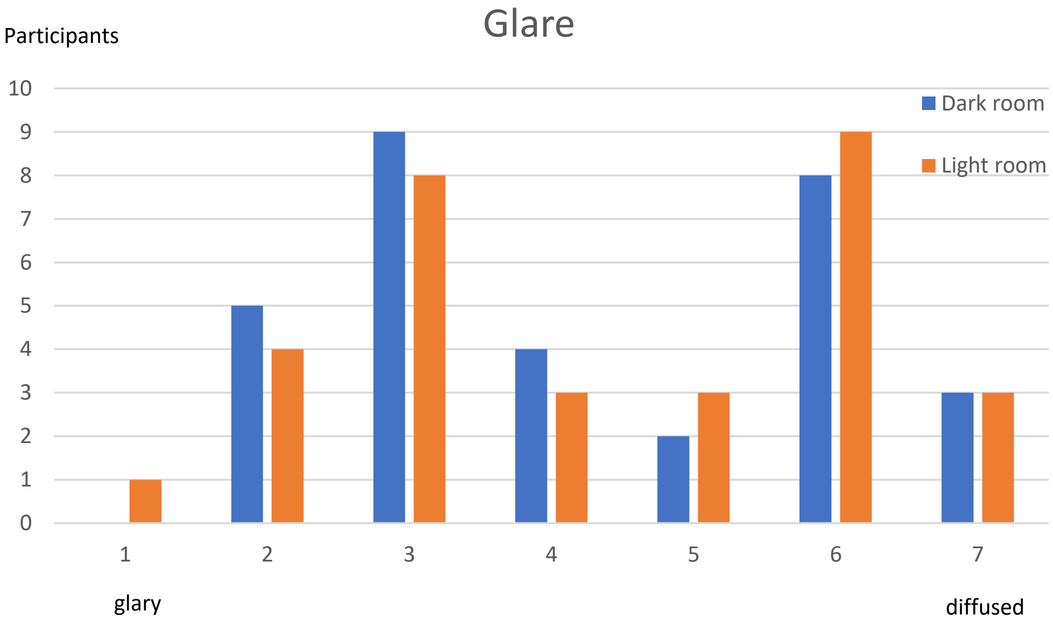


Figure 7- 27: Subject responses on the daylighting glare

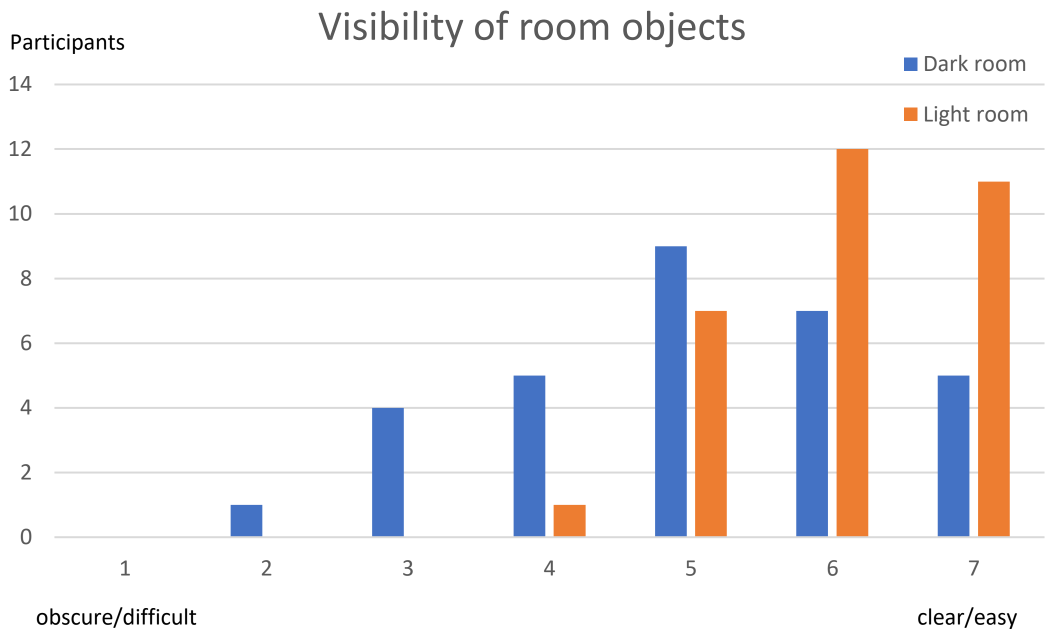


Figure 7- 28: Subject responses on the visibility of room objects

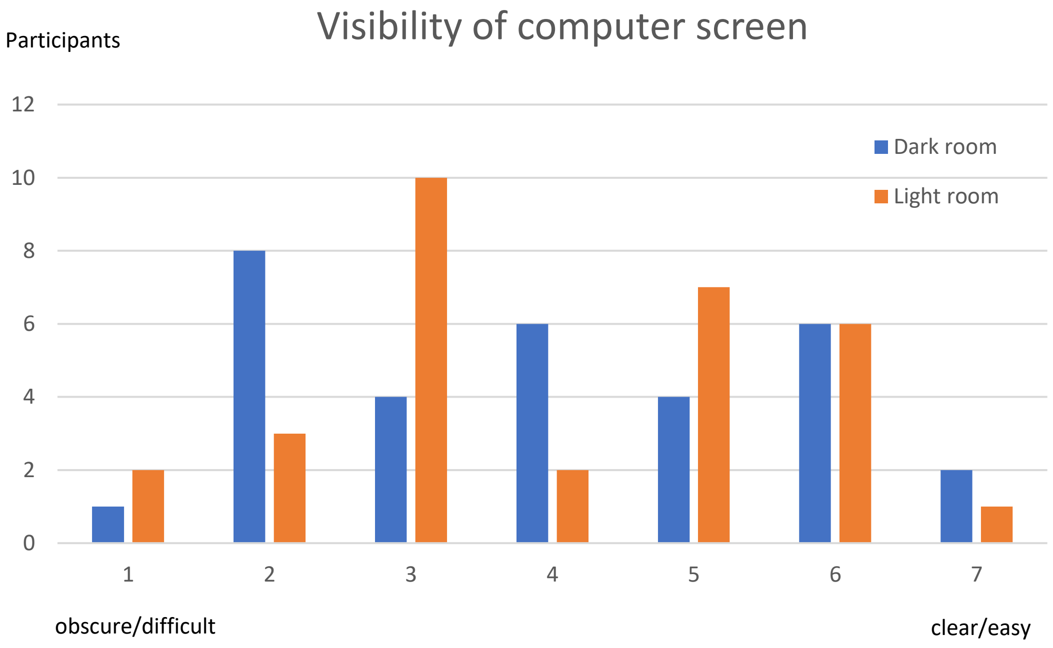


Figure 7- 29: Subject responses on the visibility of computer screen

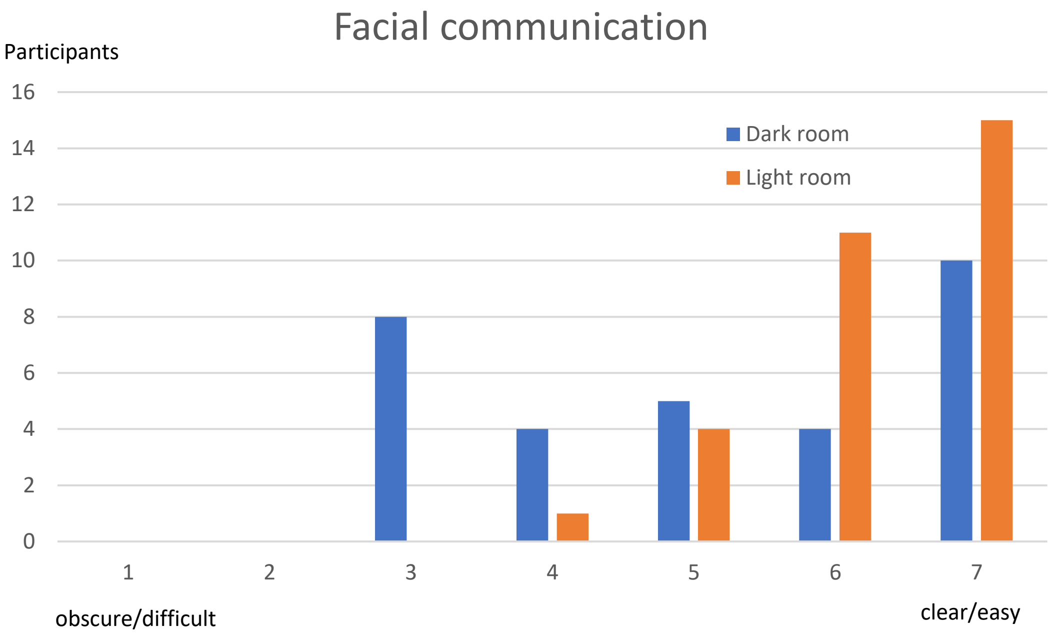


Figure 7- 30: Subject responses on the facial communication

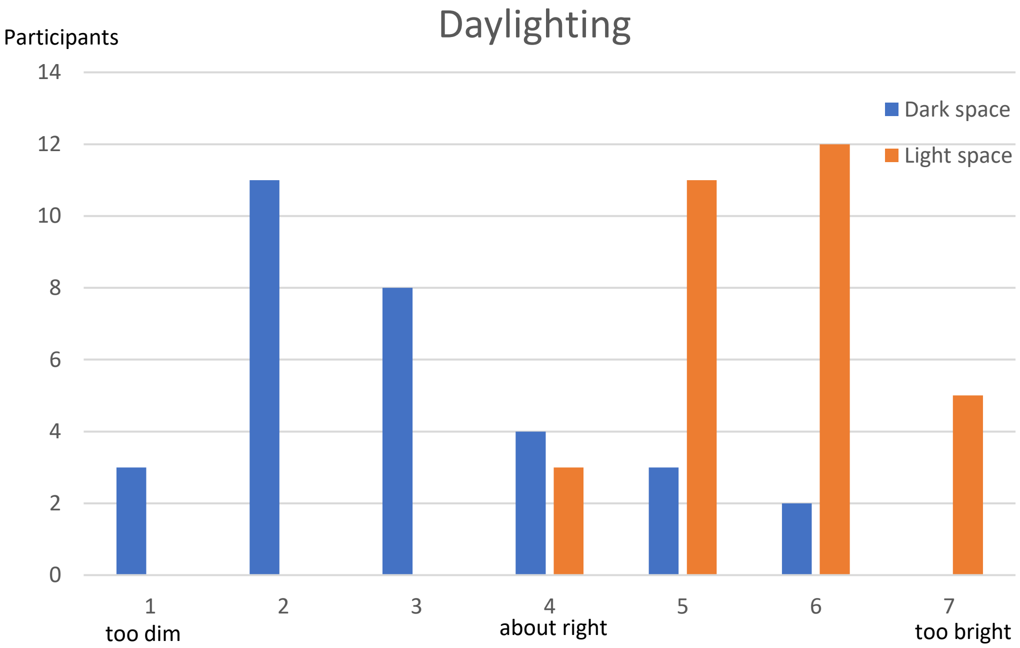


Figure 7- 31: Subject responses on the daylight adequacy

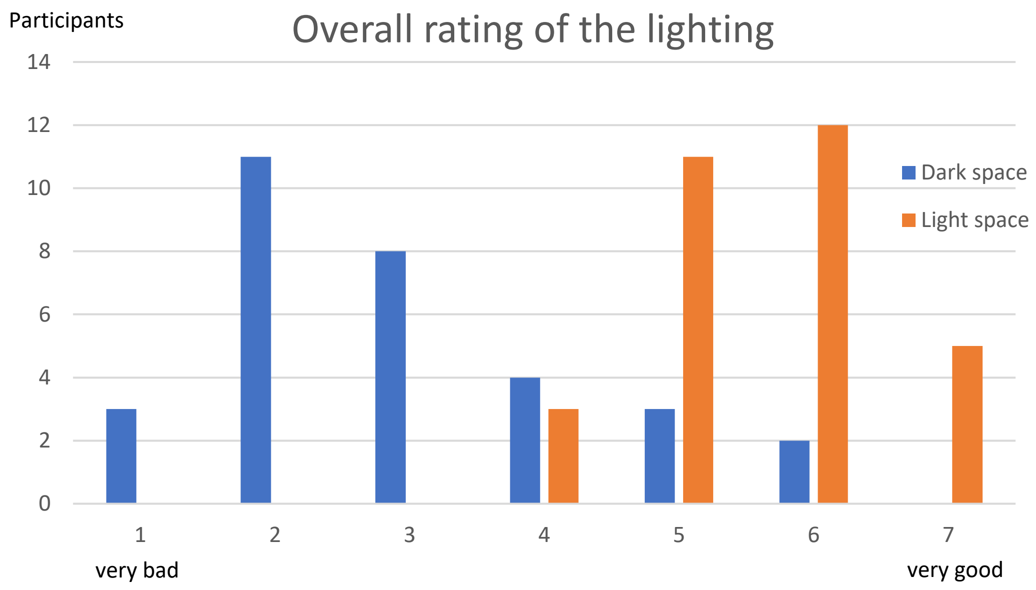


Figure 7- 32: Subject responses on the overall lighting quality

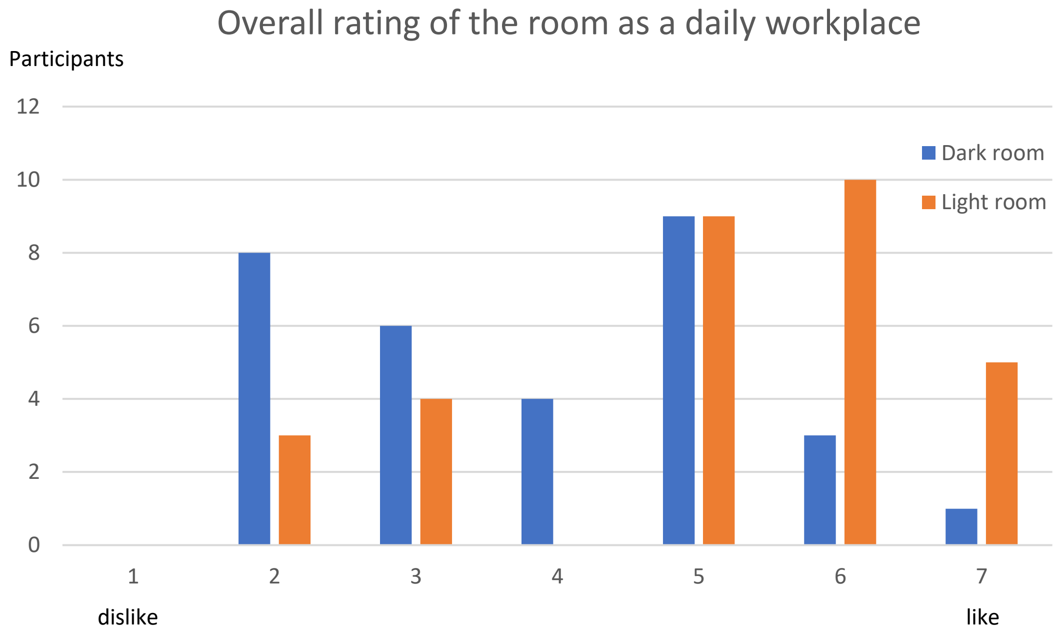


Figure 7- 33: Subject responses on “the room as a daily (9-5) workplace”

Figure 7- 26 to *Figure 7- 33* suggest that the distribution of the subject response data on the different aspects of lighting are all non-normal (non-Gausian). The results will be further reviewed in the analysis section (Section 7.4).

7.3.2 Daylighting measurements and calculation results

The illuminance measurements at each specified point and the calculated MICI values for every session are given in *Table 7- 7* below:

Session	Dark Space							Light Space						
	P1	P2	P3	P4	P5	P6	MICI	P1	P2	P3	P4	P5	P6	MICI
1	3732	2367	255	876	452	910	260	2830	1766	446	563	546	910	466
2	2170	2017	169	564	392	685	151	1983	1454	328	595	318	683	327
3	5575	3900	293	1293	425	1560	389	4460	3700	584	1421	425	1546	735
4	5820	4112	315	1270	478	1591	406	4501	3689	577	1098	403	1438	742
5	4218	2152	168	580	481	816	294	3965	1600	521	873	710	920	653
6	4142	2111	166	581	460	800	289	4223	1652	519	855	731	912	696
7	6150	2100	69	227	119	1349	429	5875	1839	351	484	286	1298	968
8	5395	2238	74	235	133	1210	376	5723	1822	346	488	271	1252	943
9	5500	2600	205	415	431	1228	383	4950	1900	295	513	501	1156	816
10	5468	2455	212	415	421	1174	381	4938	1913	288	497	510	1140	814
11	2035	1810	103	413	165	462	142	2108	1709	280	643	392	469	347
12	2219	1902	145	462	171	451	155	2115	1721	299	613	385	482	349
13	3012	3680	200	1102	288	984	210	2925	3660	342	801	457	973	482
14	3253	3677	211	1085	307	982	227	2865	3233	329	784	436	970	472
15	4200	4900	175	800	455	972	293	3165	3760	327	423	772	1024	522
16	4150	4875	175	788	437	968	289	3165	3685	325	431	769	1026	522
17	4203	4677	165	771	426	958	293	2995	3619	317	418	755	1007	494
18	3455	4050	184	668	347	934	241	2895	2950	405	552	429	910	477
19	2560	2500	247	396	321	965	178	2300	2136	472	660	401	917	379
20	2198	1847	183	495	303	875	153	2053	1546	329	589	357	815	338
21	1830	1882	124	473	257	588	128	1563	1709	284	498	403	551	258
22	2764	1923	218	574	473	798	193	2285	1612	454	610	593	787	377
23	2810	1889	224	559	461	778	196	2313	1635	453	612	588	793	381
24	2008	1982	138	624	397	648	140	1958	1691	364	658	397	614	323
25	1588	869	72	227	113	360	111	1528	710	274	547	325	431	252
26	1669	871	85	233	124	368	116	1810	769	286	533	320	449	298
27	2190	1100	264	354	545	704	153	2060	1125	442	415	542	652	340
28	2845	2780	267	542	445	988	198	2580	2329	495	684	548	979	425
29	2762	1502	219	482	644	754	193	2635	1357	509	503	544	770	434
30	2628	2620	262	685	547	766	183	2473	1931	513	633	511	742	408
31	3080	2949	257	870	450	781	215	2468	2069	551	598	520	767	407

Table 7- 7: Illuminance measurements and the calculated MICI for every experiment session

Measurement points P1-P6 are shown in Section 7.2.2.1 of this chapter.

MICI: the average MICI value of the close to the subject, refer to Section 7.2.2.3 for details of the calculation method.

7.4 Results analysis and discussion

7.4.1 On the data analysis methods

To examine which of the daylight metrics, MICI or working plane illuminances, could be best used to predict the response of the subjects in this experiment, correlation analyses were conducted.

All the subject responses were plotted on scatter diagrams for preliminary analysis (checking the general trends and any possible outliers) against all the daylight metrics. If a potential relationship was observed between the variables, the data was further analysed in IBM SPSS software by running more detailed statistic tests. The version of SPSS used in this study was IBM SPSS Statistics V25.

The distribution of the data was investigated in SPSS using various statistical and graphical methods, including measures of central tendency, skewness/kurtosis, frequency histograms, box and whisker plots. It was found that all the data in this study were not normally distributed, therefore non-parametric statistical tests were applied for all the correlation analyses.

Considering the non-parametric data and the relatively small sample size (62), Kendall's Tau was selected for the correlation tests [95]. The variation of Kendall's Tau coefficient used in SPSS is Tau-b. Values of Tau-b range from -1 (100% negative association) to 1 (100% positive association), and a value of 0 means the variables have no association. Two-tailed significance values (p) were reported for the statistical significance in all the Kendall's Tau correlation tests, and for this study a correlation would be considered significant if the significance value was smaller than 0.05. This was the same method as used for the analysis in Chapter Four.

7.4.2 Daylight metrics vs Daylight adequacy responses

One of the key relationships that this study was trying to investigate was between the daylight metrics and the subjects' perception of daylight adequacy. Figure 7- 34 below plotted the Average MICI results against subjects' response ratings of daylight adequacy (1- too dim; 7- too bright). The scatter diagram revealed that it appeared to be a linear relationship between the two variables. When the Average MICI increased and so did subject's rating for daylight availability. Applying a linear regression line to the plot indicated a strong correlation between the average MICI and the response rating for daylight adequacy, with a fitting coefficient R^2 of around 0.74.

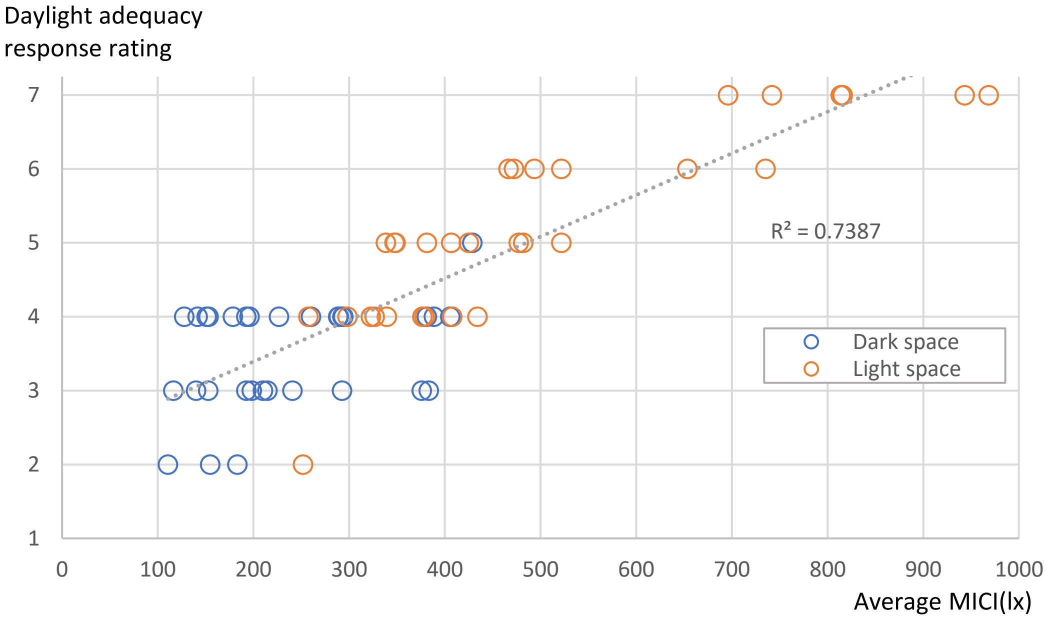


Figure 7- 34: Subjects' responses of daylight adequacy vs average MICI

Applying the Kendall rank correlation to the average MICI and the daylight adequacy response rating also produced a strong correlation between the two items, with a Kendall's Tau correlation coefficient (t) of 0.676 which was significant at p very close to zero (Table 7- 8).

Kendall's Tau-b (t)	0.676
Significance (p)	1.2829E-12
Sample size (N)	62

Table 7- 8: Kendall's Tau correlation coefficient describing the relationship between the average MICI and the subjects' response of daylight adequacy

The same analyses were repeated to investigate the relationship between point working plane illuminance (measured at the subject's sitting position) and the subjects' responses of daylight adequacy. The scatter plot of the two variables is shown in Figure 7- 35. Subject's response (1- too dim; 7-too bright) tended to rise with the increase in the point working plane illuminance value, however their relationship was not as strong as the relationship between the subject's response to the average MICI. A linear regression line was fitted to the plot, which suggested that the point working plane illuminance had a substantially weaker correlation with people's responses (R^2 = 0.211).

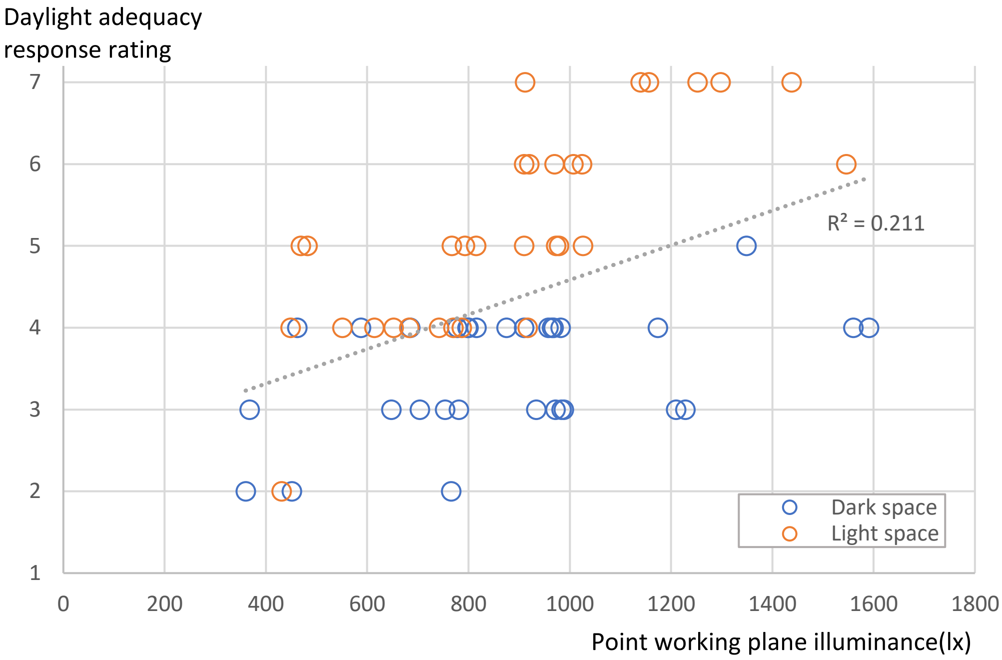


Figure 7- 35: Subjects' responses of daylight adequacy vs point working plane illuminance

Applying the Kendall's Tau correlation also indicated that although the pointed working plane illuminance and the subject's rating for daylight adequacy was correlated, the association between the two was relatively weak (Table 7- 9).

Kendall's Tau-b (t)	0.328
Significance (p)	0.001
Sample size (N)	62

Table 7- 9: Kendall's Tau correlation coefficient describing the relationship between the point working plane illuminance and the subject's response of daylight adequacy

The relationship between the average working plane illuminance and the subjects' responses of daylight adequacy was also checked. Figure 7- 36 shows the scatter plot of the two items. Although the average working plane illuminance is arguably the most frequently used metric in lighting practice, it appeared to have the weakest association with subjects' perceptions of daylight adequacy (compared with the average MICI and the point working plane illuminance). Applying a linear regression model to the two variables indicated that there was no predictable relationship ($R^2 = 0.054$).

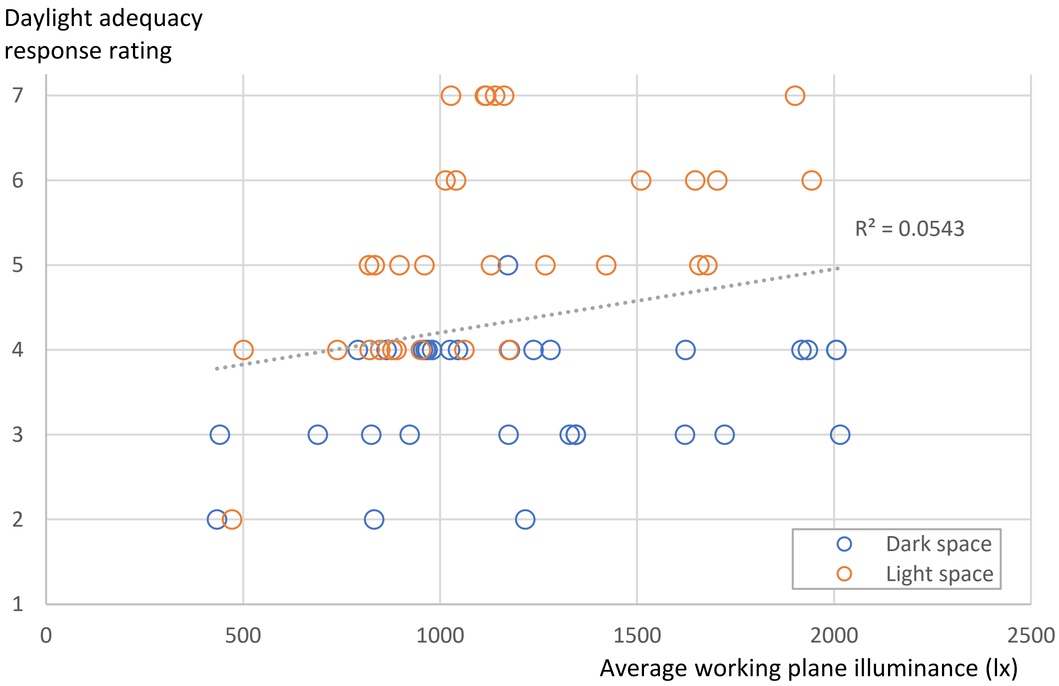


Figure 7- 36: Subjects' responses for daylight adequacy vs average working plane illuminance

Applying the Kendall's Tau correlation to the average working plane illuminance and subject's response of daylight adequacy also suggested that there was only a very weak correlation and the significance is above 0.05 indicating that the correlation is not significant (Table 7- 10).

Kendall's Tau-b (t)	0.173
Significance (p)	0.069
Sample size (N)	62

Table 7- 10: Kendall's Tau correlation coefficient describing the relationship between the average working plane illuminance and the subject's response for daylight adequacy

7.4.3 Daylight metrics vs Subjects' responses of the overall lighting quality

Given the absence of artificial lighting in both experiment spaces, the rating of overall lighting quality was essentially rating of the daylighting quality. Figure 7- 37 shows the average MICI against subject's response rating for overall lighting quality (1-very bad; 7-very good) on a scatter diagram. The diagram suggested that with both low and high average MICI values people tend to give lower scores, and high scores were only given when the average MICI was within a range of appropriate level.

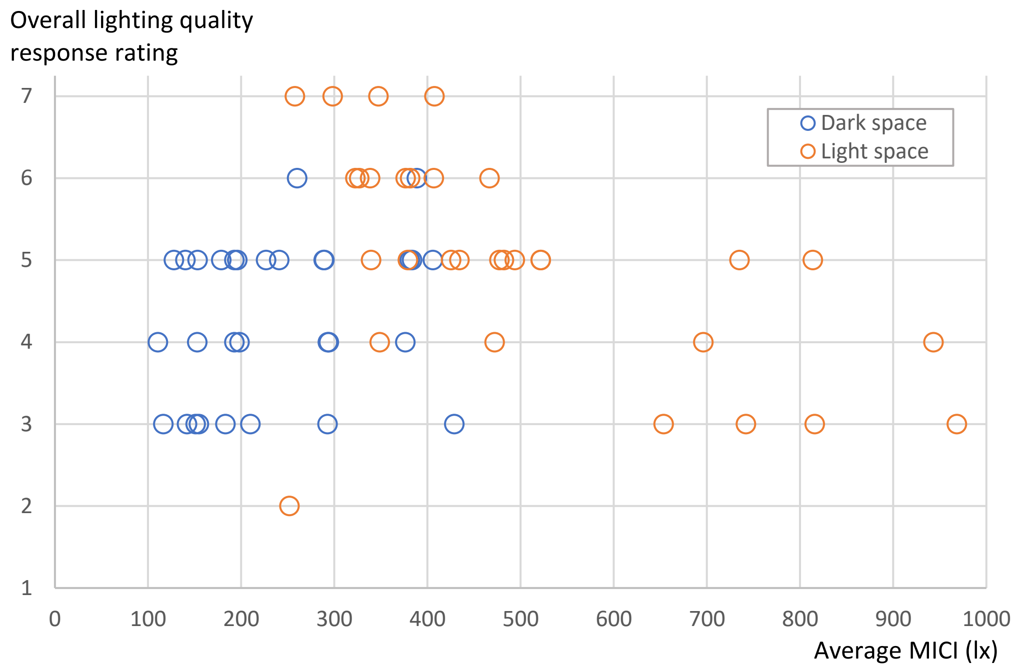


Figure 7- 37: Average MICI vs subjects' responses of the overall lighting quality

Figure 7- 37 also suggests that the average MICI in range of 250 to 450 lx was preferred in both experiment spaces, as all the high overall lighting quality scores (achieving 6 or 7) were given when the average MICI was within this range. However, MICI in this range does not mean that all subjects gave a high rating to the overall lighting quality.

For the point and average working plane illuminance, their relationships with subject's response rating for overall lighting quality were less clear (Figure 7- 38 and Figure 7- 39). Whilst the highest scores (6s and 7s) for overall lighting quality were achieved when the point/average working plane illuminance was in the range of 450 to 1500 lx, there were also several (12 for point working plane illuminance and 10 for average working plane illuminance) low scores, 2s and 3s, for this range of illuminance.

Figure 7- 38: Point working plane illuminance vs subjects' responses of the overall lighting quality

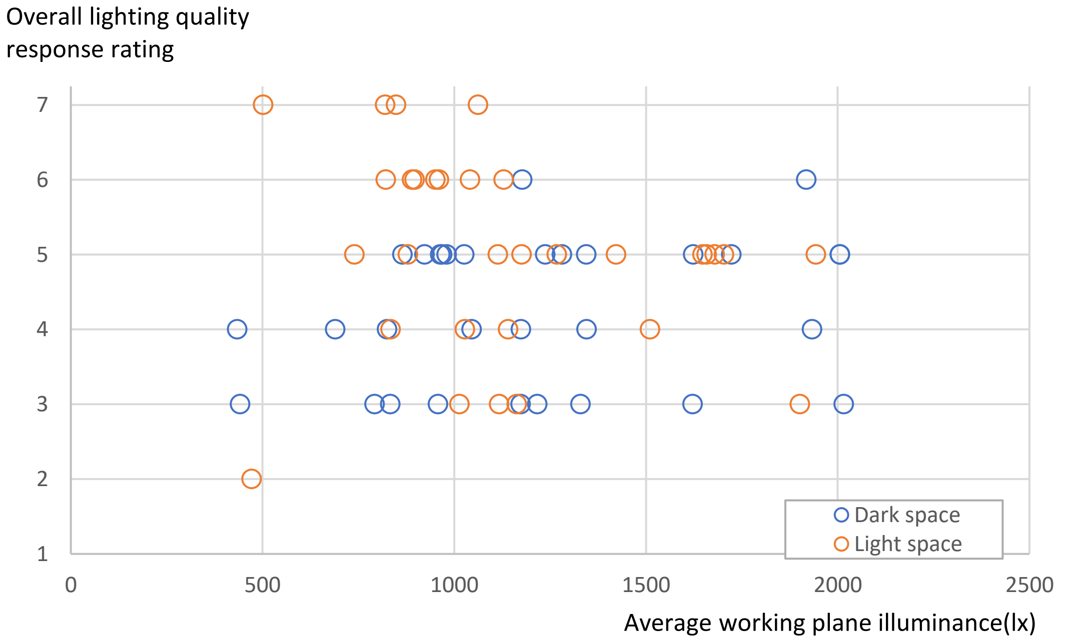


Figure 7- 39: Average working plane illuminance vs subjects' responses of the overall lighting quality

No significant correlation was found between the subject's response of the overall lighting quality and any of the tested metrics (average MICI, working plane illuminance). Refer to Annex Four for the detailed Kendall's Tau correlation test results.

7.4.4 Daylight metrics and subjects’ responses to the daylight uniformity

Because daylight uniformity describes the distribution of the daylight flux in the whole interior, it would be meaningless to compare the subject’s response rating for daylight uniformity with either the average MICI of only the subject’s sitting area, the point working plane illuminance of the subject’s sitting position or the average working plane illuminance over the desk.

A more suitable metric to describe the indoor lighting uniformity would be the Illuminance Uniformity (U).

$$U = \frac{Minimum\ illuminance\ (on\ the\ reference\ plane)}{Average\ illuminance\ (of\ the\ reference\ plane)} \qquad \text{Equation 36}$$

The Uniformity values over the desk plane for all the experiment sessions were calculated using the measured illuminance values (*Table 7- 7*) and were plotted against subject’s response rating (1 - non-uniform; 7 - uniform) for daylight uniformity on a scatter diagram.

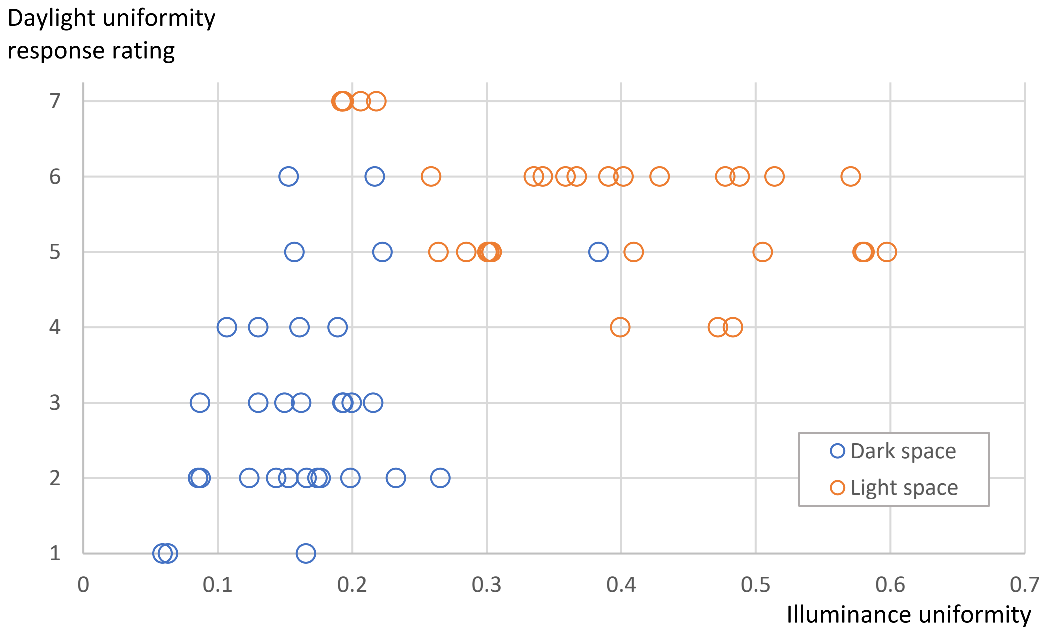


Figure 7- 40: Illuminance uniformity over the desk plane vs subject’s rating for the daylight uniformity

Figure 7- 40 suggests that subjects tended to give higher scores when a high uniformity was present in the experiment spaces, and the “light space” was perceived to have better uniformity. Moreover, it appears that the results were best fitted to a

logarithmic curve. To further explore the nature of this relationship the logarithm value (base of 10) of uniformity was plotted against the subjects' rating (Figure 7- 41).

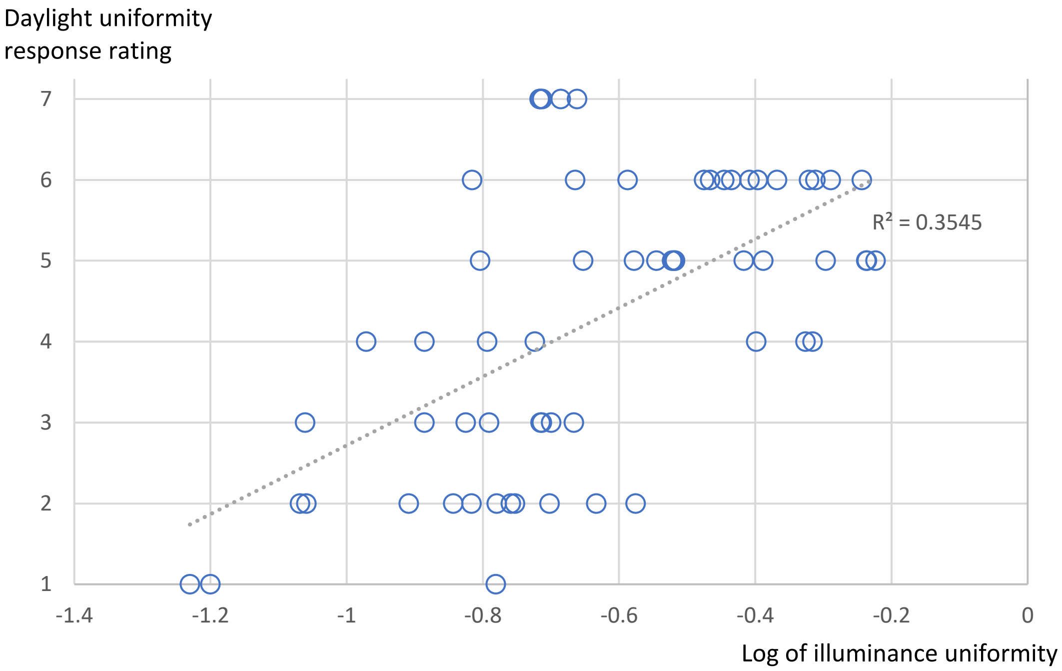


Figure 7- 41: Log of illuminance uniformity vs subject's response rating for daylight uniformity

Applying Kendall' Tau correlation to the illuminance uniformity and subject's response rating of daylight uniformity suggested a significant correlation between the two items (Table 7- 11).

Kendall's Tau-b (t)	0.395
Significance (p)	0.000022
Sample size (N)	62

Table 7- 11: Kendall's Tau correlation coefficient describing the relationship between the illuminance uniformity and the subjects' responses of daylight uniformity

7.4.5 Daylight metrics and subjects' responses to the daylight glare

Glare is a highly subjective phenomenon and research [96] [97] has shown that it is difficult to accurately evaluate daylight glare and many established glare metrics turned out to have significant inconsistency and inaccuracy issues.

In this study, no correlation was found between the subject's response rating for the daylight glare and any of the three tested metrics (the average MICI of the subject's sitting area, the point working plane illuminance at the subject's sitting position and the average working plane illuminance over the desk). Refer to Annex Four for the scatter plots and the Kendall's Tau correlation test results.

7.4.6 Daylight metrics and subjects' responses of the visibility of room objects

Object visibility is complex and depends not only on the amount of light but also the contrast of the objects against their backgrounds. In this experiment, there were a range of objects in varying positions in the room and it is not clear which objects the subjects were thinking of when answering the questionnaire. Therefore, the lighting parameters recorded in the study were not necessarily useful measures that relate to the lighting conditions close to the objects. To investigate if there was any association between the average MICI and subject's response rating of the visibility of room objects (1-obscue/difficult; 7-clear/easy), a scatter diagram of the two variables was plotted.

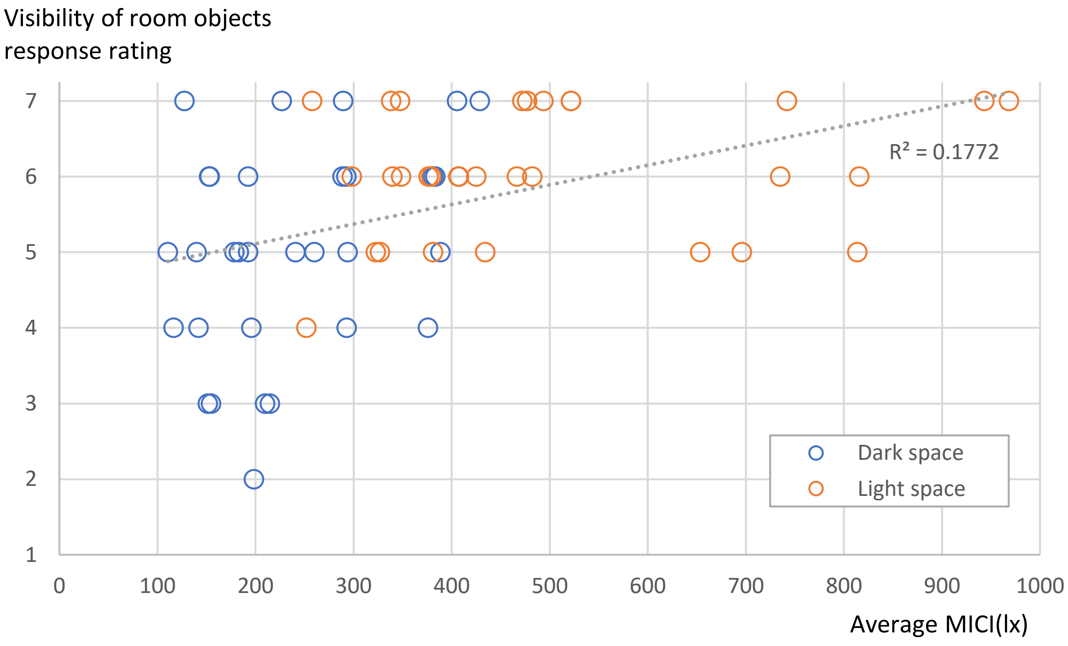


Figure 7- 42: Average MICI vs subjects' responses for the visibility of room objects

In Figure 7- 42, no strong trend can be found between the average MICI and subject's rating of the room object visibility. No subject thought negatively (assuming the rating of 4 is the neutral score) about the visibility of room objects when the average MICI reached 250 lx.

Applying Kendall' Tau correlation to the data indicated that a correlation between the average MICI and the response rating of the room object visibility was found to be significant (Table 7- 12).

Kendall's Tau-b (t)	0.362
Significance (p)	0.000156
Sample size (N)	62

Table 7- 12: Kendall' Tau correlation coefficient describing the relationship between the average MICI and the subjects' responses of the room object visibility

The scatter plots of both the point working plane illuminance and the average working plane illuminance against the subject's response rating of the room object visibility (Figure 7- 43 and Figure 7- 44) suggest no predictable pattern.

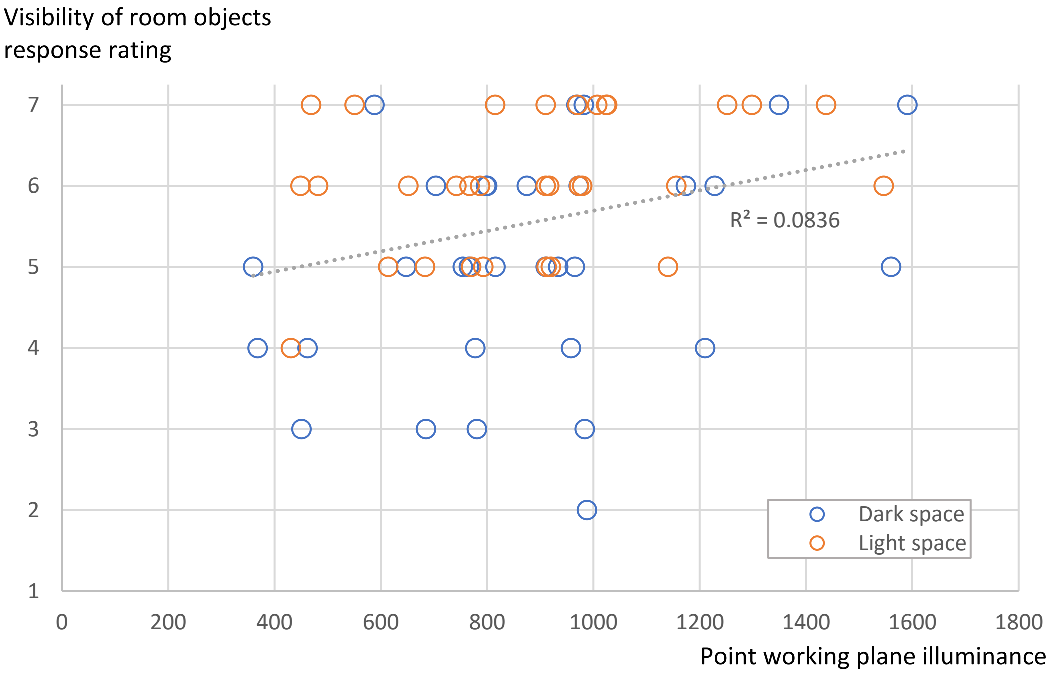


Figure 7- 43: Point working plane illuminance vs subjects' ratings for the visibility of room objects

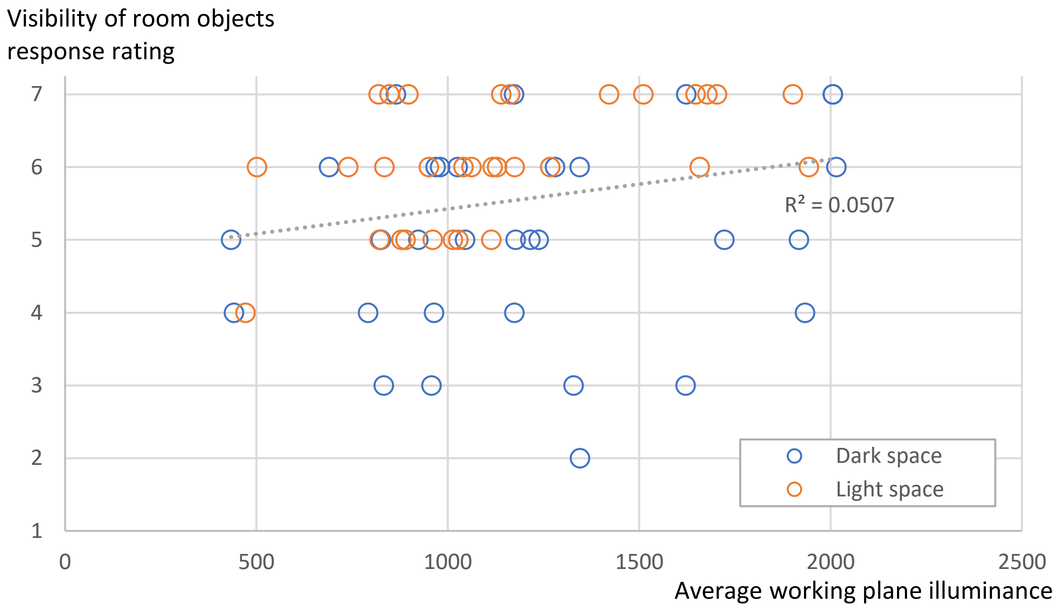


Figure 7- 44: Average working plane illuminance vs subjects' ratings for the visibility of room objects

Applying Kendall' Tau correlation to the data suggested that there was a weak association between the point working plane illuminance and the response rating of the room object visibility. A weaker association was also found between the average working plane illuminance and the response rating of the room object visibility. The significance of both these findings (Table 7- 13) was weaker than value for the correlation with the average MICI (Table 7- 12).

	Point working plane illuminance vs response rating of the room object uniformity	Average working plane illuminance vs response rating of the room object uniformity
Kendall's Tau-b (t)	0.242	0.193
Significance (p)	0.011	0.043
Sample size (N)	62	62

Table 7- 13: Kendall' Tau correlation coefficient describing the relationship between the point/average working plane illuminance and the subjects' responses of the room object visibility

7.4.7 Daylight metrics and subjects' responses on the visibility of the computer screen

This test was included as screen based work is carried out in most offices and thus the interaction of daylight on the ability to use computer screens is an important consideration of daylighting design.

In this study no correlation was found between the subject's response to the visibility of the computer screen and any of the three tested metrics (the average MICI of the subject's sitting area, point working plane illuminance at the subject's sitting position and the average working plane illuminance over the desk). Refer to Annex Four for the scatter plots and the Kendall's Tau correlation test results.

7.4.8 Daylight metrics and subjects' responses of the facial communication

One of the main reasons for people to attend a workplace is to communicate with colleagues, which involves looking at their faces. It is therefore also important to ensure an appropriate amount of daylighting provided at people's face level so that good facial communication can be achieved.

Figure 7- 45 plots the average MICI against subject's response of facial communication (1-face obscure/difficult; 7-face clear/easy). There is no clear trend shown in the diagram, and the distribution pattern looks similar with scatter plot of the average MICI against the subject's response of room object visibility (Figure 7- 42). No subject thought negatively (assuming 4 is the neutral score) about the facial communication in the "dark space" when the average MICI value reached 300 lx and all subjects had given neutral or positive scores for facial communication in the "light space".

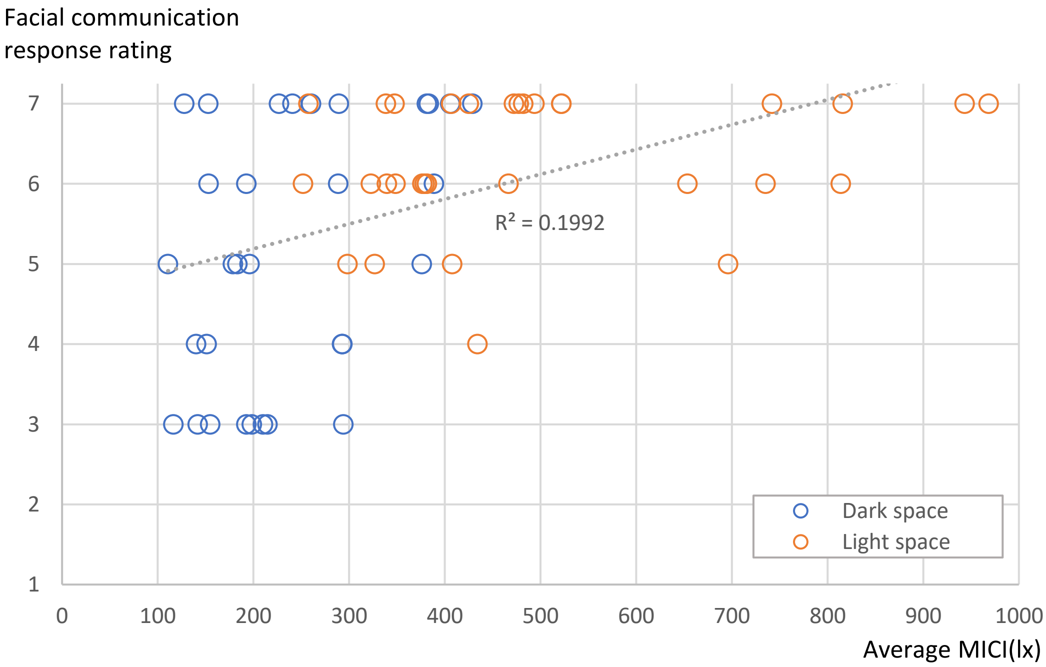


Figure 7- 45: Average MICI vs subjects' responses of facial communication

Applying Kendall' Tau correlation suggested a significant correlation between the average MICI and subject's response of facial communication (Table 7- 14).

Kendall's Tau-b (t)	0.378
Significance (p)	0.000088
Sample size (N)	62

Table 7- 14: Kendall' Tau correlation coefficient describing the relationship between the average MICI and the subjects' responses of the room object visibility

Plotting the point working plane illuminance and average working plane illuminance against the subject's response of facial communication (Figure 7- 46 and Figure 7- 47) also showed no predictable pattern.

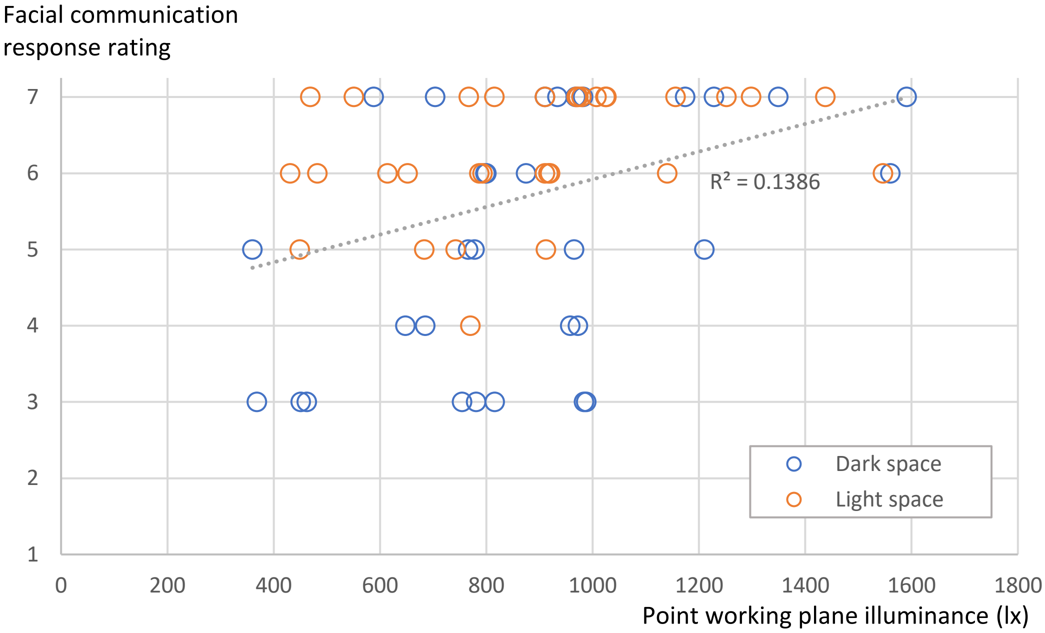


Figure 7- 46: Point working plane illuminance vs subjects' responses of facial communication

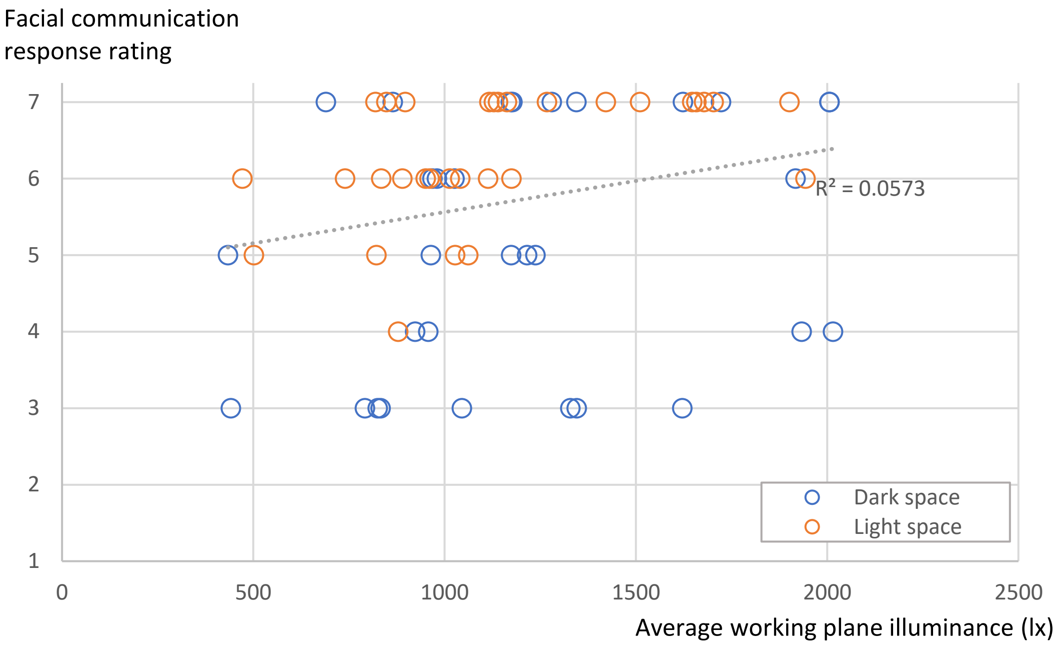


Figure 7- 47: Average working plane illuminance vs subjects' responses of facial communication

Associations were found between the working plane illuminances and subject's response rating of facial communication. However, the correlations (Table 7- 15) were weaker and less significant than the correlation with MICI (Table 7- 14).

	Point working plane illuminance vs response rating of the facial communication	Average working plane illuminance vs response rating of the facial communication
Kendall's Tau-b (t)	0.306	0.238
Significance (p)	0.001	0.014
Sample size (N)	62	62

Table 7- 15: Kendall' Tau correlation coefficient describing the relationship between the point/average working plane illuminance and the subjects' responses of the facial communication

Subjects could have been thinking of the facial communication between themselves and the researcher when answering the questionnaire. Therefore, the light level at the researcher's sitting position was also worth investigating.

The average MICI based on 8 points (two planes at different height) surrounding the researcher's sitting position was calculated (the same method used to calculation the average MICI at the subject's sitting position) and plotted against the response rating of facial communication. Figure 7- 48 reveals a similar scatter pattern when compared with the average MICI at subject's sitting position against the subjects' responses (Figure 7- 45).

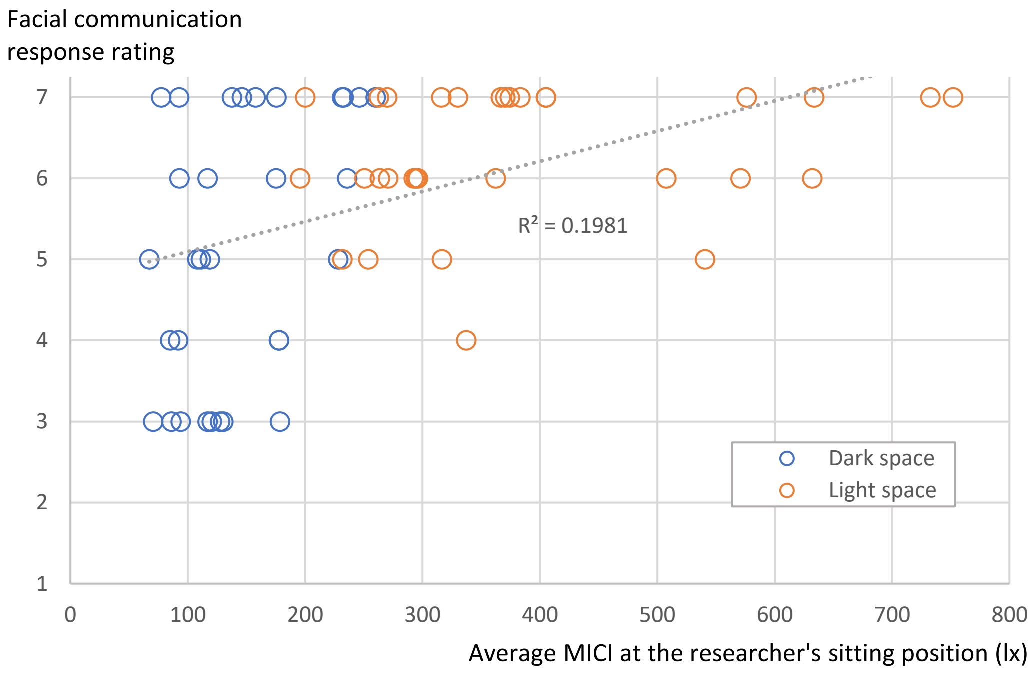


Figure 7- 48: Average MICI at the researcher's sitting position vs subject's response of facial communication

The point working plane illuminance at the researcher's sitting position (illuminance measurement – P3) was also plotted against the response of facial communication (Figure 7- 49). No clear relationship was found in the diagram.

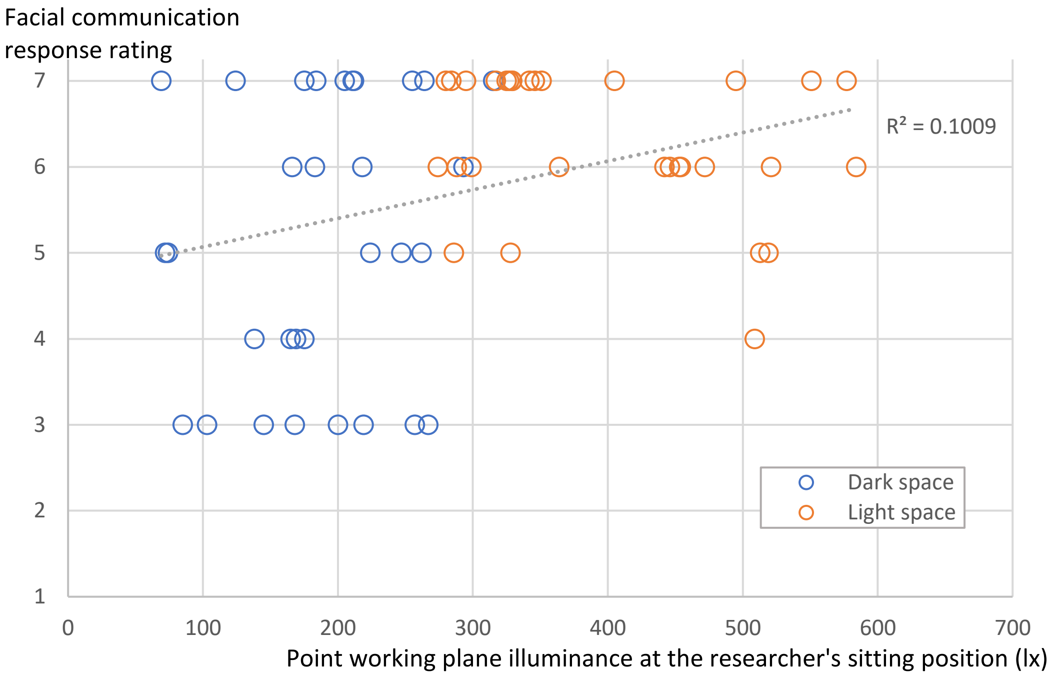


Figure 7- 49: Point working plane illuminance at the researcher's sitting position vs subjects' response of facial communication

Applying Kendall' Tau correlation to the data, a similar correlation was found between the average MICI at the researcher's position and the subject's response of facial communication (when compared with the average MICI at the subject's position). A weaker association was also found between the point working plane illuminance at the researcher's position and the subject's response of facial communication (Table 7- 16).

	Average MICI (at the researcher's position) vs response rating of the facial communication	Point working plane illuminance (at the researcher's position) vs response rating of the facial communication
Kendall's Tau-b (t)	0.359	0.222
Significance (p)	0.000192	0.021
Sample size (N)	62	62

Table 7- 16: Kendall' Tau correlation coefficient describing the relationship between the average MICI/point working plane illuminance at the researcher's sitting position and the subject's response of the facial communication

The scatter points pattern of the daylight metrics against the response rating of facial communication was very similar to the pattern of the same metrics against the response rating of the visibility of room object. Plotting the response ratings of these two survey questions against each other suggested a strong correlation (Figure 7- 50). Applying Kendall' Tau also confirmed that there was a strong association between the response ratings of the two questions (Table 7- 17).

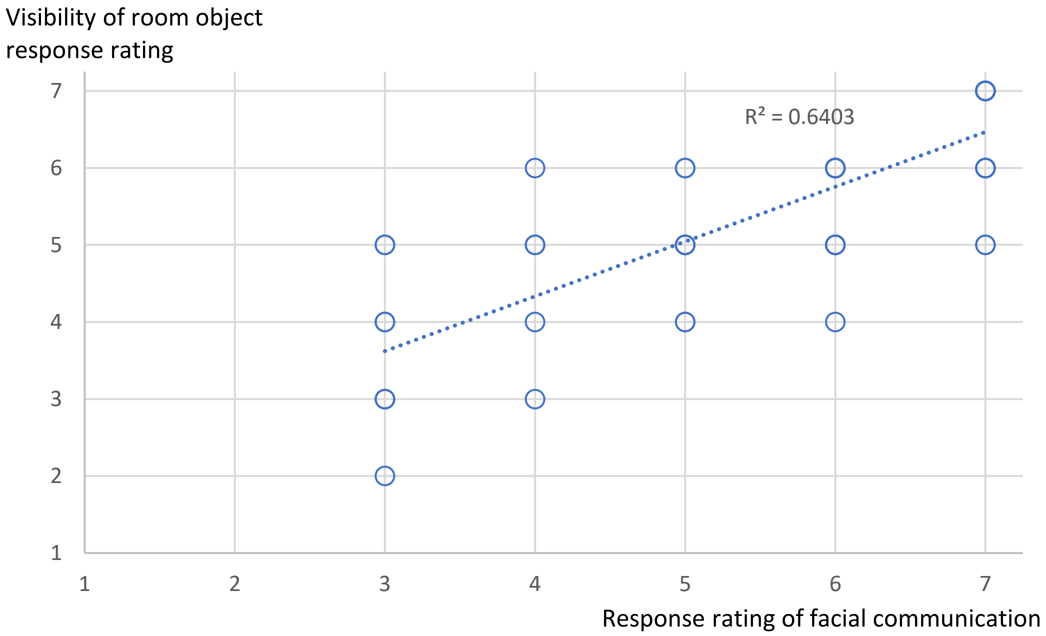


Figure 7- 50: Subject's response rating of facial communication vs subject's response rating of room

Kendall's Tau-b (t)	0.726
Significance (p)	6.8398E-12
Sample size (N)	62

Table 7- 17: Kendall' Tau correlation coefficient describing the relationship between the subjects' responses of facial communication and the subjects' responses of the room object visibility

7.4.9 Daylight metrics and subjects' responses on considering the experiment space as a daily workplace

Figure 7- 51, Figure 7- 52 and Figure 7- 53 are scatter plots showing the relationship between the daylighting metrics and the responses to the question "What do you think of this room as a daily (9-5) workplace?" where rating 1 was "dislike" and 7 was "like".

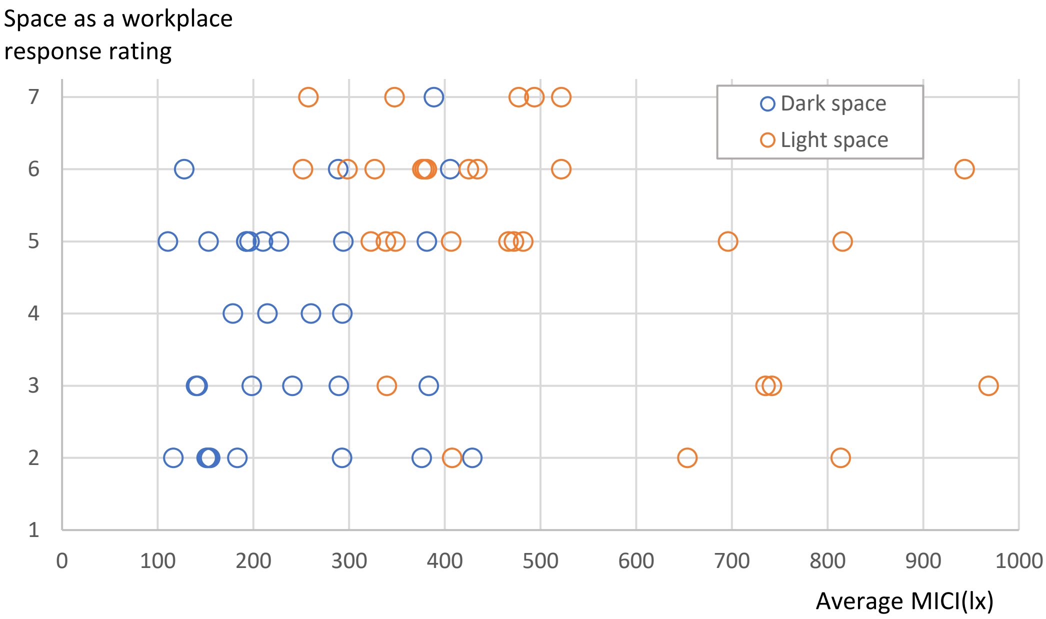


Figure 7- 51: Average MICI vs subjects' ratings on the experiment space as a daily workplace

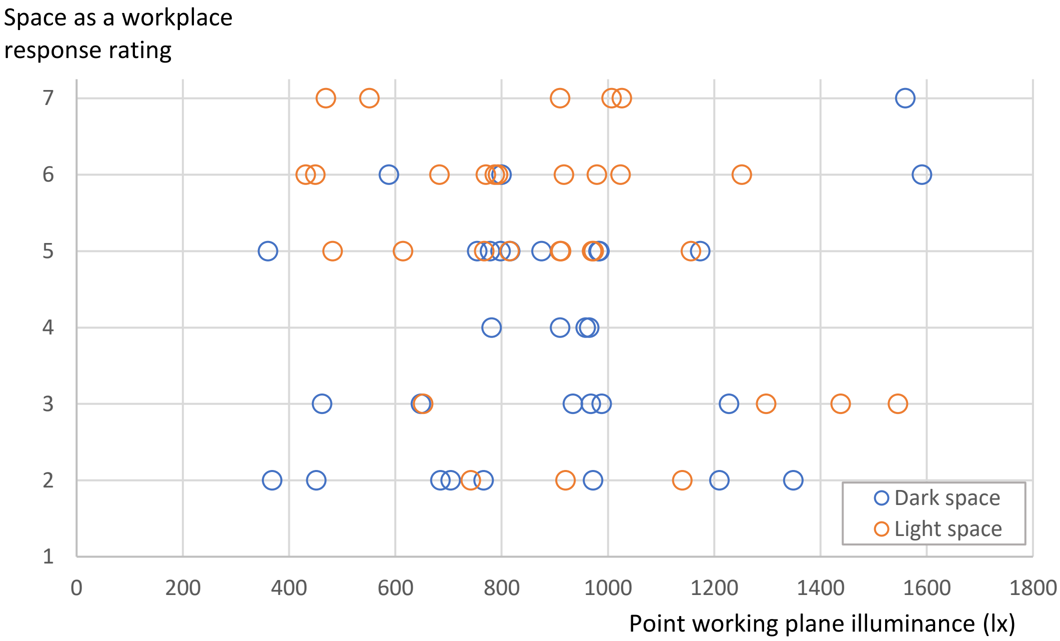


Figure 7- 52: Point working plane illuminance vs subjects' ratings on the experiment space as a daily workplace

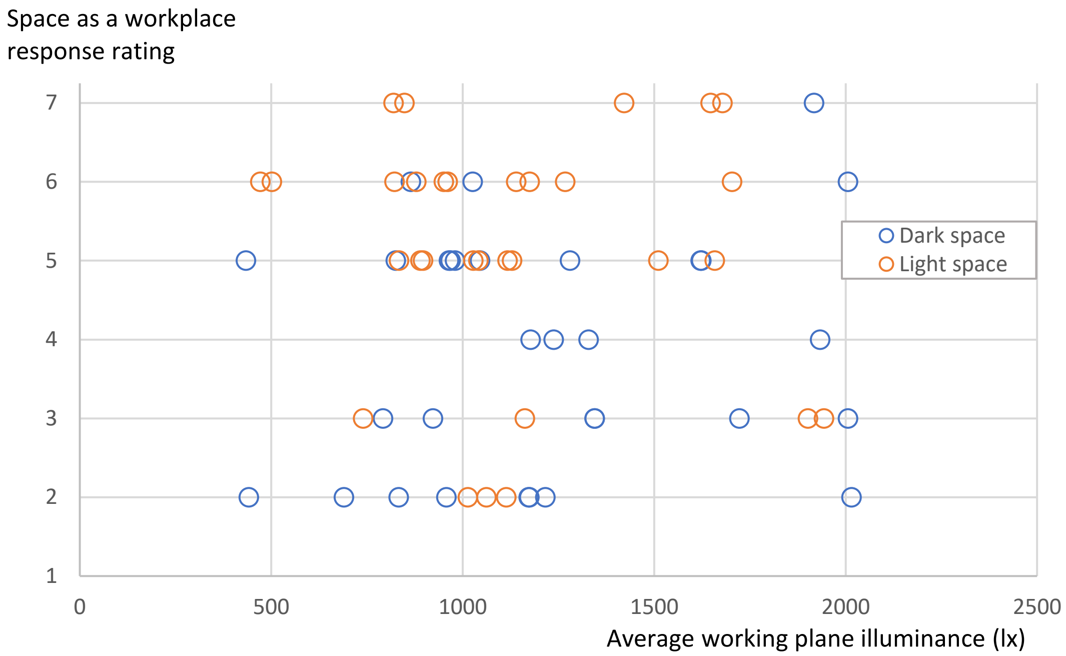


Figure 7- 53: Average working plane illuminance vs subjects' ratings on the experiment space as a daily workplace

No clear relationship was found on the scatter plots. Applying Kendall' Tau correlation to the data also suggested that there was no significant correlation between the subject's response and any of the three tested metrics (Table 7- 18). Although not correlated, the association between the subject's response and the average MICI appeared to be much stronger than that of the point and average working plane illuminances.

	Average MICI vs response rating of space as daily workplace	Point working plane illuminance vs response rating of space as daily workplace	Average working plane illuminance vs response rating of space as daily workplace
Kendall's Tau-b (t)	0.173	-0.029	-0.038
Significance (p)	0.067	0.756	0.690
Sample size (N)	62	62	62

Table 7- 18: Kendall' Tau correlation coefficient describing the relationship between the three tested metrics (average MICI, point and average working plane illuminance) and the subject's rating of the question "What do you think of this room as a daily (9-5) workplace?"

Above analyses suggested that there were more things for the subjects to consider rather than the lighting alone when giving the rating for this question ("What do you think of this room as a daily workplace?"). It was, however, very clear that the vast majority of subjects preferred the "light space" over the "dark space" as their daily workplace. Figure 7- 54 shows the distribution of the responses rating for the question in the two experiment spaces.

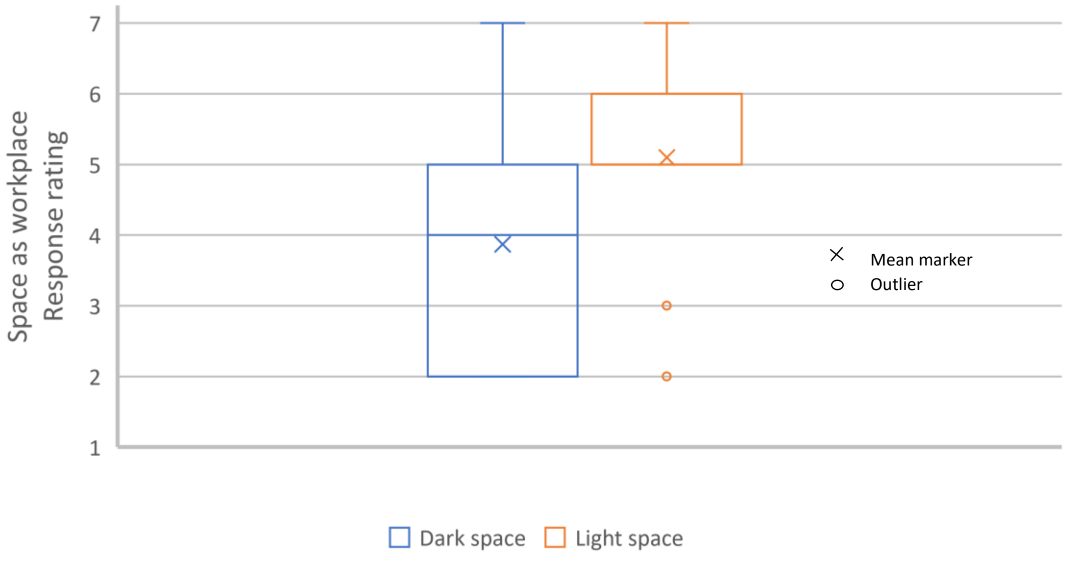


Figure 7- 54: Box and whisker chart showing the distribution of the subject's response rating for the question "what do you think of this room as daily (9-5) workplace?"

7.5 Conclusions draw from the controlled experiment

As a follow-up to the POE case study, this controlled experiment was designed to further test MICI and the traditional working plane illuminance metrics and investigate which daylight parameter best corresponds to people's perception of daylight availability. The two controlled experiment spaces were set up similarly in many ways but differ in the amount of daylight received on the working plane relative to their MICI values, in a way that the influence on subjects' responses from other factors such as the room decoration were be kept at a minimal and acceptable level while differences in the daylight parameters were different enough to make comparisons. The experiment results (subject's rating over the room appearance) suggested that this experiment setup had successfully created conditions for testing the daylight metrics with regard to ensuring that the spaces appeared similar.

By making the comparisons of the daylight metrics with subjects' responses, the following conclusions can be draw from this study:

- For predicting the daylight adequacy of the experiment spaces, MICI showed a very strong correlation with the subject responses and this correlation was stronger with the coefficient of correlation being more than double than that of either the point or average working plane illuminance. This suggests that MICI may be a better indicator of daylight adequacy than working plane based daylight metrics.

- For describing the visibility of room objects and facial communications, MICI was also significant correlated to subject responses. Although not as strong as the association to the daylight adequacy responses, it performed better than the working plane illuminance. This suggests that MICI value may predict good visibility of all room objects and excellent facial communications, and it does appear to support these aspects better than the working plane based daylight metrics. However, it is possible that other factors also play a role in the visibility of faces and objects.

- For the daylighting glare and the visibility of the computer screen, although MICI was still relatively better correlated to subject responses than working plane illuminances, their associations were found to be insignificant. This finding is not unexpected as glare is a complex phenomenon that depends greatly on subject and the light distribution rather than the absolute amount of light; and screen visibility is driven by screen luminance and the presence of veiling reflections.

- For the daylighting uniformity it was found that the minimum to average illuminance uniformity ratio was significantly correlated to the subject responses, and their relationship appeared to be logarithmic. This suggests that the illuminance uniformity is a useful parameter for describing the indoor daylight distribution.

7.6 Limitations

This study was set up in such a way so that MICI and the working plane illuminances could be treated as independent variables. However, under daylighting these parameters are all a function of the sky brightness, the building geometry and surface properties. Correlations are inevitable between the parameters.

Figure 7- 55, Figure 7- 56 and Figure 7- 57 are scatter plots showing the relationship between MICI and the two working plane metrics for the “dark” space, the “light” space and both spaces together, respectively.

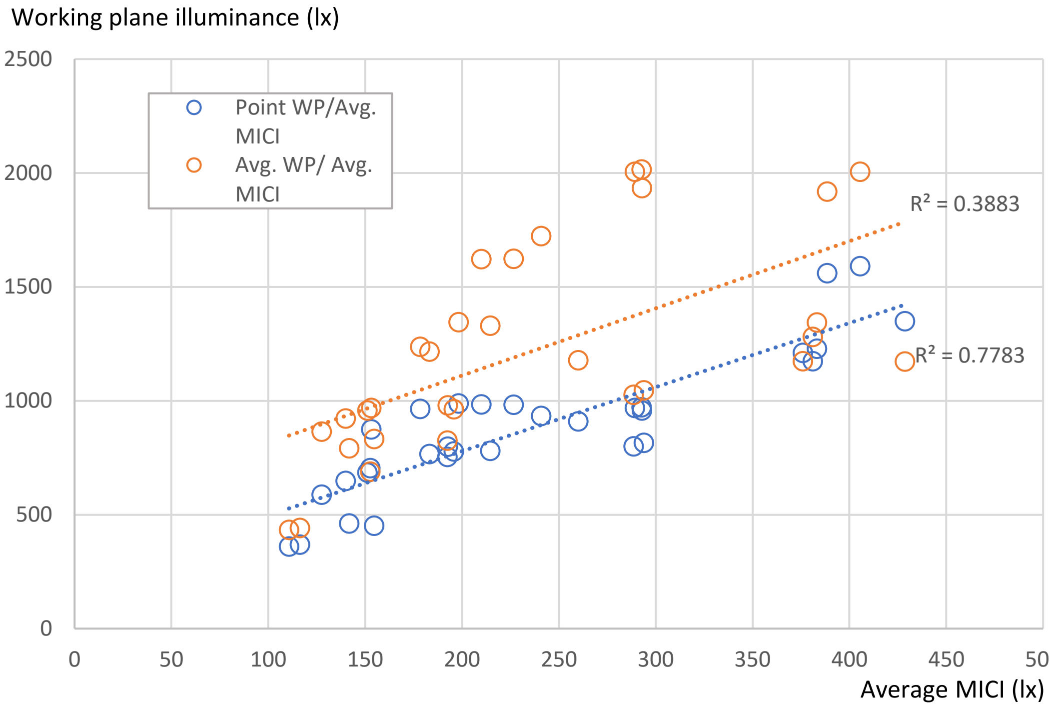


Figure 7- 55: Scatter plot of the average MICI against the point/average working plane illuminance for the “dark” space

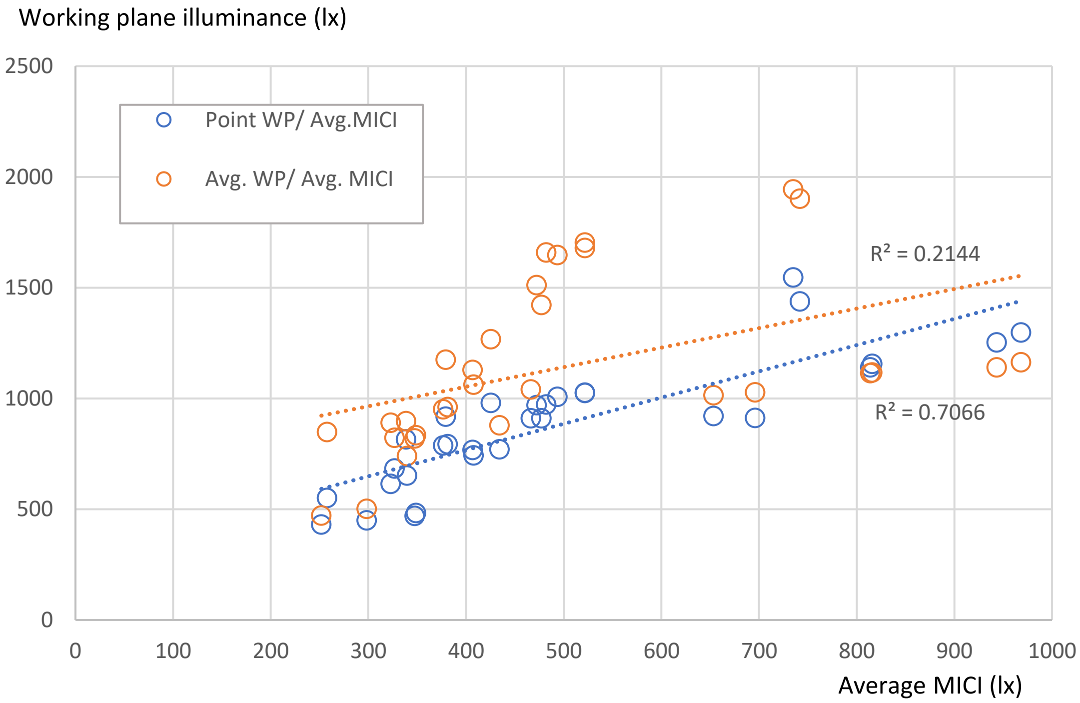


Figure 7- 56: Scatter plot of the average MICI against the point/average working plane illuminance for the “light” space

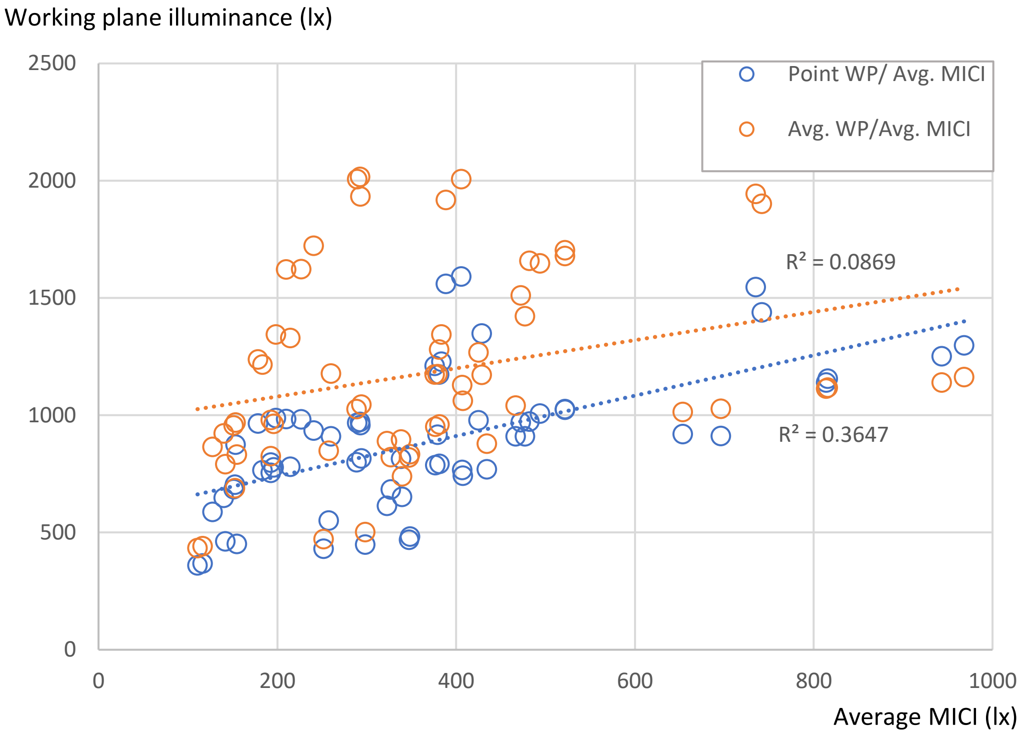


Figure 7- 57: Scatter plot of the average MICI against the point/average working plane illuminance for both experiment spaces

The correlations were tested using Kendall's tau and the results are shown in Table 7- 19 and Table 7- 20.

	Average MICI vs Point WP Illuminance (dark space)	Average MICI vs Point WP Illuminance (light space)	Average MICI vs Point WP Illuminance (both spaces)
Kendall's Tau-b (t)	0.711	0.739	0.452
Significance (p)	2.2055E-8	5.4946E-9	2.2665E-7
Sample size (N)	31	31	62

Table 7- 19: Kendall' Tau correlation coefficient describing the correlation between the average MICI and the point working plane illuminance in experiment spaces

	Average MICI vs Average WP Illuminance (dark space)	Average MICI vs Average WP Illuminance (light space)	Average MICI vs Average WP Illuminance (both spaces)
Kendall's Tau-b (t)	0.566	0.581	0.304
Significance (p)	0.000008	0.000004	0.000489
Sample size (N)	31	31	62

Table 7- 20: Kendall' Tau correlation coefficient describing the correlation between the average MICI and the average working plane illuminance in experiment spaces

This suggests that MICI is not truly independent of either of the working plane illuminance metrics. However, it does show that when the data for the two spaces is combined the correlation is weaker than for either of the spaces on their own. This, in turn, demonstrates that the experimental strategy partially succeeded. Given that MICI correlates much more strongly to the perception of daylight adequacy than either of the two working plane illuminance metrics, it could be argued that the correlation with MICI is the important relationship and the weaker working plane correlations are due to the relationship between working plane illuminance and MICI.

7.7 Chapter summary

This chapter presented the work of a controlled environment study where two very similar spaces (which only differed in light conditions) were set up to test the relationship between daylight metrics and people responses.

It was found that the new metric MICI has a strong correlation with subject responses of perceived daylight adequacy. Moreover, it was also found the association between MICI and daylight adequacy is significantly stronger than the working plane illuminance and daylight adequacy. MICI also outperformed working plane illuminance on describing some other aspects of lighting including the visibility of room objects and facial communication, although these correlations are not as strong as it is for the perceived daylight adequacy.

Compared to the POE case studies, this controlled experiment successfully reduced the correlations between the tested metrics. As all daylight metrics are functions of the sky brightness, the building geometry and surface properties, correlations are inevitable between the parameters.

Chapter eight: Discussion

8.1 Chapter introduction

As explained in the previous chapters, studies (including the study between MICI and MRSE, POE case studies and the controlled experiment study) have been conducted to investigate the new metric MICI and its relationship to people's perception of daylight adequacy.

This chapter reviews all the studies conducted, summarises the findings and compares the results from different studies.

8.2 A summary of the studies conducted

8.2.1 From MRSE to MICI

This PhD study was a journey of searching for alternative daylight metrics that can better reflect people's perception of daylight adequacy and hence are able to better characterise the daylight properties of a modern daylit environment. MRSE was initially considered as a potential candidate and its applicability in daylight design was investigated. However, after testing the metric in real buildings, MRSE was soon found out to be difficult to apply in complex buildings. The concept of MICI was hence developed. As a metric that describes the density of inter-reflected light at a point within a space, the average MICI of all points in the volume of the space was shown to have the same value as MRSE in a range of six plane rooms. This was done by comparing the relationship between MICI and MRSE values in 10,000 separate rooms that were randomly generated in terms of both the room geometry and the luminances of the room surfaces. As discussed in Chapter three, the average MICI of the 10,000 tested rooms showed a very close correlation with MRSE with a R^2 value (of linear regression) greater than 0.999. The average ratio of MRSE to MICI was close to 1 with a standard deviation of 0.0035. With this close relationship with MRSE, it is hence reasonable to assume that MICI can also predict the perceived adequacy of illuminance. As MICI is more universally applicable and can be calculated at any given point(s) within the space, it may also be useful in a room where the lighting is very non-uniform such as daylit spaces. Therefore, the focus of this PhD study became to investigate whether the metric MICI correlates to people's perception of daylight adequacy better than the existing daylight metrics.

8.2.2 MICI and other daylight metrics in real buildings

As discussed in Chapter 6, the performance of MICI together with daylight factor and daylight autonomy was tested in real buildings where the calculated daylight metrics were compared with building users' rating (using the BUS survey) of the overall daylight availability throughout the year. In Building 1 where the seating plan was given, subject responses were able to be traced back to the exact location of individual's desk and were compared with the point daylight factor, point daylight autonomy and the average MICI (at a range of different heights) calculated at the centre of desks. All three metrics were found to have significant correlation with people's perception of daylight adequacy, and MICI showed the marginally strongest association (see Table 6- 13 for details).

For Building 2 and Building 3, because no seating plan was provided, the individual daylight ratings could only be traced back to the general area of the subject's working department. Therefore, the BUS responses were compared with the average and median daylight factor, spatial and median daylight autonomy, average and median MICI of the approximate area of each working department in the building. As a result, the correlations of three daylight metrics to the building user's responses were quite poor mostly with no correlation. The only exceptions were achieved by the average daylight factor and average MICI in Building 2, and both correlations were very poor (see Table 6- 13 for details).

In all three case buildings, the highest correlation coefficients between daylight metrics and users' responses were mostly achieved by MICI (with one exception in building 2 where the average daylight factor showed a marginal better correlation over the average MICI with the BUS responses). This suggested that the new metric MICI was at least as good as the current metrics. Judging from the results in Building 1, all of the tested metrics can be considered useful at predicting user response to daylight adequacy in a given building.

Another important finding of the case studies was that various daylight metrics in the three different buildings showed significant correlations between each other. In general, all of the daylight metrics are a function daylight flux coming through the windows and the inter-reflections inside the building. Although the three case buildings differed in building geometry, they had a lot of common features such as the internal finishes. This means that the correlations between different metrics are inevitable, and it is a limitation to the building case studies. To further investigate the relationship of each daylight metrics to people's perception of daylight, an extreme condition needs to be created to reduce the correlations between the metrics.

8.2.3 MICI and the working plane illuminance in a controlled environment

A controlled experiment was designed as the follow-up to the case studies, where two daylit spaces were set up to be similar in many ways (such as the room geometry, furniture, room decoration, window size and view) but differed in the amount of illuminance received on the working plane relative to the MICI values. This was achieved by controlling both the daylight flux entering the windows and the inter-reflections within the spaces (refer to Chapter five for details). In total, 31 subjects participated the experiment where they conducted various office activities in both experimental spaces and completed a questionnaire. By comparing the measured and calculated daylight metrics with subjects' responses, it was found that the average MICI (calculated at the subject's sitting position) had a significantly stronger correlation with the subject responses to daylight adequacy than that of either the point working plane illuminance (measured at the subject's sitting position) or the average working plane illuminance (for the entire desk), refer to Table 8- *1* for detailed results. This suggests that MICI may be a better indicator of daylight adequacy than working plane based daylight metrics.

	Average MICI vs response of daylight adequacy	Point daylight factor vs response of daylight adequacy	Average daylight factor vs response of daylight adequacy
Kendall's Tau-b (t)	0.676	0.328	0.173
Significance (p)	1.2829E-12	0.001	0.069
Sample size (N)	62	62	62

Table 8- 1: Results of the Kendall's Tau coefficient analyse for the relationship between the subject responses of daylight adequacy and different daylight metrics

The experiment also showed that MICI was better correlated with subject responses about the visibility of room objects and facial communication than measures of working plan illuminance (refer to *Table 8- 2* and *Table 8- 3*). However, the association was not as strong as with the daylight adequacy responses. This suggests that a good average MICI level in the space appears to promote good visibility of room objects and good facial communication. As for the screen visibility and the daylight glare, the experiment results revealed no significant correlation between the daylight metrics and subject responses (refer to *Table 8- 4* and *Table 8- 5*). This suggests that MICI or the working plane illuminance alone cannot be used to describe the daylight glare nor the screen visibility, as these aspects of daylighting are excepted to be affected by many other factors (e.g. glare is greatly depended on the subject and the light distribution; and screen visibility is mainly driven by the screen luminance and the presence of veiling reflections). Additionally, the experiment found that the minimum to average illuminance uniformity ratio was significantly correlated to the subject responses (refer to Table 7- 11: Kendall's Tau correlation coefficient describing the relationship between the illuminance uniformity and the subjects' responses of daylight uniformity

for details). This suggests that the illuminance uniformity is a useful indicator of describing the indoor daylight distribution.

	Average MICI vs response of room object visibility	Point working plane illuminance vs response of room object visibility	Average working plane illuminance vs response of room object visibility
Kendall's Tau-b (t)	0.362	0.242	0.193
Significance (p)	0.000156	0.011	0.043
Sample size (N)	62	62	62

Table 8- 2: Results of the Kendall's Tau coefficient analyse for the relationship between the subject responses of room object visibility and different daylight metrics

	Average MICI vs response of facial communication	Point working plane illuminance vs response of facial communication	Average working plane illuminance vs response of facial communication
Kendall's Tau-b (t)	0.378	0.306	0.238
Significance (p)	0.000088	0.001	0.014
Sample size (N)	62	62	62

Table 8- 3: Results of the Kendall's Tau coefficient analyse for the relationship between the subject responses of facial communication and different daylight metrics

	Average MICI vs response of screen visibility	Point working plane illuminance vs response of screen visibility	Average working plane illuminance vs response of screen visibility
Kendall's Tau-b (t)	0.013	-0.008	-0.097
Significance (p)	0.892	0.931	0.296
Sample size (N)	62	62	62

Table 8- 4: Results of the Kendall's Tau coefficient analyse for the relationship between the subject responses of screen visibility and different daylight metrics

	Average MICI vs response of daylight glare	Point working plane illuminance vs response of daylight glare	Average working plane illuminance vs response of daylight glare
Kendall's Tau-b (t)	0.049	0.01	-0.034
Significance (p)	0.605	0.916	0.718
Sample size (N)	62	62	62

Table 8- 5: Results of the Kendall's Tau coefficient analyse for the relationship between the subject responses of daylight glare and different daylight metrics

Although the controlled experiment was set up in such a way that the MICI values of the two spaces were significantly different relative to the working plane illuminances, correlations were still found between the daylight metrics (refer to Table 7- 19 and Table 7- 20 for details). This once again suggests that correlations between the daylight metrics are inevitable, as all these parameters are a function of the sky brightness, the building geometry and the surface properties. Nevertheless, when compared with the previous POE case studies, the controlled experiment has successfully managed to reduce the correlations between the metrics while ensuring the created spaces appeared similar and "office-like". Given that MICI correlates much more strongly to the perception of daylight adequacy than the working plane illuminances, it could be argued that the correlation with MICI is the most important relationship and the weaker correlation with working plane illuminance is due to the relationship between MICI and work plane illuminance.

8.3 Results from the case studies and the controlled experiment

In total, this study has tested MICI in 5 different office environments (3 real buildings and 2 experimental spaces). When building users' responses of daylight adequacy were able to be compared with MICI values locally at a relatively precise position, the results suggested a quite consistent correlation across buildings. For both Building 1 (of the case studies) and the controlled experiment, MICI was significant correlated to the daylight adequacy response with a Kendall's Tau coefficient of around 0.65 (0.643 for Building 1 and 0.676 for the controlled experiment) and the significance $p<0.001$. If combine the data of the two studies together, a similar relationship still exists between the two parameters. Figure 8- 1 shows the scatter plot of the average MICI (calculated at subject's desk) against the subject responses of daylight adequacy. Applying a linear regression trend line to the plot indicates a strong correlation with a R^2 value of around 0.67.

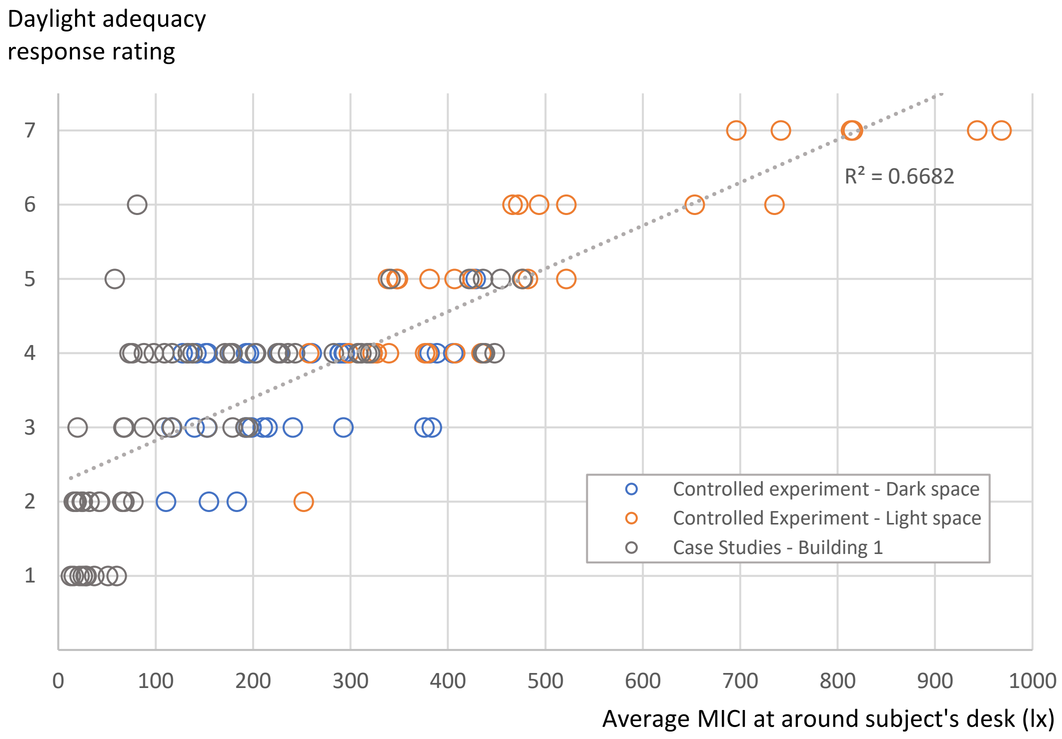


Figure 8- 1: MICI vs daylight adequacy responses from the results of Building 1 and the controlled experiment combined

Applying the Kendall rank correlation to the combined results also suggested a strong and similar correlation between MICI and the responses of daylight adequacy, with a Kendall's Tau coefficient of 0.665 which was significant at p almost zero (Table 8- 6).

Kendall's Tau-b (t)	0.665
Significance (p)	4.6889E-24
Sample size (N)	127

Table 8- 6: Kendall's Tau correlation coefficient describing the relationship between MICI and daylight adequacy responses of the combined study results

Even for the combined results of the two case buildings (Building 2 and Building 3) where subject responses were only able to be traced back to a general building area, a significant correlation (t=0.373, p=0.047; refer to Table 6- 14 for details) was still found between the average daylight adequacy rating (of different building zones) and the average MICI values (of different building zones). This suggests that MICI is a reliable indicator of daylight adequacy across different buildings.

Figure 8- *2* is a box and whisker plot showing the subject responses of daylight adequacy against the average MICI at around subjects' desks (for the combined results of Building 1 and the controlled experiment). The wide-stretching "whiskers" indicate that different subjects have given the same response ratings under a range of MICI levels, especially towards the middle point of the scale (4 - "about right"). This is not unexpected as the perceived spatial brightness is highly subjective and the responses were collected at various locations and under different weather conditions. However, the interquartile ranges (represented by the "boxes" in the chart) of the responses spread quite evenly with very limited overlap (small overlaps exist between the scale of 1 - 2 at MICI level around 24 - 44 lx and between the scale of 3-4 at MICI level around 158 – 213 lx). This suggests that MICI is an effective indicator of the perceived spatial brightness across different buildings and lighting conditions. As for the most desirable amount of daylight in buildings, it is suggested that it should be a MICI range of approximately 150 to 350 lx as this comfortably contains the inter quartile range for the score of 4, this area is highlighted in Figure 8- *2*.

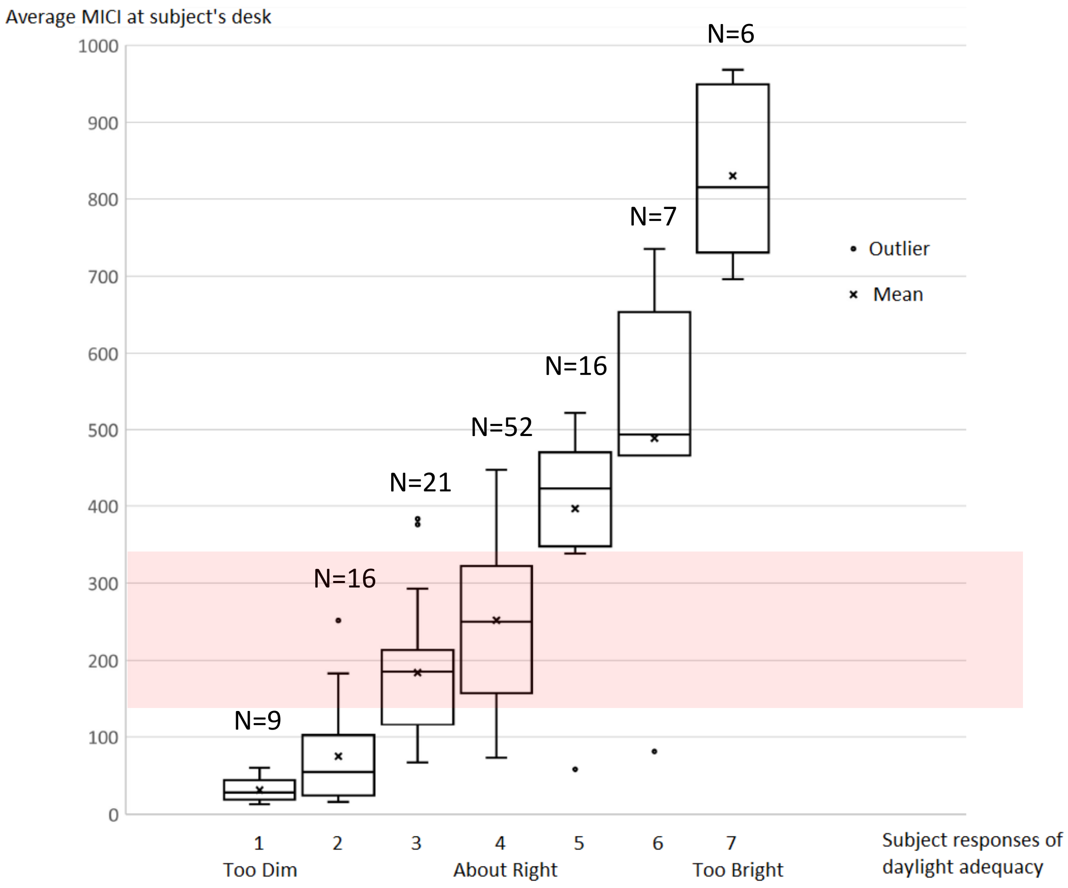


Figure 8- 2: Box and whisker plot showing the subject responses of daylight adequacy against the average MICI (combined results of Building 1 and the controlled experiment), N is the sample size of each group.

8.4 Chapter summary

In the study of comparing MICI with MRSE, MICI showed its similarity to MRSE and from this it was inferred that it had the same correlation to PAI. In the POE case studies, where MICI was tested as a daylight metric along with other metrics, MICI showed strong correlation with people’s responses of perceived daylight adequacy in one of the studied buildings, however, due to the correlations between MICI and other daylight metrics this study did not demonstrate that MICI is significantly better than the other metrics. In the controlled experiment MICI again showed a very strong correlation to perceived daylight adequacy, moreover in this study it was able to show that MICI was much better than the other metrics as the correlation between MICI and the other metrics was much reduced.

By examining the data from one of the sites in the case study and the controlled experiment together. It was concluded that MICI is a reliable indicator of daylight adequacy across the different sites and it was also found that a MICI in the range 150 lx to 350 lx was judged to be “about right”.

Chapter nine: A comparison to previous studies

9.1 Chapter introduction

Currently daylight factor remains the dominant daylight metric. Alternatives metrics such as the CBDM metrics and median daylight illuminance have been proposed, however they are all based on the same concept that is the illuminance level on horizontal working plane. Very little recent research has been conducted to investigate whether daylight illumination on the working plane meets the human needs. A study by Wells [98], in which he compared people's desk distance from the nearest daylight source (and hence the amount of daylight on their desks) with the responses of how comfortably people felt under the lighting (on a 3 point scale rating: too dull for comfort, comfortable, too bright for comfort), found that people's perception of how dominant daylighting was to the overall lighting is independent to the their working distance from the window.

This PhD research into daylight and human needs, to the best of our knowledge, is the first for many years. Most daylight research, over recent years, have been mainly investigating the means of calculating daylight availability. Due to this limitation for the comparison with other research it is necessary to draw work on electric lighting, in particular Cuttle and Duff studies on MRSE and the perceived adequacy of illumination.

This Chapter compares the findings from this study and Duff's research on MSE and PAI. A divergence of the results on the recommended MICI and MRSE values will also be discussed.

9.2 A comparison to Duff's results

Since MICI is a newly developed metric based on concept of MRSE, the only past studies that this PhD study can make comparisons with are the Duff's studies of MRSE and Perceived Adequacy of Illumination [99].

As already introduced in Section 2.6.1, Duff's tests include a lighting booth experiment, an office setup experiment with uniform light distribution and a similar office setup experiment but with non-uniform light distribution. His object was to investigate the correlation of MRSE to the perceived spatial brightness and PAI, and draw comparisons to the working plane illuminance.

There are many similarities between Duff's experiments and this study. Both studies had experiments set up in office or office-alike environments and investigated the relationships between MRSE or MICI (which is derived from the MRSE concepts and, as discussed in Chapter three, has a very deep connection with MRSE) to people's perceptions of lighting. In the questionnaire design of the two studies, had similar scales[12] that were used to collect subject responses of the perceived spatial brightness (or the perceived daylight adequacy for this study). This makes the direct comparisons of the results from the two studies possible.

Duff's experiments focused on electrical lighting and the maximum value of MRSE of only 100 lx, whereas experiments of this study were under various daylight conditions and the MICI values varied from 13 to 968 lx. Therefore, to make the comparison, the low-end section of the result where the MICI value is under 100 lx was extracted from Figure 8- 1 (the combined results of Building 1 and the controlled experiment).

Figure 9- *1*, Figure 9- *2* and Figure 9- *3* respectively show the low-end section (MICI less than 100 lx) of the study result together with Duff's results of his lighting booth experiment, the office setup experiment with uniform lighting distribution and the office setup experiment with non-uniform lighting distribution. Note that the response ratings of the spatial brightness in Duff's experiments were the mean values from all subjects. The closely matched pairs of linear trend lines in all three figures indicate substantial agreements between the study results, and this is especially true between the results of this study and Duff's office setup experiment with non-uniform lightings. In Figure 9- *3* the trend lines of the two data set are nearly coincident with a similar regression equation. This is not unexpected as Duff's office setup with non-uniform lightings is very similar with the experiment conditions of this study (office environment under

---

[12] A seven point semantic differential scale with one end (rating of 1) representing "very dim", the other end (rating of 7) representing "very brightness" and the middle point (rating of 4) representing "about right/neither dim nor bright".

daylighting, which is also with highly uneven lighting distribution). In summary, for MICI values under 100 lx, the results of this study showed a very similar relationship between MICI and the perceived daylight adequacy, when compared with Duff’s results of MRSE and the perceived spatial brightness.

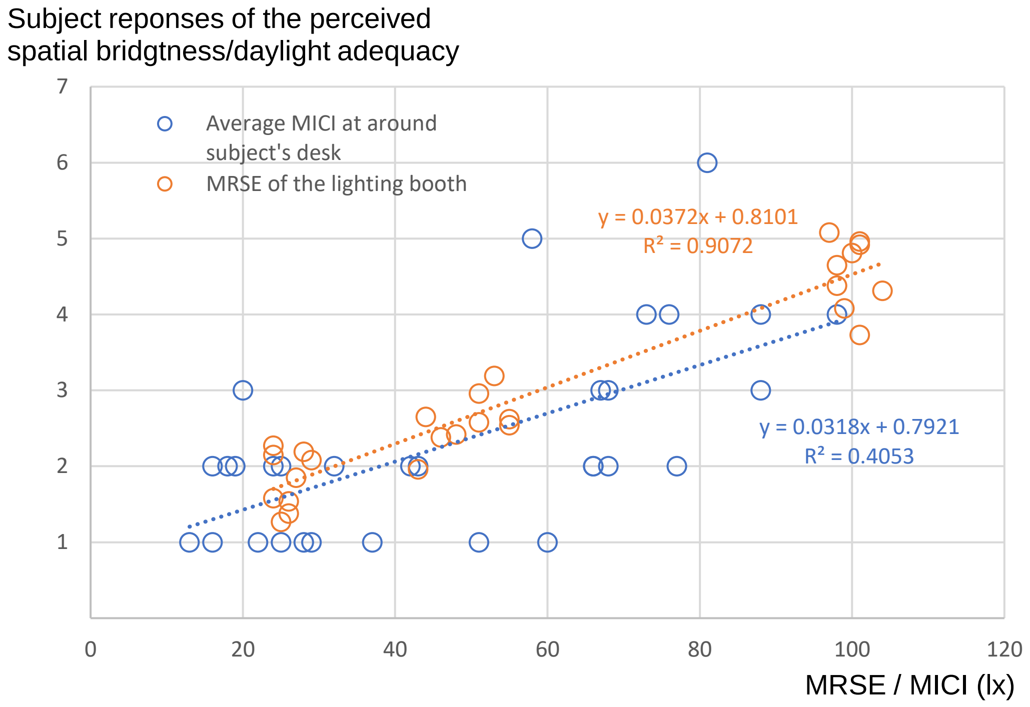


Figure 9- 1: A result comparison with Duff’s lighting booth experiment

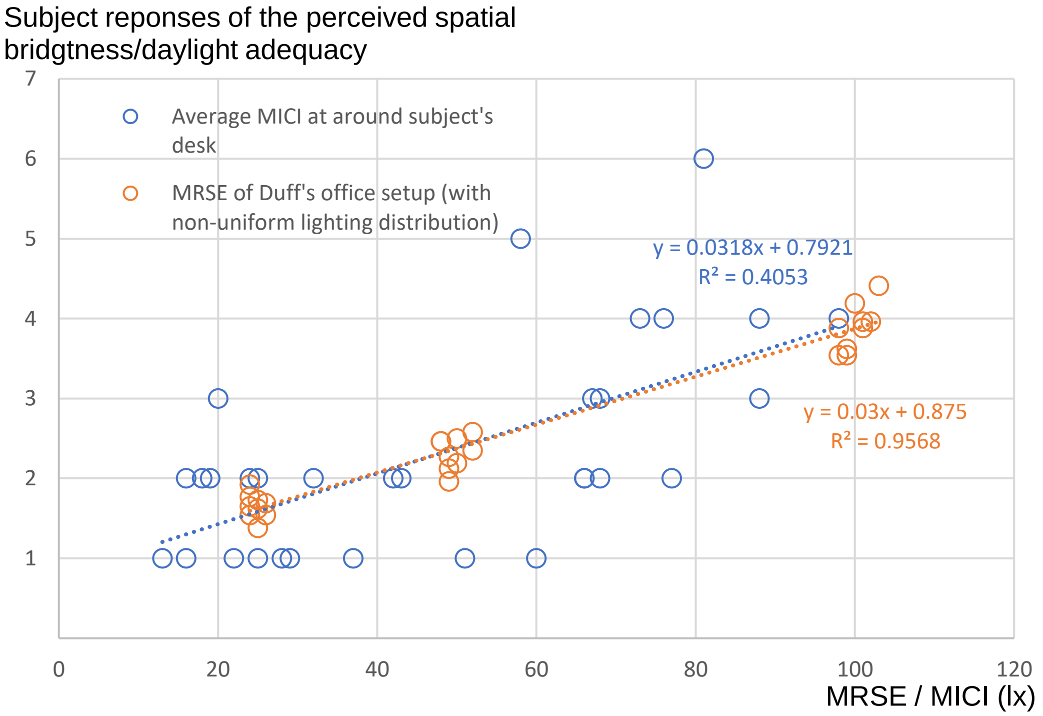


Figure 9- 2: A result comparison with Duff’s office setup (uniform lighting distribution) experiment

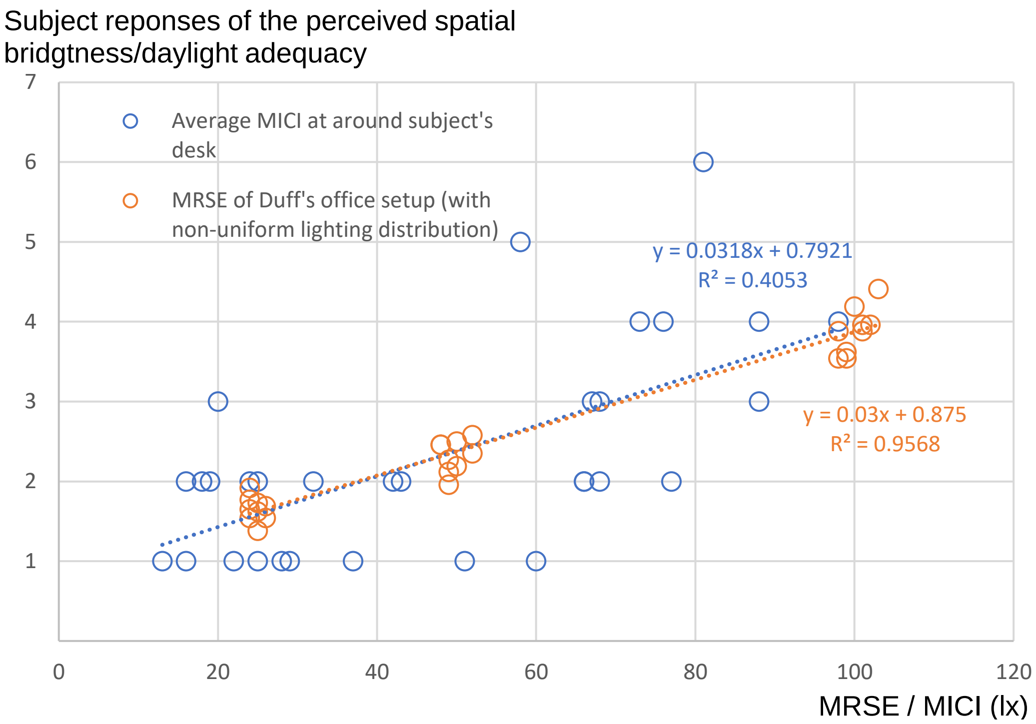
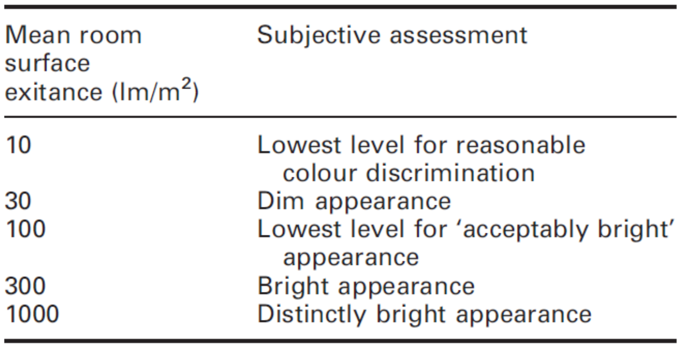


Figure 9- 3: A result comparison with Duff's office setup (non-uniform lighting distribution) experiment

9.3 A divergence in the recommended MICI/MRSE value

As discussed in Section 8.3, under the experiment conditions of this study the most desirable MICI level under daylighting is between approximately 150-350 lx. It is higher than Cuttle's recommended MRSE target of 100 lx which he suggested was the minimum necessary for an acceptably bright room. Table 9- *1* shows Cuttle's recommended values of MRSE.



Mean room surface exitance (lm/m^2)	Subjective assessment
10	Lowest level for reasonable colour discrimination
30	Dim appearance
100	Lowest level for 'acceptably bright' appearance
300	Bright appearance
1000	Distinctly bright appearance

Table 9- 1: Recommended values for MRSE from Cuttle (Table 1 from the paper "Towards the third stage of lighting profession" *[7]*)

However, more recently Cuttle has revised his suggestions for MRSE values based on Duff's research and other studies. In his "The lighting design objectives (LiDOs) procedure" article [100], Cuttle proposed the new values as listed in Table 9- *2* below.

Perceived Brightness of Illumination (PBI)	MRSE (lm/m^2)
Bright	150
Slightly bright	120
Neither dim nor bright	90
Slightly dim	60
Dim	30

Table 9- 2: Proposed PBI/MRSE relationship from Cuttle (Table 1 from the article "The lighting design objectives (LiDOs) procedure" *[100]*)

Studies conducted by Leo at al [101] [102] also found that for a space to appear "light", the average luminance within the most importance area of the field view (i.e. the horizontal 40° band centred at normal eye height) needs to be at least 30 cd/m^2. For a space to "start appear bright" an average luminance of around 40 cd/m^2 is required. These findings agree with Cuttle's MRSE/PBI scale (Table 9- 2).

These suggested values from Cuttle seem to suggest that subjects may rate as adequate MRSE (and hence MICI) values slightly lower than the values found in this study (corresponding to a score of 4 on the dim to bright scale). There are a number of potential explanations for this. Firstly, the adjectives used by Cuttle do not fully correspond with the scale used in this study, it could be inferred that a lighting level that was "adequate" is lower than one judged to be "just right". Secondly, there is the potential for range bias, as this study included some high values of MICI (up to nearly 1000 lx) which would be very difficult to achieve with the electric lighting systems used in the rooms Cuttle considered. Finally, it is possible that subjects expect more light when they are in a daylit environment.

In Duff's office experiment with non-uniform light conditions, less than 20% of the total participants responded "Yes" to the question "the lighting in the space is adequate?"

at the MRSE level of around 100 lux (see Figure 9- 4). Duff concluded that under non-uniform lighting scenes participants did not relate level of perceived adequacy of illumination to MRSE. It is possible that in non-uniform spaces, including most side-lit and daylit rooms, subjects require higher illumination before considering a space to be adequately lit. It is also important to note that Duff used a slightly different form of questionnaire to this study. The two questions used are summarised in Table 9- *3* below.

Moreover, given the problem of associating light adequacy response with the perceived adequacy response, it might be reasonable to assume that under non-uniform lighting conditions MICI will perform better than MRSE, as MICI can be "sub-sampled" and calculated at any point(s) in the volume of space for different light distributions.

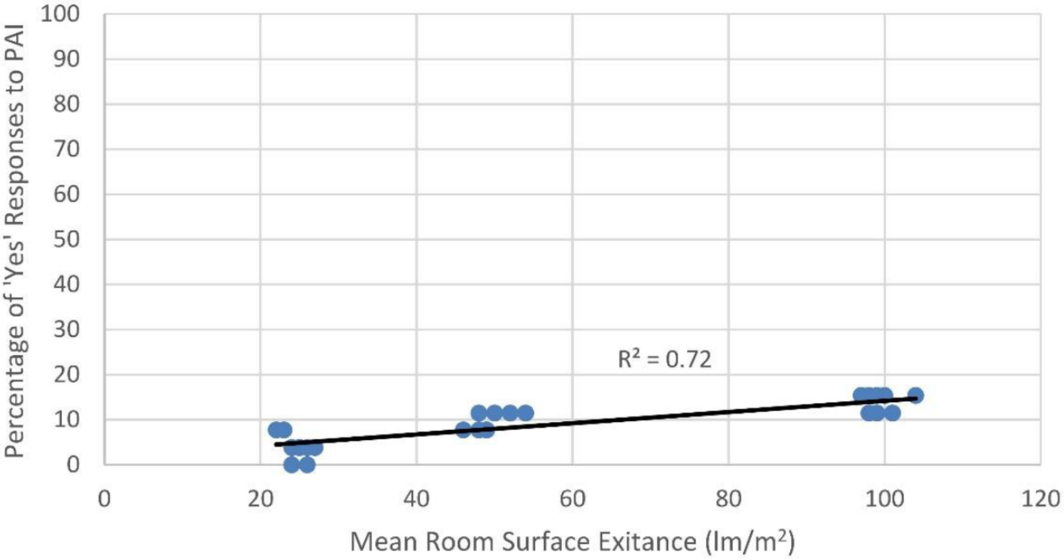


Figure 9- 4: The percent YES responses to PAI against MRSE in Duff's office setup experiment with non-uniform light scenes (Figure by Duff *[99]*)

Duff's Question: on the scale below, please rate the brightness of the entire space	Question form this study: What do you think of the lighting in this whole room? – Daylighting
1-Very dim	1-Too dim
2-Dim	2
3-Slightly dim	3
4-Neither dim nor bright	4-About right
5-Slightly bright	5
6-Bright	6
7-Very bright	7-Too bright

Table 9- 3: Difference between Duff's question and this study's question

One limitation of Duff's study was that MRSE was only tested up to a maximum level of 100 lux. He suspected that:

> *"…as levels of MRSE increase above this value (100 lx), ratings of brightness may plateau, perhaps producing the expected logarithmical relationship."* [99]

The findings of this study, to certain extent, has confirmed this hypothesis. As shown in Figure 8- *2*, the relationship between MICI and subjects' ratings of daylight adequacy appears to be indeed logarithmical.

9.4 Chapter summary

This chapter compared the results of this PhD study with previous studies, in particular Duff's works on MRSE and PAI. Due to the fact that Duff only tested MRSE in a range limited to 10 lx to 100 lx, it was only possible to compare the low end portion of the results from this study to Duff's results. When the data were plotted in the same figure it was shown that the relationship between MICI and perceived daylight adequacy from this study is substantially similar with the relationship between MRSE and the perceived spatial brightness in Duff's study.

In terms of the recommend MRSE/MICI value, the results of this study indicated a MICI range of 150-350 lx to be perceived as the "about right" level whereas according to Cuttle and Duff a MRSE level of 100 lx would be considered as "acceptably bright".

This divergence is likely due to the fact that the experiments were conducted in different lighting conditions. Cuttle and Duff’s experiments were mostly conducted in a uniformly lit “box” room, whereas in this study the test spaces were daylit rooms with non-uniformity light distribution. It is possible that in non-uniform spaces people require higher illumination before considering a space to be adequately lit. It is also possible that in daylit spaces people have come to expect higher illuminances.

Chapter ten: Implementations of MICI in lighting practice

10.1 Chapter introduction

This chapter discusses the potential implementations of MICI in the daylighting and artificial lighting practices.

10.2 MICI in daylight practice

The results of this study have suggested that MICI is a reliable daylight metric for predicting the daylight availability in buildings and is better correlated with people's perception of daylighting adequacy than other working plane based metrics such as daylight factor. This means that MICI may be used as the replacement of the current metrics in daylighting practice. For office environment the recommended MICI level, according to the findings of this study, should be 150-350 lx around the task area. While this gives an indication of how the perceived daylight adequacy of office spaces may be related to values of MICI, it is not possible at this stage to predict the impact of the use of MICI on real environments. This is because all of the buildings in which the concept of MICI was tested were designed on the basis of daylight factor. If MICI was used in building designs, it is quite possible that the process of optimising MICI in the building may change of form of buildings, and the user perception of these buildings is currently unknown.

The study has also developed a method for the calculation of MICI. Although the process is slightly more complicated (involves the calculation of both the total illuminance and the direct illuminance on all six faces of the reference cube) than other daylight metrics, most software (as long as it can do daylight calculation) should be able to perform the calculation. Additional post-processing is currently required to derive MICI from the calculated illuminance values. This is currently conducted on a spreadsheet and, in the future, could be integrated into lighting software/packages by the developers.

For rooms with simple geometry, a single "room-average" MICI value (equivalent to MRSE) can also be manually calculated for a quick estimation of the room daylighting availability by using Sumpner's principle. The only information required for the calculation are only the total flux entering the window and the reflectance of room surfaces.

One potential problem of implementing MICI in daylight practice is that practically MICI is very hard to measure. A possible solution to this involves using a luminance camera with an ultra wide-angle lens under the following procedures:

1. To measure MICI, HDR images need to be taken to capture the luminance of all points (360°) around the reference point.

2. In the captured HDR images, the recorded luminance value of each individual pixel needs to be examined. Above a given threshold the luminance contribution from the pixel can be considered as direct luminance. All pixels with the luminance value exceeding the threshold will be excluded from the calculation.

3. Convert the rest of the pixels' luminance values to a total illuminance based on their solid angle and orientation, and then averaging the illuminance values of all six cube faces to give the MICI value of the reference point.

The challenging part of this method is to determine the threshold of the direct luminance, which brings up another question that is what should be counted as the indirect daylight flux? Unlike in electrical lighting where the indirect light flux can be defined as the inter-reflected flux by discounting flux direct from the light source(s), in daylighting lights from the light source (skylight & sunlight) may have already been through multiple inter-reflections, for example off other buildings, before entering the window. This study has only considered the internally reflected light as the indirect part of the daylight flux. Determining what counts as indirect flux could be a problem, because it is not clear if externally reflected light should be included. The problem is made even harder with complex fenestration systems (e.g. double facade) where various elements of the system reflect light. Further research is required to assess the impact of light reflected outside the room on the building user's perception of daylight adequacy.

10.3 MICI in artificial lighting design

While this study has only tested MICI in daylighting, it is highly likely that the metric will also work well in artificial lighting. Given MICI's deep connection with MRSE, it is reasonable to believe MICI will show a similar correlation to the perception of illumination adequacy and the perceived brightness in electrical lighting. Moreover, MICI may be more useful than MRSE under non-uniform lighting conditions, given its nature of being able to be sub-sampled. Artificial lighting with non-uniform distribution might not be very common in offices, however, it is common in some other environments such as restaurants and galleries.

Cuttle has proposed a design procedure for electrical lighting based on MRSE and TAIR concepts. He called the method "The Lighting Design Objectives (LiDOs) procedure" [100] and encouraged lighting designers to test it in practice. The LiDOs procedure focuses on providing illumination for its influence on the appearance of the space, and objects within the space rather than visual performance. To use this MRSE/TAIR design procedure, firstly, it is necessary to create a MRSE value; taken from Table 9- *2* to ensure expectation of ambient illuminance is met. Then it is necessary to develop an illuminance hierarchy of the space (creating visual emphasis), and the target/ambient illuminance ratios need to be decided for each of the major room surfaces and objects of interest. Cuttle has also provided a reference table (see Table 10- *1*) showing the relationship of TAIR and visual emphasis. After carefully balancing the target MRSE and TAIR levels a total amount of direct flux and its distribution can be developed. Cuttle summarised the procedures using a flow chart (see Figure 10- *1*). Finally, the designers can select suitable luminaires and their mounting positions based on the direct flux distribution.

Visual Emphasis	TAIR
Emphatic	40
Strong	10
Distinct	3
Noticeable	1.5
Absent	1.0

Table 10- 1: Proposed visual emphasis/TAIR relationship (Table 2 from Cutte's article "The lighting design objectives (LiDOs) procedure" *[100]*)

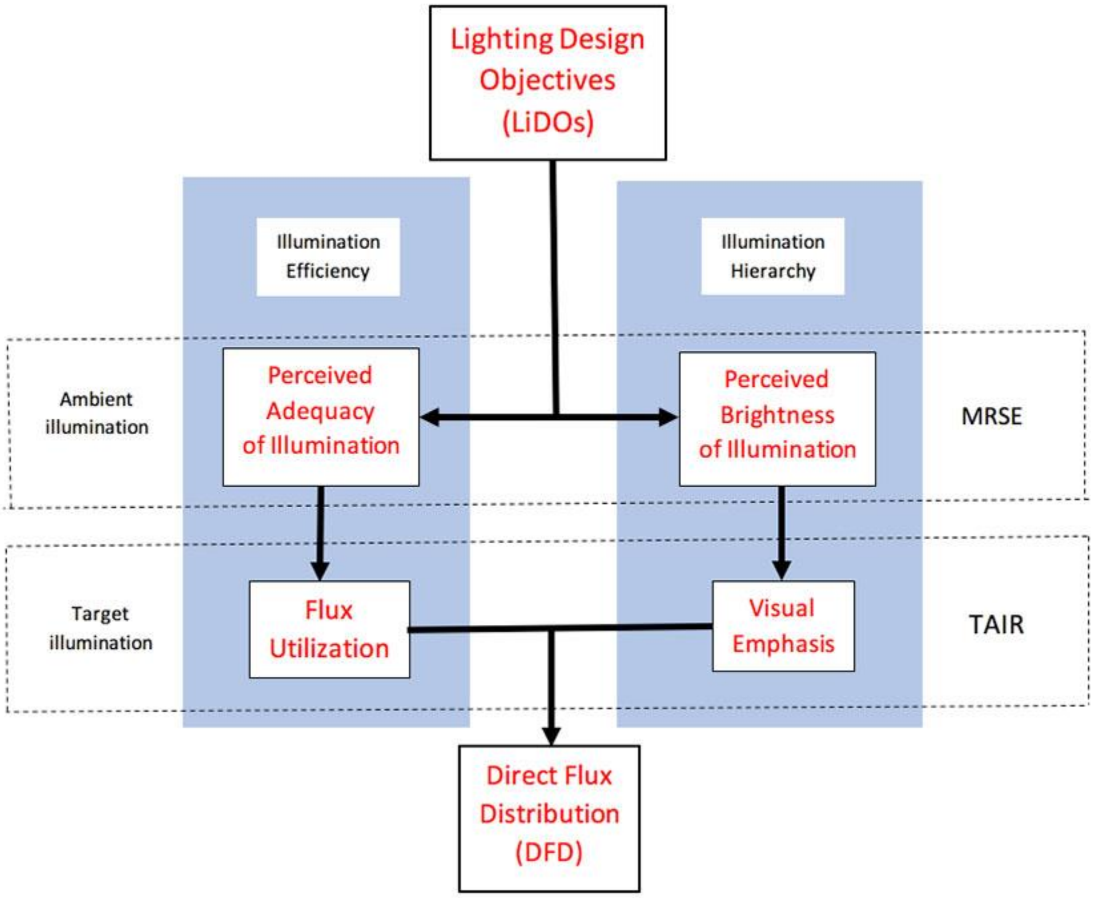


Figure 10- 1: The LiDOs procedure chart (Figure 1 from Cutte's article "The lighting design objectives (LiDOs) procedure" *[100]*)

The LiDOs procedure provides a new way of approaching lighting design, and it is believed that MICI can also work perfectly with this design procedure. Given that the room-wide average MICI equals the value of MRSE, MRSE can be replaced by MICI in the LiDOs procedure. The use of MICI instead of MRSE will have a few advantages. Firstly, MICI can be more universally applied to buildings with complex geometry. For open-plan spaces or more complicated room shapes (examples were given in Section 3.3) where the MRSE concepts start to break down, MICI can be calculated at any given point(s) regardless of the geometries. Secondly, because that MICI can be sub-sampled, it gives the flexibility for this design procedure to be used under non-uniform lightings. Instead of using one single MRSE value to describe the ambient illuminance of the entire space (which may give problems in spaces that have an uneven light distribution), the space can now be sub-divided into zones with different ambient illumination and each being described by an average MICI value at the local level. This can further refine the lighting design and also make the design of illuminance hierarchy/visual emphasis with TAIR more accurate. It may also be quite useful for some advanced lighting designs such as open plan art galleries, shopping centres and hospitality projects.

Implementing MICI in the LiDOs procedure may add complications to calculation process especially for balancing the target ambient MICI and the TAIR levels of the important room surfaces and objects. Fortunately, with the help of lighting simulation software, it is possible to engineer a desired lighting scene for the given environment. In addition, this study has developed a spreadsheet that calculates both the MRSE value and MICI values for a room, based on luminances on room surfaces (refer to Section 3.6).

In summary, although it may be hard to work out the most suitable direct flux distribution for buildings with complex geometries, MICI may provide the designers with a useful tool to tackle both general and more complex lighting designs in practice.

10.4 Chapter summary

This chapter discussed how MICI can be applied in lighting practice. Although this new metric requires a slightly more complicated calculation process and is very difficult to measure indirectly, MICI can be a useful tool for both daylighting and electrical lighting designs.

Chapter eleven: Conclusion

11.1 Context

With the changes in the way people use the modern office environment, the current daylighting metrics which still solely focus on the horizontal work plane are no longer necessarily the best way to specify daylight. This study investigated the possibilities of applying MRSE concepts, which were initially developed for electrical lighting design, to daylighting. Problems were found when applying MRSE in a range of daylit interiors and a new metric MICI was developed. It is believed that MICI is an improvement over MRSE with its universal applicability and its relationship to the perceived adequacy of illumination at a point in the room. The study then changed its focus from MRSE to MICI, exploring the relationship of this new metric to people's perception of daylight adequacy and drawing comparisons with the working plane based daylight metrics.

11.2 Research findings

The following section reviews the main findings of this study by re-visiting the research objective (as listed in Section 3.6). A short conclusion was given for both the research objectives and the research hypothesis.

- *Compare the performance of various daylight metrics, including daylight factor, CBDM metrics, and MICI and assess which metric best correlates with the perception of daylight adequacy*

It was found that MICI correlated with the perception of daylight adequacy as well or better than conventional daylight metrics in the 3 case study buildings and was significantly better than working plane illuminance in the controlled study. Moreover, in each element of the study there was some degree of correlation between the daylight metrics and it is possible to explain the correlation of the traditional daylight metrics to building users' perceptions via their correlation with MICI.

For the study hypothesis (as stated in Section 3.7):

> *As MICI is a metric derived from MRSE it is hypothesised that MICI will show better connections with people's perception of adequate daylighting than other daylight related metrics.*

This hypothesis was found to be correct. MICI indeed showed better association with people' perception of daylight adequacy than other working plane based daylight metrics.

11.3 Research impacts

The following section reviews the impact of this study by re-visiting the potential research benefits (as listed in Section 3.6).

1. *To establish the most effective daylight metric for assessing daylight adequacy.*

MICI was found to correlate very well with the perceptions of daylight adequacy. It was found that MICI in the range of 150 to 350 lx was rated by most subjects as "about right". However, previous studies on electric lighting has suggested slightly lower values of illuminances and further work is necessary to establish a minimum value for an acceptable MICI level in daylit interiors.

2. *To contribute to the knowledge of daylight designs.*

The application of MICI to building and daylight design is likely to increase the use of highly reflective surfaces, internal light shelves and the control of light entering the room be external overhangs rather than smaller windows or tinted glass.

3. *To contribute to the knowledge of daylight calculations and simulations.*

Ways to calculate the new metric of MICI have been developed and used within this study. Moreover, through a series of calculations it has been demonstrated that the average MICI (of the entire room) is the same of MRSE in a range of rooms.

11.4 Research limitations and suggestions for future works

As already been discussed extensively, one main limitation of this study is that daylight metrics were not completely independent variables. Although the controlled experiment was designed to reduce the associations between the metrics, all of the daylight metrics are functions of the sky brightness, the building geometry and the surface properties, and as a result the correlation is inevitable. Nevertheless, the controlled experiment successfully reduced correlation between the daylight metrics (compared with the POE case studies) and found that the correlation between MICI and the perception of daylight adequacy was significantly stronger than other metrics. It is possible that the existing relationships of other metrics to the users' perceptions were due to their correlations with MICI.

Another limitation of the study is that MICI was tested in only a few daylit buildings (three office buildings and 2 controlled environments). These selected cases cannot represent a comprehensive range of offices, not to mention buildings with other function types (for example commercial and residential buildings) in which the role of daylighting may be significantly different. Moreover, the tested buildings were all designed on basis of daylight factor (buildings were specifically designed to achieve certain levels of daylight factor). If MICI replaced daylight factor and was used in building designs, it is quite possible that the form of buildings may change in the process of optimising MICI. Then the user perception of these building (designed on basis of MICI) will become uncertain again. For the future work, it will be useful to know how the use of MICI would affect building designs, and whether the correlation between MICI and the user perception will change under such conditions.

In terms of defining the "indirect light", this study has only considered the internally reflected light as the indirect part of the daylight flux. Whether or not the externally reflected daylight should be counted as the indirect flux in the MICI calculation is yet unknown. Further research is required to investigate the impact of externally reflected daylight on the building users' perceptions of daylight adequacy.

Finally, as discussed in Section 6.3.2, MICI is likely to also work well with artificial lighting, especially for non-uniform lighting conditions. However, further testing is required to establish if MICI as a metric works better than MRSE in spaces that have non-uniform electric lighting.

References

[1] R. Hobday, The Healing Sun: Sunlight and Health in the 21st Century, Forres, Scotland: Findhorn Press, 2000.

[2] D. Berson, F. Dunn and M. Takao, “Phototransduction by Retinal Ganglion Cells that Set the Circadian Clock,” *Science,* vol. 8, 2002.

[3] R. Lucas, S. Peirson, D. Berson, T. Brown, H. Cooper, C. Czeisler, M. Figueiro, P. Gamlin, S. Lockley, J. O'Hagan, L. Price, I. Provencio, D. Skene and G. Brainard, “Measuring and Using Light in The Melanopsin Age,” *Trends in Neurosciences,* vol. 37(1), pp. 1-9, January 2014.

[4] CCIV 244, “Nefertiti as Divine Protector of Akhenaten’s Sarcophagus,” [Online]. Available: http://ccivcopy.site.wesleyan.edu/project-5/1120-2/. [Accessed 06 July 2016].

[5] The Telegraph, “Shed Love: A Selection of Images of Readers' Sheds and Sheds of The Famous,” [Online]. Available: http://www.telegraph.co.uk/gardening/gardeningpicturegalleries/8926077/Shed-love-a-selection-of-images-of-readers-sheds-and-sheds-of-the-famous.html?image=23. [Accessed 06 July 2016].

[6] M. Rea, “What Ever Happened to Visual Performance,” in *The Trotter-Paterson Lecture 2012*, 2012.

[7] C. Cuttle, “Towards The Third Stage of The Lighting Profession,” *Lighting Research and Technology,* vol. 00, pp. 1-21, 2009.

[8] C. Cuttle, “A New Direction for General Lighting Practice,” *Lighting Research and Technology,* vol. 45, pp. 22-39, 2013.

[9] P. Chynoweth, “Progressing the Rights to Light Debate – Part 1: A Review of Current Practice,” *Structural Survey ,* vol. 22(3), pp. 131-137, 2004.

[10] P. Chynoweth, “Progressing the Rights to Light Debate,” *Structural Survey,* pp. Vol.23 Iss 4 pp. 251-264, 2005.

[11] P. Moon and D. E. Spencer, “Illumination from A Non-uniform Sky,” *Transaction of the Illumination Engineering Society,* vol. 37, 1942.

[12] CIE, CIE016-1970, Daylight, ISBN 978 3 901906 66 4, Commission Internationale de L'Eclairage, 1970.

[13] International Lighting Vocabulary, “17-279 Daylight Factor,” CIE, 2014. [Online]. Available: http://eilv.cie.co.at/term/279. [Accessed 08 09 2019].

[14] S. Darula, Daylighting in The Exterior and in The Interior, Bratislave: Slovenska Technicka Univerzita, 2011.

[15] R. G. Hopkinson, P. Petherbridge and J. Longmore, Daylighting, London: Heinemann, 1966.

[16] E. W. Sumptner, “The Diffusion of Light,” *Proc. Phys. Soc (London),* vol. 12, pp. 10-29, 1892.

[17] R. G. Hopkinson, J. Longmore and P. Petherbridge, “An Empirical Formula for the Computation of the Indirect Component of Daylight Factor,” *Trans. Illum. Eng. Soc. (London),* vol. 14, no. 7, pp. 201-219, 1954.

[18] J. A. Lynes, “A Sequence for Daylighting Desgin,” *Lighting Research and Technology,* vol. 11, no. 2, pp. 102-106, 1979.

[19] V. Crisp and P. J. Littlefair, “Average Daylight Factor Predicton,” in *CIBS naional lighting conference 1984*, London, 1984.

[20] M. Naeem and M. Wilson, “A Study of The Application of The BRE Average Daylight Factor Formula to Rooms with Window Areas Below The Working Plane,” in *2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies in the 21st Century*, Crete island, Greece, 2007.

[21] A. F. Dufton, “Protractors for the Computation of Daylight Factors,” *Building Research and Technology,* p. Paper No.28, 1946.

[22] BRE, “Estimating Daylight in Buildings: Part 1,” *Building Research Establishment Digest 309,* 1986.

[23] N. Baker, A. Fanchiotti and K. Steemers, Daylighting in Architecture: A European Reference Book, New York: Routledge, 1993.

[24] P. Tregenza, “Opinion: Climate-bsaed Daylight Modelling or Daylight Factor,” *Light Research and Technology,* vol. 46, p. 618, 2014.

[25] P. Littlefair, Site Layout Planning for Daylight and Sunlight: A Guide to Good Practice, BR 209, Warford: BRE Trust, 2011.

[26] P. R. Tregenza, “The Daylight Factor and Acutal Illuminance Ratios,” *Lighting Research and Technology,* vol. 12, no. 2, pp. 64-68, 1980.

[27] CIBSE, “CIBSE Weather Data Sets,” The Charted Institution of Building Services Engineers , [Online]. Available: https://www.cibse.org/weatherdata. [Accessed 28 10 2019].

[28] R. Perez, P. Ineichen, R. Seals, J. Michalsky and R. Stewart, “Modeling Daylight Availability and Irradiance Components from Direct and Indirect Global Irradiance,” *Solar Energy,* vol. 44, no. 5, pp. 271-289, 1990.

[29] R. Kittler, R. Perez and S. Darula, “A New Generation of Sky Standards,” in *The 8th European Lighting Conference. Lux Europa 1997*, Amsterdam, 1997.

[30] P. Tregenza, “Subdivision of The Sky Hemisphere for Luminance Measurements,” *Lighting Research and Technology,* vol. 19, pp. 13-14, 1987.

[31] P. R. Tregenza, “Daylight Coefficients,” *Lighting Research and Technology,* vol. 15, no. 2, pp. 65-71, 1983.

[32] P. J. Littlefair, “The Luminance Distribution of An Average Sky,” *Lighting Research and Techology,* vol. 13, no. 4, pp. 192-198, 1981.

[33] H. Nakamura, M. Oki and Y. Hayashi, “Luminance Distribution of Intermediate Sky,” *Light and Visual Environment,* vol. 9, pp. 6-13, 1985.

[34] M. Perraudeau, “Luminance Models,” *Proceeding CIBSE National LIghting Conference, Cambridge,* pp. 291-292, 1988.

[35] R. Kittler , “Standardardisation of Outdoor Conditions for Calculation of The Daylight Factor with Clear Skies,” *Proc. Conf. Sunlight in Buildings, Rotterdam,* pp. 273-286, 1967.

[36] BS ISO 15469:2004, “Spatial Distribution of Daylight - CIE Standard General Sky”.

[37] R. Perez, R. Seals and J. Michalsky, “All-weather Model for Sky Luminance Distribution-preliminary Configuration and Validation,” *Solar Energy,* vol. 50, no. 3, pp. 235-245, 1993.

[38] P. R. Tregenza, “Analysing Sky Luminance Scans to Obtain Frequency Distributions of CIE Standard General Skies,” *Lighting Research and Technology,* vol. 36, no. 4, pp. 271-279, 2004.

[39] CIE, “Guide to Recommended Practice of Daylight Measurement,” *ISBN 978 3 900734 50 3,* 1989.

[40] C. F. Reinhart and O. Walkenhorst, “Validation of Dynamic RADIANCE-based Daylight Simulations for A Test Office with External Blinds,” *Energy and Buildings,* vol. 33, pp. 683-697, 2001.

[41] J. Mardaljevic, “Simulation of Annual Daylighting Profiles for Internal Illuminance,” *Lighting Research and Technology,* vol. 32, no. 3, pp. 111-118, 2000.

[42] IES, The Lighting Handbook, 10th Edition, Illuminating Engineering Society , 2011.

[43] IES, Approved Method: IES Spatial Daylight Autonomy(sDA) and Annual Sunlight Exposure(ASE), Illumination Engineering Society , 2013.

[44] J. Mardaljevic and A. Nabil, “Useful Daylight Illuminances: A New Paradigm for Assessing Daylight in Buildings,” *Light Research and Technology,* vol. 37, pp. 41-59, 2005.

[45] A. Nabil and J. Mardaljevic, “Useful Daylight Illuminances: A Replacement for Daylight Factors,” *Energy and Buildings,* vol. 38, pp. 905-913, 2006.

[46] The UK Government , “Priority School Building Programme,” 12 March 2014. [Online]. Available: https://www.gov.uk/government/collections/priority-school-building-programme-psbp. [Accessed 16 September 2019].

[47] U.S. Green Building Council, “Green Building Leadership Is LEED,” USGBC, [Online]. Available: https://new.usgbc.org/leed. [Accessed 16 September 2019].

[48] J. Mardeljevic, “Climate-based Daylight Modelling and its Discontents,” in *CIBSE Technical Symposium*, London, UK, 16-17 April 2015.

[49] R. Perez, R. Seals, J. Michalsky and P. Ineichen, “Geostatistical Properties and Modeling of Random Cloud Patterns for Real Skies,” *Solar Energy,* vol. 51, no. 1, pp. 7-18, 1993.

[50] J. Mardeljevic , “The BRE-IDMP Dataset: A New Benchmark for The Validation of Illuminance Prediction Techniques,” *Light Research and Technology,* vol. 33, no. 2, pp. 117-136, 2001.

[51] J. Mardaljevic, J. Christoffersen and P. Raynham, “A Proposal for a European Standard for Daylight in Buildings,” in *Lux Europa 2013 12th European Lighting Conference*, Krakow, Poland , 2013.

[52] BSI, “BS EN 17037: 2018 Daylight in Builidngs,” The British Standards Institution, 2018.

[53] J. Mardaljevic and J. Christoffersen, “A Roadmap for Upgrading National/EU Standards for Daylight in Builidings,” in *CIE Midterm conference - Towards a new century of light*, Paris, France , 2013.

[54] BS EN 12464-1, “Light and Lighting-Lighting of Work Places-Part 1: Indoor Workplaces,” *Published in the UK by British Standards,* 2011.

[55] J. Duff and K. Kelly, “A New Approach to Interior Lighting Design: Early Stage Research in Ireland,” *SDAR Journal of Sustainable Design & Applied Research ,* vol. 2, no. 1, pp. 16-22, 2014.

[56] J. Duff, “On A New Method for Interior Lighting Design,” Dublin Institute of Technology , 2015. [Online]. Available: https://arrow.dit.ie/engdoc/85/. [Accessed 23 09 2019].

[57] J. Duff, K. Kelly and C. Cuttle, “Spatial Brightness, Horizontal Illuminance and Mean Room Surface Exitance in A Lighting Booth,” *Lighting Research and Technology ,* vol. 49, no. 1, pp. 5-15, 2015.

[58] J. Duff, K. Kelly and C. Cuttle , “Perceived Adequacy of Illumination, Spatial Brightness, Horizontal Illuminance and Mean Room Surface Exitance in A Small Office,” *Lighting Research and Technology ,* vol. 49, no. 2, pp. 133-146, 2017.

[59] C. Cuttle, “Cubic Illuminance,” *Lighting Research and Technology,* vol. 29, no. 1, pp. 1-14, 1997.

[60] J. A. Lynes, W. Burt, G. K. Jackson and C. Cuttle, “The Flow of Light into Buildings,” *Trans. Illum. Eng. Soc.,* vol. 31, no. 3, pp. 65-91, 1966.

[61] P. Moon and D. E. Spencer , The Photic Field, Cambridge: MIT Press , 1981.

[62] SLL, SLL Code for Lighting, London: CIBSE, 2018.

[63] J. Entwistle, “Cuttle's theory: the profession responds,” *Newsletter: The Society of Light and Lighting,* vol. 3, no. 1, pp. 6-8, 2010.

[64] K. Mansfield , “Comment 2: Towards the Thrid Stage of Lighting Profession,” *Lighting Research and Techology,* vol. 00, pp. 17-18, 2009.

[65] P. Boyce, “Lighting Quality for All,” in *Proceedings of the SLL International Lighting Conference*, Dublin, April 2013.

[66] P. Raynham, J. Unwin and L. Guan, “A New Metric to Predict Perceived Adequacy of Illumination,” *Lighting Research and Technology,* vol. 51, no. 4, pp. 642-648, 2019.

[67] P. A. Jay, “Lighting and Visual Perception,” *Lighting Research and Technology,* vol. 3, pp. 133-146, 1971.

[68] CIE 198: 2011, “Determination of Measurement Uncertainties in Photometry,” *ISBN: 978-3-902842-00-8,* 2011.

[69] I. Ashdown, Radiosity: A Programmer's Perspective, New York: Wiley, 1991.

[70] Relux, “ReluxDesktop - A New Approach to Planning,” Relux, [Online]. Available: https://reluxnet.relux.com/en/relux-desktop.html. [Accessed 19 05 2020].

[71] DIALux, “DIALux is the Software for Professional Lighting Design,” DIALux, [Online]. Available: https://www.dial.de/en/dialux/. [Accessed 19 05 2020].

[72] AGI32, “The Lighting Industry's Premier Calculation Tool,” LightingAnalysts, [Online]. Available: https://lightinganalysts.com/software-products/agi32/overview/. [Accessed 19 05 2020].

[73] A. Iversen, N. Roy, M. Hvass, M. Jorgensen, J. Christoffersen, W. Osterhaus and K. Johnsen, Daylight Calculations in Practice, Copenhagen: Danish Building Research Institute, Aalborg University, 2013.

[74] G. W. Larson, “The Holodeck: A Parallel Ray-caching Rendering System,” 1998. [Online]. Available: http://radsite.lbl.gov/radiance/papers/index.html. [Accessed 23 10 2015].

[75] Radiance-online, “Detailed Description,” Radiance-online, 13 01 2012. [Online]. Available: https://radiance-online.org/about/detailed-description.html. [Accessed 28 11 2018].

[76] DAYSIM, “Engineering Guide,” DAYSIM, [Online]. Available: http://daysim.ning.com/page/program-structure. [Accessed 28 11 2018].

[77] G. G. Roy, “A Comparative Study of Lighting Simulation Packages Suitable for Use in Architectural Design,” 10 2000. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.595.2404&rep=rep1&type=pdf.. [Accessed 28 11 2018].

[78] R. Bunn, Towards a Theory of Carrying Capacity. Evidence form Long-Term Longitudinal Case-Studies of Occupant Satisfaction in Non-Domestic Buildings, Doctoral thesis. University College London, 2018.

[79] R. Cohen, M. Staneven, B. Bordass and A. Leaman , “Assessing Building Performance in Use 1: The PROBE Process.,” *Building Research and Information ,* vol. 29, no. 2, pp. 85-102, 2001.

[80] M. Gardiner , H. White, M. Munzinger and W. Ray, “Low Carbon Builidng Programme 2006 to 2011: Final Report,” August 2011. [Online]. Available: https://www.gov.uk/government/publications/low-carbon-building-programme-2006-to-2011-final-report. [Accessed 25 09 2019].

[81] Innovate UK, “Building Performance Evaluation Programme: Findings from Non-domestic Projects Report,” January 2016. [Online]. Available: https://www.gov.uk/government/publications/low-carbon-buildings-best-practices-and-what-to-avoid. [Accessed 25 09 2019].

[82] S. Wilson and A. Hedge , The Office Environment Survey: A Study of Building Sickness. A Study Sponsored by the Health Promotion Research Trust., London: Bulstrode Press, 1987.

[83] G. J. Raw, S. K. Coward, C. E. Aizlewood, K. Rathouse and D. J. Wilde, “What Do "Real People" Mean by Indoor Air Quality?,” in *Proceedings of Indoor Air 2002. Vol 3. pp 156-161*, Monterey California, 2002.

[84] A. T. Parkinson , R. Reid, H. McKerriw and D. Wright, Evaluating Positivist Theories of Occupant Satisfaction: A Satistical Analysis, Routledge. ISSN: 0961-3218: Building Research and Information, 2017.

[85] ASHRAE, “Weather Data,” ASHRAE, [Online]. Available: https://www.ashrae.org/technical-resources/bookstore/ashrae-international-weather-files-for-energy-calculations-2-0-iwec2. [Accessed 25 09 2019].

[86] G. W. Larson and R. Shakespeare, Rendering with Radiance: the Art and Science of Lighting Visualization, Davis, California, USA: Space and Light , 2003.

[87] AUTODESK, “3D CAD Software,” AUTODESK, [Online]. Available: https://www.autodesk.com/solutions/3d-cad-software. [Accessed 28 10 2019].

[88] G. Ward, “RADIANCE Manual Pages- GENSKY (1),” RADIANCE-Online , 24 04 1998. [Online]. Available: https://radiance-online.org/learning/documentation/manual-pages/pdfs/gensky.pdf. [Accessed 28 10 2019].

[89] SPSS, “IBM SPSS Statistics,” IBM, [Online]. Available: https://www.ibm.com/products/spss-statistics. [Accessed 28 10 2019].

[90] E. Ne'eman and R. G. Hopkinson, “Critical Minimum Acceptable Window Size: A Study of Window Design and Provision of View,” *Lighting Research and Technology ,* vol. 2, no. 1, pp. 17-27, 1970.

[91] E. C. Keighley , “Visual Requirements and Reduced Fenestration in Offices: A Study of Window Shape,” *Building Science ,* vol. 8, pp. 311-320, 1973.

[92] E. C. Keighley, “Visual Requirements and Reduced Fenestration in Offices: A Study of Multiple Apertures and Window Area,” *Building Science ,* vol. 8, pp. 321-331, 1973.

[93] EnergyPlus, “Weather Data by Location: Weather Data Download - London Gatwick 037760 (IWEC),” EnergyPlus, [Online]. Available: https://energyplus.net/weather-location/europe_wmo_region_6/GBR//GBR_London.Gatwick.037760_IWEC. [Accessed 28 10 2019].

[94] M. S. Rea, “Visual Performance with Realistic Methods of Changing Contrast,” *Journal of the Illuminating Engineering Society ,* vol. 10, no. 3, pp. 164-177, 1981.

[95] A. P. Field, Discovering Statistics Using SPSS for Windows: Advanced Techniques for The Beginner, London: Sage, 2000.

[96] J. Y. Suk, M. Schiler and K. Kensek, “Discomfort Glare Metrics: Investigating Their Accuracy and Consistency in Daylight Glare Evaluation by Using Human Subject Study Data,” in *Facade Tectonics World Congress* , LA, USA, 2016.

[97] J. Y. Suk, “Evaluating Daylight Glare and Identifying Its Dominant Cause in Computer-Based Office Task Environment,” in *the 15th IBPSA Conference*, San Francisco, CA, USA, 2017.

[98] B. W. P. Wells, “Subjective Responses to the Lighting Installation in Modern Office Building and their Design Implications,” *Building Science,* vol. 1, pp. 57-68, 1965.

[99] J. Duff, PhD Thesis: On A New Method for Interior Lighting Design, Dublin: Dublin Institute of Technology, 2015.

[100] C. Cuttle, “The Lighting Desgin Objectives (LiDOs) Procedure,” Illuminating Engineering Society, 7 11 2018. [Online]. Available: https://www.ies.org/fires/the-lighting-design-objectives-lidos-procedure/. [Accessed 3 10 2019].

[101] D. L. Loe, K. B. Mansfield and E. Rowlands, “Appearance of Lit Environment and Its Relevance in Lighting Design: Experimental Study,” *Lighting Research and Technology ,* vol. 26, no. 3, pp. 119-133, 1994.

[102] D. L. Loe , K. P. Mansfield and E. Rowlands, “A Step in Quantifying the Appearance of a Lit Scene,” *Lighting Research and Technology,* vol. 32, no. 4, pp. 213-222, 2000.

[103] J. Unwin and L. Guan, “Clear as Daylight,” *The Lighting Journal,* vol. Lighting Journal October 2016, pp. 16-19, 2016.

[104] D. Bourgeois, C. F. Reinhart and G. Ward, “Standard Daylight Coefficient Model for Dynamic Daylighting Simulations,” *Building Research & Information ,* vol. 36, no. 1, pp. 68-82, 2008.

[105] J. E. Flynn, T. J. Spencer, O. Martyniuk and C. Hendrick , “Interim Study of Procedures for Investigating the Effect of Light on Impression and Behaviour,” *Journal of the Illuminating Engineering Society ,* vol. 3, pp. 87-94, 1973.

[106] J. A. Veitch , “Psychological Process Influencing Lighting Quality,” *Journal of the Illuminating Engineering Society ,* vol. 30, pp. 124-140, 2001.

Annex One: A preliminary study on the RADIANCE simulation parameters

RADIANCE is a highly flexible and sophisticated modelling tool, and the accuracy of the calculation is controlled by many simulation parameters. One particularly important parameter for calculating MICI is the Ambient Bounces (-ab) setting, as it defines how many times of light reflecting bounces RADIANCE will count before it stops tracing each emitted ray. To investigate the optimal -ab setting for the MICI calculation of this study, a test study was conducted over a small section area of one of the studied case buildings (*Figure A1-1*).

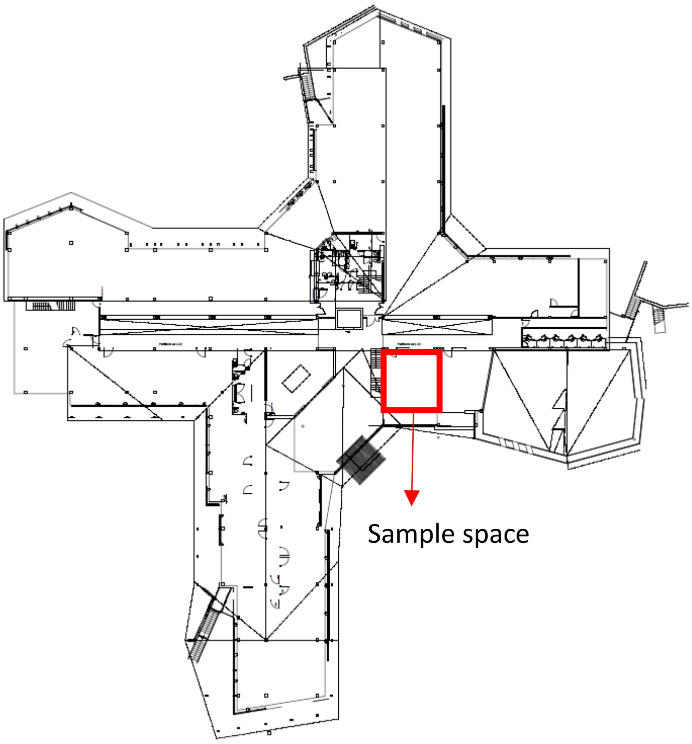


Figure A1-1: The sample room (Building 3 - 1F)

This selected sample space has a room dimension of 7m (Length) x 7m (Width) x 2.5m (Height). In the room, a calculation grid was lard out every 1m between each point horizontally and 0.4m vertically. Under a CIE Standard Overcast Sky with an external illuminance of 14900 lx, the average values of daylight factor (on the 0.8m height plane) and the average MICI values of the entire space were calculated under different -ab settings. Other settings remained unchanged during the calculations and were same settings as listed in *Table 6-* 3: *RADIANCE parameters used for the daylight calculations*

. *Table A1-1* shows the results of the calculated average daylight factor, average MICI and the total calculation under different -ab settings.

	-ab 2	-ab 3	-ab 4	-ab 5	-ab 6	-ab 7	-ab 8	-ab 9	-ab 10
Avg. DF	1.4%	1.7%	1.9%	2.0%	2.1%	2.1%	2.2%	2.2%	2.2%
Avg. MICI	138	183	225	243	259	264	271	273	275
calculation time	26s	40s	52s	66s	76s	92s	121s	134s	146s

Table A1-1: Daylight factor and MICI values under difference Ambient Bounces settings

Figure A1-2 below shows that with higher -ab value, the DF and MICI results increases. However, when -ab value reached around 8 the changes of DF and MICI value in the room became quite minor.

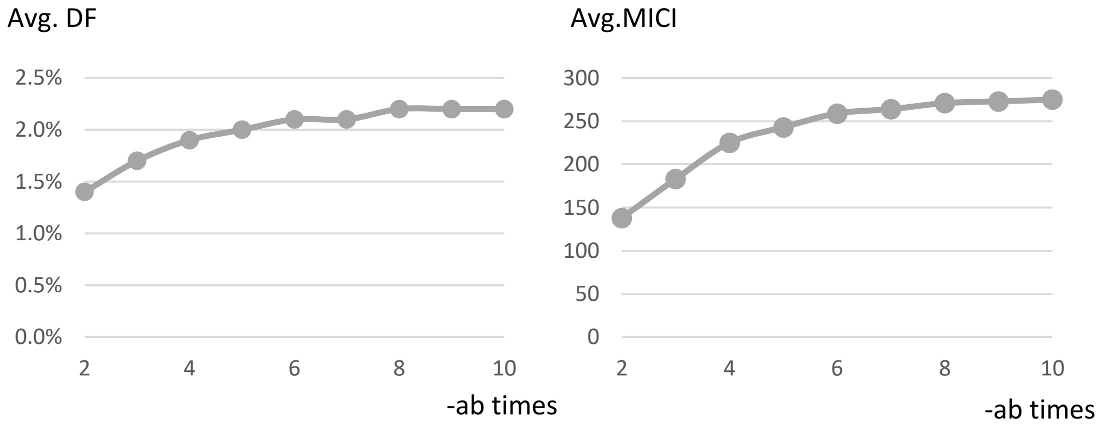


Figure A1-2: Ambient Bounces time vs average DF (left) and average MICI (right) results

Considering that the calculation time also increased quite largely with high -ab settings (note that this calculation is just for a sample space, and the calculation time needed for the entire building will be much longer), it was therefore decided to use a value of 8 as the RADIANCE -ab setting for this study.

Annex Two: Calculating the room average MICI (or MRSE) under daylighting with Hopkinson's split flux method

The average MICI in a side-daylit room can be calculated to a first approximation using Hopkinson's split flux method. Detailed calculation processes are as below:

The total light flux entered the room is estimated by:

$$\phi = E_w \cdot A_w$$

Where E_w is the illuminance measured at the centre of the window reading;

A_w is the area size of the window.

The flux is split and assumed to be accordingly absorbed by the lower and upper surfaces of the room. The lower and upper room surfaces are separated by the plane of the mid-height of the window.

According to Hopkinson [17], the reflection from the ground should generally be assumed to have a brightness 1/10th of the mean sky brightness.

Hence the First Reflected Flux for the lower room surfaces should be:

$$\text{First Reflect Flux (lower)} = 0.9\phi \cdot R_{fw}$$

Where R_{fw} is the average reflection factor of the lower room surfaces.

And the First Reflected Flux for the upper room surfaces should be:

$$\text{First Reflect Flux (upper)} = 0.1\phi \cdot R_{cw}$$

Where R_{cw} is the average reflection factor of the upper room surfaces.

For the average reflection factor of the lower room surfaces (R_{fw}), it equals:

$$\mathrm{R_{fw}} = \frac{\mathrm{R_{floor}{\cdot}A_{floor}{+}R_{wall}{\cdot}A_{lower\ wall}}}{\mathrm{A_{floor}{+}A_{lower\ wall}}}$$

Where R_{floor} is the reflectance of the floor;

R_{wall} is the reflectance of the wall;

A_{floor} is the area of the floor;

$A_{lower\ wall}$ is the area of those parts of the wall below the plane of the mid-height of the window (excluding the window wall).

Similarly, the average reflection factor of the upper room surfaces (R_{cw}) equals:

$$\mathrm{R_{cw}} = \frac{\mathrm{R_{ceiling}{\cdot}A_{ceiling}{+}R_{wall}{\cdot}A_{upper\ wall}}}{\mathrm{A_{ceiling}{+}A_{upper\ wall}}}$$

Where $R_{ceiling}$ is the reflectance of the ceiling;

R_{wall} is the reflectance of the wall;

$A_{ceiling}$ is the area of the ceiling;

$A_{upper\ wall}$ is the area of those parts of the wall above the plane of the mid- height of the window.

Since the average MICI value of the entire room numerically equals MRSE (as discussed in Chapter 3.6). It can then be calculated by:

$$\mathrm{MICI(room\ average)} = \frac{\mathrm{First\ Reflected\ Flux}}{\mathrm{A_r}(1-R)}$$

Where A_r total area of surfaces in the room (ceiling, floor, wall and window);

R is the average reflectance of all surfaces in the room;

$$\mathrm{R} = \frac{\mathrm{R_{ceiling}{\cdot}A_{ceiling}{+}R_{floor}{\cdot}A_{floor}{+}R_{wall}{\cdot}A_{wall}{+}R_{window}{\cdot}A_{window}}}{\mathrm{A_r}}.$$

Therefore,

$$\mathrm{MICI(room\ average)} = \frac{\phi(0.9R_{fw} + 0.1R_{cw})}{\mathrm{A_r}(1-R)}$$

Annex Three: The questionnaire (controlled experiment)

Questionnaire

Tick your information in the checkboxes below:

I acknowledge that I am voluntarily participating this experiment ☐

My Gender is: Male ☐ Female ☐

My age band is: 18-25 ☐ 25-40 ☐ 40-60 ☐ 60+ ☐

---

1. What do you think of the appearance of this room?

Room Decoration

1	2	3	4	5	6	7

Dislike Like

Window View

1	2	3	4	5	6	7

Beautiful Ugly

Room as a working environment

1	2	3	4	5	6	7

Un-comfortable Comfortable

Any impressions of the room:

(use any adjective to describe how the room feels like, or how you feel like in the room)

____

____

____

2.On the next few pages, there will be two lists of paired numbers. Please identify all the pairs with **DIFFERENT** numbers

Gloomy
Radiant
Tense
Relaxed
Interesting
Uninteresting
Dim
Bright
Stimulating
Subdued
Spacious
Confined
Dramatic
Diffuse
Dark
Inadequately lit
Depressing
Disturbing
Sombre
Indistinct
Adequately lit
Formal
Mottled
Glaring
Details indistinct
Details distinct
Non-glaring
Uniform
Informal
Balanced
Simple
Spacious
Even
Disturbing
Cheerful
Inviting
Warm
Sunny
Shaded
Uninviting
Enclosed

25109	25109
74674	74674
53821	53821
65543	65543
15133	15133
75301	75301
40686	40696
97426	97426
94286	94286
47766	47766
64340	64340
50213	50213
97001	97001
29520	29520
95493	95493
54268	54268
10551	10551
81017	81017
11753	11753
37177	37177
58033	58033
65658	65658
33644	33644
64687	64687
52728	52728
34920	34920
84700	84700
53037	53037
83713	83713
58166	58166
79009	79009
85530	75530
79894	69894
71435	71435

61338	61338
73277	73277
77204	77204
37106	37106
33076	33076
78121	78121
23151	23151
18315	18315
50195	50195
66054	66054
95271	95271
76077	76077
44426	44426
89068	89068
27116	27116
58712	58712
69122	69122
45003	45003
88757	88757
99302	99302
33273	33273
75446	75446
49554	49554
92519	92519
22865	22865
44445	44445
10691	10691
92452	92452
28513	28513
33362	33362
56144	56144
73834	73934
58640	58640
73533	73533

98879	98879
35844	35844
37145	37145
43223	43223
93430	93430
77231	77231
26851	26851
39558	39558
97146	97246
86240	86240
50399	50399
30812	30812
98384	98384
46634	46634
91234	91234
84737	84737
20252	20252
82542	82542
87970	87970
26930	26930
35716	35716
86361	86361
40391	40391
15348	15348
67783	67783
30105	30105
42638	42638
56565	56565
49121	49121
39584	39584
62314	62314
77106	77106
15308	15308
31572	31572

69633	69633
40229	40229
85598	85598
61647	61647
59267	59267
78763	78763
38818	38818
84834	84834
46271	46271
22670	22670
12206	12206
46567	46567
51591	51591
26740	26740
27574	27574
78882	78882
91344	91344
83011	83011
26296	26296
32214	32214
50612	50612
80085	80085
93668	93668
93068	93068
19126	19126
25549	25549
82689	82689
80882	80882
46799	46799
33427	33427
30291	30291
63139	63139
81766	81766
20007	20007

3.What do you think of the lighting in this **WHOLE** room?

Uniformity

1	2	3	4	5	6	7

Uniform Non-uniform

Glare

1	2	3	4	5	6	7

Glary Diffused

Visibility of objects in the room

1	2	3	4	5	6	7

Clear/easy Obscure/difficult

Visibility of computer screen

1	2	3	4	5	6	7

Obscure/difficult Clear/easy

Facial communication

1	2	3	4	5	6	7

Face obscure/difficult Face clear/easy

Daylighting

1	2	3	4	5	6	7

Too dim About right Too Bright

Overall rating for the lighting

1	2	3	4	5	6	7

Very bad Very good

4. What do you think of this room as a (daily 9-5) work place?

Room as a daily work place

1	2	3	4	5	6	7
Dislike						Like

Any comments about this room (as a daily work place)?

Annex Four: Additional results from the controlled experiment

1. Kendall's Tau correlation test results for the relationship between daylight metrics (average MCI, point working plane illuminance and average working plane illuminance) and subjects' responses of overall lighting quality:

	Average MICI vs overall lighting quality responses	Point working plane illuminance vs overall lighting quality responses	Average working plane illuminance vs overall lighting quality responses
Kendall's Tau-b (t)	0.081	-0.95	-0.042
Significance (p)	0.396	0.323	0.658
Sample size (N)	62	62	62

Table A4-1: Kendall's Tau correlation coefficient describing the relationship between different daylight metrics and the subjects' responses of overall lighting quality

2. Relationship between daylight metrics and subjects' responses of daylighting glare(1-glary; 7-diffused):

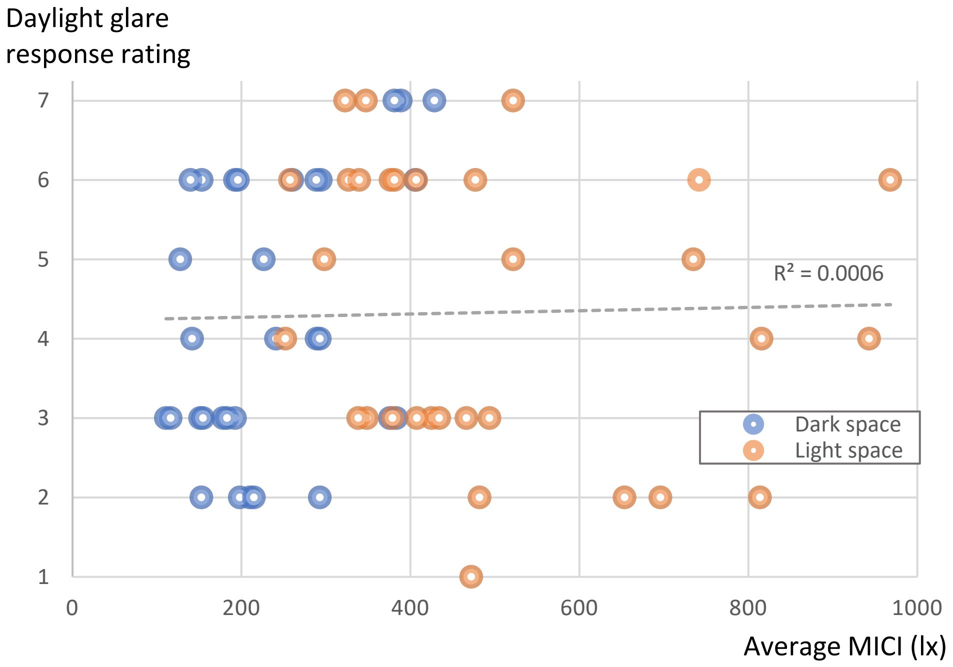


Figure A4-1: Average MICI vs subjects' responses of daylighting glare

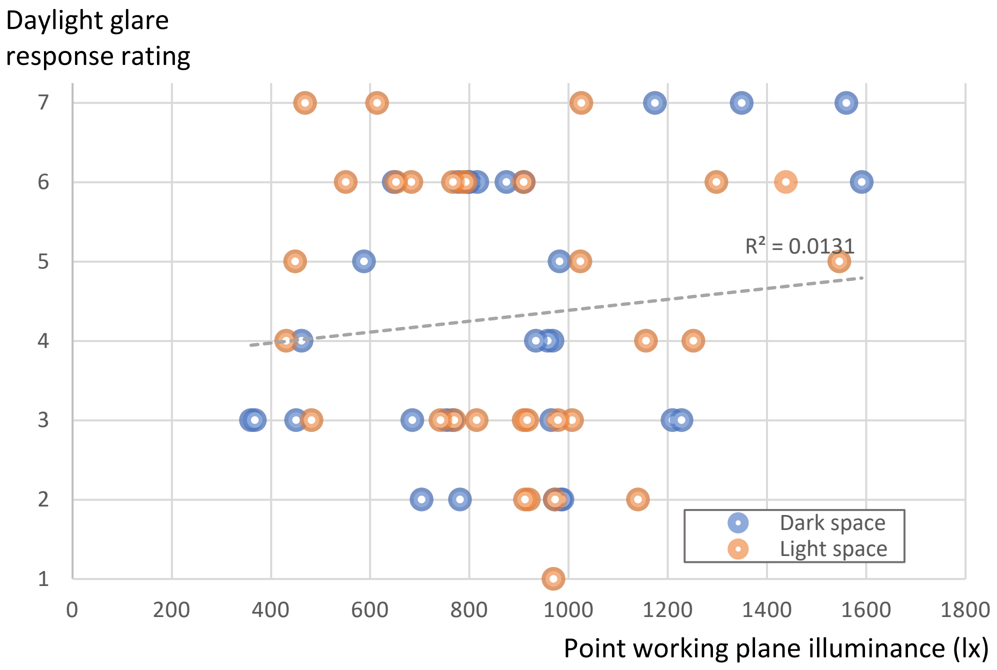


Figure A4-2: Point working plane illuminance vs subjects' responses of daylighting glare

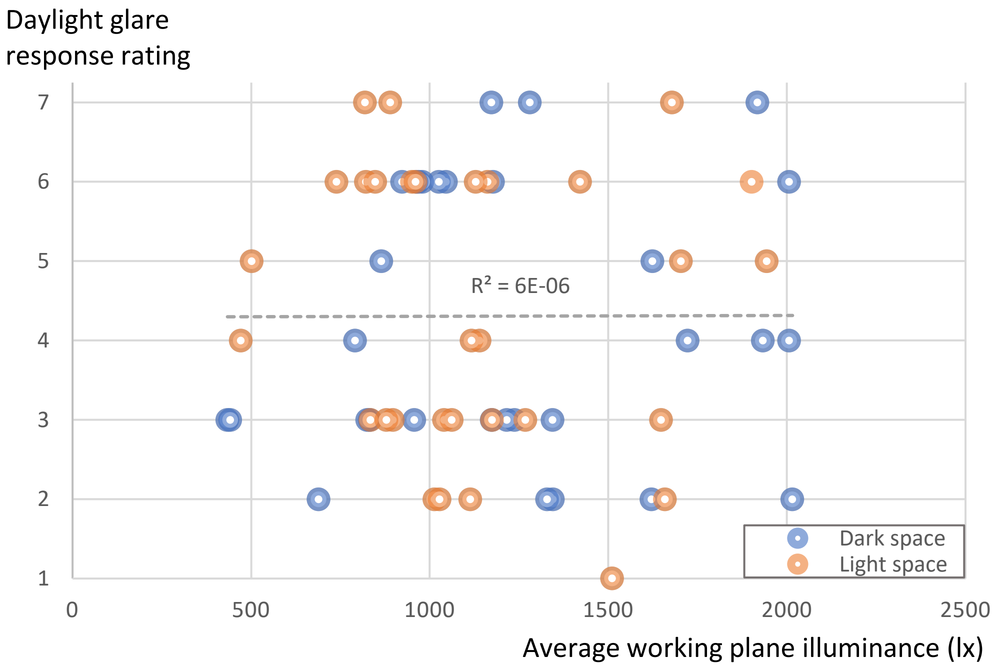


Figure A4-3: Average working plane illuminance vs subjects' responses of daylighting glare

	Average MICI vs daylighting glare responses	Point working plane illuminance vs daylighting glare responses	Average working plane illuminance vs daylighting glare responses
Kendall's Tau-b (t)	0.049	0.010	-0.034
Significance (p)	0.605	0.916	0.718
Sample size (N)	62	62	62

Table A4-2: Kendall's Tau correlation coefficient describing the relationship between different daylight metrics and the subjects' responses of daylighting glare

3. Relationship between daylight metrics and subjects' responses of computer screen visibility (1-Obscure/Difficult; 7-Clear/Easy):

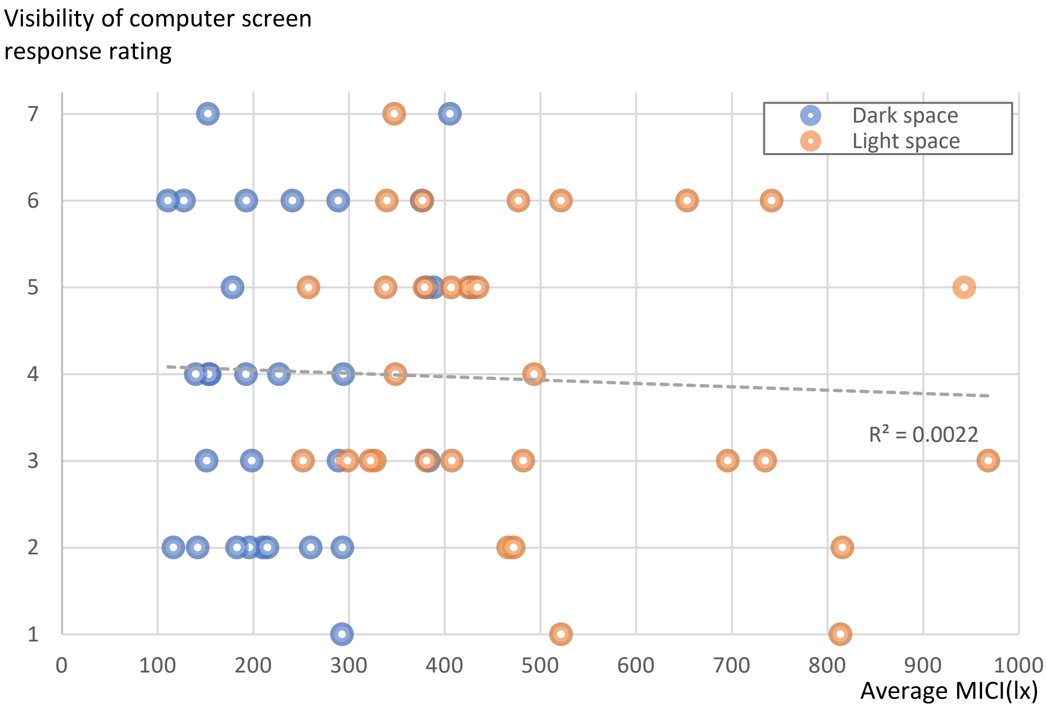


Figure A4-4: Average MICI vs subjects' responses of screen visibility

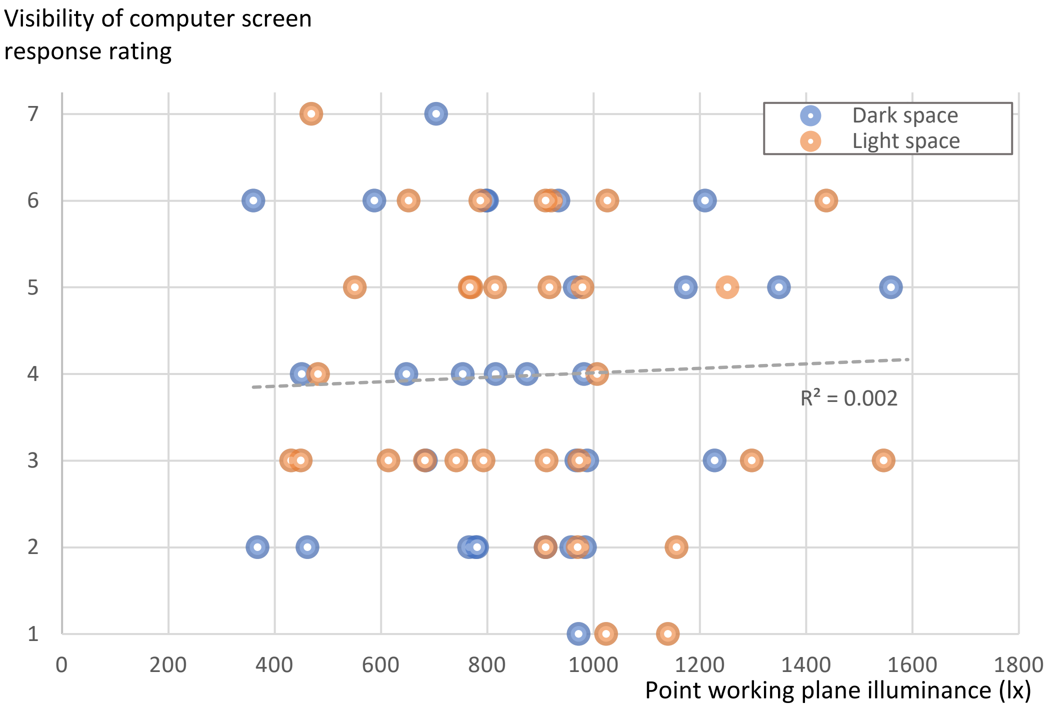


Figure A4-5: Point working plane illuminance vs subjects' responses of screen visibility

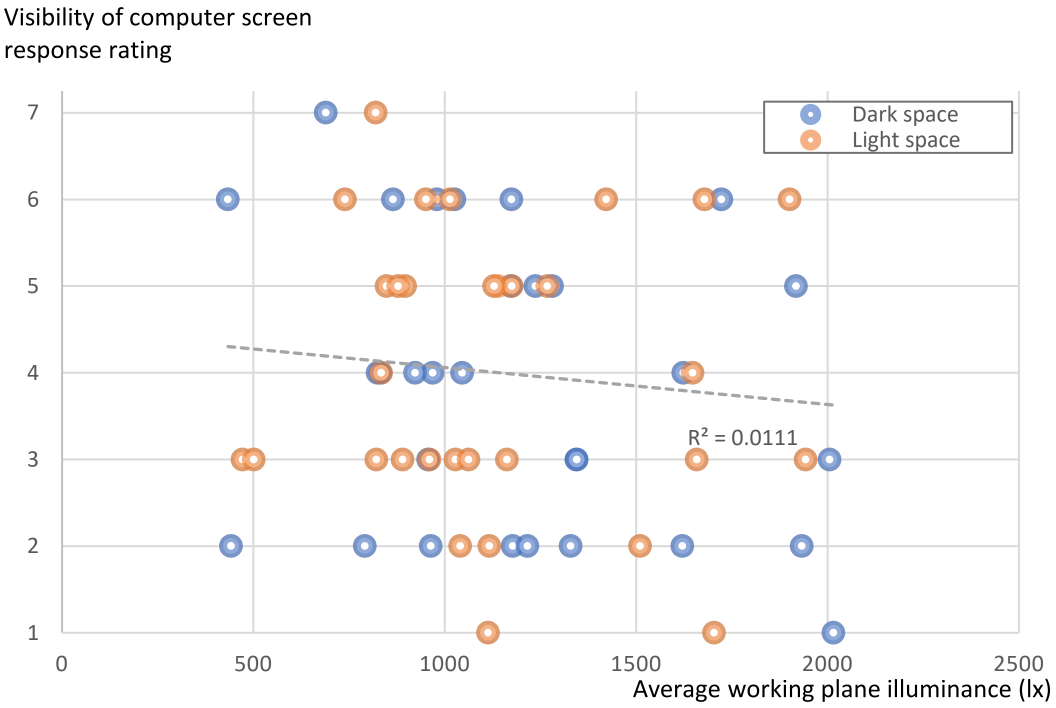


Figure A4-6: Average working plane illuminance vs subjects' responses of screen visibility

	Average MICI vs screen visibility responses	Point working plane illuminance vs screen visibility responses	Average working plane illuminance vs screen visibility responses
Kendall’s Tau-b (t)	0.013	-0.008	-0.097
Significance (p)	0.892	0.931	0.296
Sample size (N)	62	62	62

Table A4-3: Kendall’s Tau correlation coefficient describing the relationship between different daylight metrics and the subjects’ responses of screen visibility