Investigating the effect of daylight on seating preferences in an open-plan space: A comparison of methods

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by

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ABSTRACT

As a dynamic element revealing architectural space, daylight not only provides substantial illumination but may also influence how occupants interact with the space. This thesis investigates one aspect of interaction, whether there is an effect of daylight on seat choice behaviour. Previous studies have provided limited evidence of an association between daylight and seating preferences of individuals, in part because each study employed different methods to measure and quantify seating preferences of individuals. This concern is compounded by the fact that previous research has tended to use a unique set of daylight metrics in addition to a unique set of measurement points in the test space. This raises the discussion as to the method by which daylighting conditions were evaluated and the procedure with which seating preferences were sought.

This study used two procedures to examine whether daylight affects seating preferences in an open plan room. The first was a stated preference approach in which individuals were asked to indicate the factors they perceived to influence their choice of seat location. Responses were sought from both those who were about to enter the room and those who were already seated in the room. Daylight was suggested to be the most important factor amongst those respondents already seated in the room, but was less important among those people who responded at the entrance.

The second was a revealed preference approach which draws inferences on seating preferences from the actual choices made by individuals in the test room. The data were collected using two methods. One was a snapshot method, recording actual seating behaviour of individuals at regular intervals and the other was a walk-through method, following individuals from the moment they entered the room until they chose a seat. The influence of daylight was investigated using a dynamic simulation modelling method to predict daylight illuminance in the test space. The method was to derive a set of daylight metrics for each individual seat over the observation period. Results showed that higher illuminances led to increased seat occupancy, but only in close proximity to windows. It was found that using a questionnaire to ask people about their seat choice when already seated led to the suggestion that daylight had stronger influence than was found in the revealed preference approach.

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LIST OF ABBREVIATIONS

BS EN	British Standard European Norm
BSI	British Standards Institution
CBDM	Climate-Based Daylight Modelling
CIBSE	Chartered Institution of Building Services Engineering
CIE	International Commission on Illumination
DA	Daylight Autonomy
DF	Daylight Factor
E	Illuminance
IESNA	Illuminating Engineering Society of North America
Kt	Clearness Index
L	Luminance
MBE	Mean Bias Error
NAO	National Audit Office
RMSE	Root Mean Square Error
SLL	Society of Light and Lighting
SPSS	Statistical Package for the Social Sciences
TMY	Typical Meteorological Year
UDI	Useful Daylight Illuminance

CHAPTER 1. INTRODUCTION

This thesis explores association between daylight and occupant behaviour, specifically the potential influence of daylight on seating preferences in open-plan library workspaces. The approach consists of two phases, the first focusing on surveys asking for the reasons for the choice of seat locations (stated preference) and the second focusing on direct observation of actual seating behaviour (revealed preference). This introductory chapter provides background and context for the study, defines its objectives and outlines the structure of the thesis.

1.1 Background

The ability to perceive the visual environment is dependent upon vision. Human vision is a complex system which involves the acquisition of information through the visual senses and the processing and interpretation of this sensory information into a meaningful representation of the visual environment. This first information gathering task occurs in the eye, and the resulting visual map is sent to the brain, which ultimately processes the image and produces the sense of vision (sight) (Boyce, 2014). Light is fundamental to this process, without light there would be no vision and the visual environment would not be perceptible. To perceive the visual environment a space needs to be lit, whether by daylight delivered through windows or artificial light from electric light sources. Daylight is a constant source of light provided throughout the daylight hours. When daylight becomes insufficient, it can be supplemented by artificial light, which eventually takes over during hours of darkness.

Current lighting practice demonstrates a continued emphasis on the issue of how much light is required for people to perform a particular visual task (Cuttle, 2015; Rea, 2000). The objectives of lighting are widely accepted and recognized by the lighting industry, these include to contribute to the safety of those doing the work, provide a pleasant visual environment and promote well-being and health (Boyce et al., 2003; Boyce, 2014; Hopkinson et al., 1966). The nature of daylight differs from artificial light in that it is dynamic, constantly changing with time of day, time of year, and with variations in weather conditions. This characteristic variety provides a dynamic and appealing appearance, ultimately leading to a visual environment which is inspiring and stimulating for the occupants (Ander, 2003; Leslie, 2003;

Phillips, 2000). Although electric lighting installations increase the visibility of the task, they rarely provide any variation over time or space (Boyce et al., 2003; Boyce, 2014). The need for daylight stems from these essential dynamic characteristics of daylight which electric light cannot replicate.

Daylight was an important design element and remained the primary means of lighting in buildings until the early twentieth century, when for various reasons, not least the development of reliable artificial light sources, the necessity of daylight was beginning to be questioned (Baker and Steemers, 2002; Phillips, 2004; Steane, 2011). There was in fact substantial evidence to support the use of artificial light in contemporary spaces, including scientific innovations, greater lamp efficiency and supplementary lighting systems. Daylight was increasingly restricted and supplemented with artificial light, which became an important lighting strategy as the result of such technological developments and transformations in lighting.

The advancements in lighting technology resulted in a greater dependence on a more controlled visual environment where primary illumination was provided by artificial light. Since the energy crisis of the 1970s, however, the tendency to use artificial lighting has increasingly been criticized for its being one of the major contributors to energy consumption in buildings (Fontenelle, 2008; Leslie 2003; Reinhart et al., 2006; Ruck et al., 2000). Given the widespread increased sensitivity to the environment, currently broadened to the concept of ‘sustainability’, recent efforts are directed by designers towards increasing the use of daylight in buildings since it is recognized as being one of the passive design tools that could significantly reduce dependence on electricity for illumination, thereby reducing the overall building energy consumption. As a consequence, together with its functional role in providing the necessary practical and appealing visual conditions for interior spaces, daylighting has an important role to play in reducing energy consumption in buildings.

Given that people in industrialised countries spend a majority of their time indoors (Klepeis et al., 2001; Wiley et al., 1991), the provision of sufficient daylight illumination is important. By providing a visual link with the natural world outside, daylight can potentially improve health, awareness and feelings of wellbeing in a space, while also contributing job satisfaction and productivity (Heschong, 2002; Rangi and Osterhaus, 1999; Veitch and Gifford, 1996; Veitch et al., 2007). Such benefits of daylight are supported by the Workplace (Health, Safety and Welfare)

Regulations 1992, which require access to daylight for all workers where reasonably practicable (TSO, 1992). Daylight has also non-visual effects on the human body, in particular with respect to maintaining circadian rhythms (the 'body clock') over a daily 24-hour cycle adjusted by external cues in the environment, the most important of which is daylight (Burgess et al, 2002; Boyce et al, 2003; Lockley, 2009).

Given its known benefits, people generally have a strong preference for daylight as a source of illumination, and when given a choice, they prefer windows in their workspaces (Collins, 1975; Cuttle, 1983; Farley and Veitch, 2001; Wotton and Barkow, 1983). Increasing window area does not necessarily lead to greater satisfaction with the visual environment however. A better view of the outdoor natural environment might be accompanied by excessive levels of daylight, leading to an increase in discomfort glare and overheating. It is necessary therefore to control the admission of daylight into a space by means of window openings, glazing as well as the effective use of shading devices.

Satisfaction with the visual environment is largely dependent upon availability of individual choice and control over the immediate visual conditions. This is often referred to as adaptive opportunity and includes all modifications a person might make within their environment to suit their preferences (Baker and Standeven, 1994). With respect to the physical context, adaptive opportunities range from interactions with the building fabric (i.e. adjusting blinds, switching on electric lighting) to behavioural responses (i.e. altering position or moving from one place to another) (Steemers et al, 2004; Tregenza and Wilson, 2011). Such adaptive opportunities provide occupants with means for personally controlling their environment in ways that enhance their comfort and satisfaction (Reinhart, 2014; Steemers et al, 2004). For example, window blinds can let people create a range of visual conditions and counteract possible visual problems. If they cannot modify the surroundings themselves in such a way, e.g. shading is not adjustable or not installed, then they may decide to change their position or move to another area to avoid discomfort.

The extent to which building occupants can control their visual environment depends on the adaptive opportunities available to them in particular contexts. Typically, an open-plan space provides a variety of seating areas, and the user subsequently has the option to sit closer to a window to get more daylight and access to a view of outside, or sit farther away from the window when they experience visual discomfort due to glare (Baker and Steemers, 2002). This is particularly evident in public and communal spaces in which desks/seats are shared and are not formally allocated to one person, such as library reading rooms, cafes/bars or other social settings. However, these types of adaptive opportunities are generally limited in spaces that impose restrictions on movement or choice of seat, such as offices with fixed workstation layout or classrooms where each student has an assigned seat. Much the same argument could be made for lighting control systems. On entering a space, people may switch on electric lighting manually when indoor illuminance levels from daylight are low, or may otherwise have to rely on automatic control systems that adjust electric lighting levels. It is thus evident that when users have individual choice and control over the amount of daylight, their response is constrained by the range of available adaptive opportunities in the space, such as the ability to adjust shading devices, individual control of electric lighting, or moving from one place to another.

The presence of adaptive opportunities affects how users can interact with the building, but little further evidence is available beyond that which has been discussed so far, which relates the visual environment with occupant seating behaviour. Choosing to be in any one particular space and changing seating position and/or location are considered effective ways of responding to the environment (Baker, 2000; Nikolopoulou and Steemers, 2003). The process by which an occupant locates/orientates themselves depends in large part on the sensory information available in the environment, although it may be mediated by thoughts and cognitive processes (Gilbert, 2012). While it is plausible that daylight could affect this process, either as an enabler or barrier - for example occupants may prefer to sit near the window when they need more light to perform specific visual tasks, or they may want to sit away from daylight when it causes visual or thermal discomfort- these and other issues relating to the potential relationship between daylight and occupant behaviour remain to be further explored.

The research presented in this thesis focuses on those behavioural aspects of daylight that are often disregarded but in fact are crucial to understand how the architectural space can be enhanced and transformed by this dynamic design element. In this context, daylight is discussed as a medium that alters the information content of the visual field and facilitates the seat selection process. More specifically, the research investigates the extent, if any, to which the effect of daylight on seating behaviour can be predicted. An important question being addressed is what kinds of visual environments people might aspire to and what physical conditions they might seek when given the choice. A library reading room is considered as the physical setting for the investigation, although the research method is conceptually equally applicable to other social settings such as cafes or restaurants as long as physical constraints of space do not exist and people are free to move and choose a particular location. Two methods were used to determine preferences of individuals: stated and revealed preference methods. The stated preference method relies on data from surveys that ask respondents to consider all relevant choice attributes and state their preferences directly. The revealed preference method relies on the observation of actual choices made by individuals to measure preferences.

Understanding the way people position themselves in relation to daylight could potentially have implications for the spatial design, the footprint and internal planning of buildings. If it were possible to identify behavioural patterns associated with daylighting conditions, then designers might be able to make more informed decisions regarding daylight performance, ensuring that occupants are located and oriented to make the most of the natural light. These could include design recommendations for spatial orientation, configuration of window openings, or space planning such as placement of furniture in relation to windows.

1.2 Aims and objectives

The aim of this study is to determine whether and how daylight affects behaviour in open plan library workspaces, with seating preferences used as a quantitative measure for occupant behaviour. The method involves asking participants to provide information about the reasons for their seat choice decisions through a questionnaire. The proposed approach allows for the examination of the perceptions of the participants regarding the conditions that influence their seat choice before and after entering the test room. The results contribute to understanding the relative importance of daylight to seat choice alongside other factors. The next step is to investigate actual seat choice behaviour through observation. This also involves estimating daylight illuminance for the observation period using dynamic simulation modelling, and comparing results with those obtained from observations. The research objectives are summarized as follows:

1. Investigate perceived factors that affect seating behaviour by means of questionnaires (stated preference surveys)
2. Investigate actual seating behaviour through observations (revealed preference surveys)
3. Predict daylight illuminance for the precise observation periods through computer simulation and evaluate simulation results using a set of daylight performance metrics
4. Evaluate the capability of each metric to predict seating behaviour by comparing measures of seat use with daylight performance metrics

The experiments took place in an open-plan reading room in a university library in Sheffield. The study addresses four research questions. The first is whether daylight is perceived to be important when choosing a seat and how these perceptions vary before and after the seat choice is made. The second is whether there is a relationship between daylight and actual seat choice behaviour and the third question examines whether different observational approaches yield the same results. Finally, the fourth question explores the ability of daylight performance metrics to predict seat choice behaviour.

1.3 Thesis structure

The thesis comprises seven chapters, a summary of which is given below and is illustrated in Figure 1.1 at the end of this section.

Following this introductory chapter, Chapter 2 reviews what is currently known about the relationship between daylight and seating behaviour. The first part of Chapter 2 is intended to provide an overview of basic characteristics of daylight and a discussion of the theoretical perspectives on seating behaviour. The second part presents a review of previous research to establish the extent to which behavioural impacts of daylight have already been validated and to develop research questions to be investigated which are presented at the end of Chapter 2. Chapter 3 provides a general description of the room where the research is undertaken, and reports the findings from stated preference surveys aimed at estimating the relative importance of daylight when choosing a seat.

Chapter 4 reports on three experiments designed to examine revealed preferences of individuals. The methods discussed involve recording seat occupancy at predetermined time intervals (snapshot approach) and tracking the seating behaviour of individuals over space and time (walk-through approach). Chapter 5 describes the process for assessing the daylight performance of the test room using a simulation-based approach, and compares the results with the corresponding occupancy patterns. Chapter 6 summaries the work presented in the previous chapters and discusses the findings in relation to previous research. Chapter 7, the final chapter, provides the overall conclusions and discusses their implications for daylight and seat choice behaviour research, and concludes with suggestions for future research.

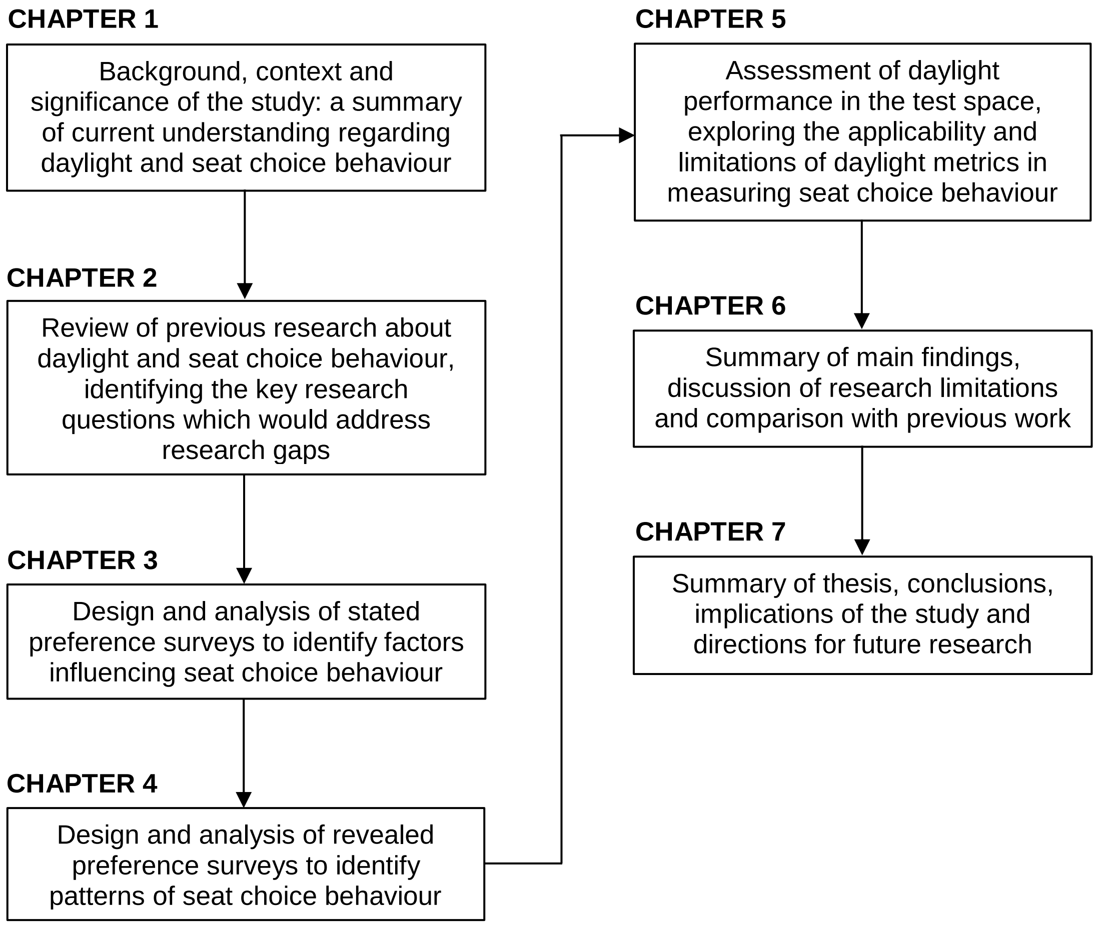


Figure 1.1. Schematic diagram of the thesis structure, showing the organisation of chapters.

1.4 Summary

Research has shown that daylight is an important aspect of visual environment and that a good provision of daylight is desirable in terms of occupants’ health and well-being as well as its potential to create a pleasant and visually stimulating environment. Yet, daylight has lost its primary importance due to the development and growth in use of artificial light over the last century. The dependence on artificial light have receded only recently with rapidly growing context of energy conscious design. The increased awareness of its benefits coupled with the desire to improve the energy efficiency of buildings has generated the need to incorporate daylight into the design process. For these reasons, daylight has often been preferred over artificial lighting as a source of illumination.

Daylight not only remains an essential source of illumination to accommodate visual demands of occupants, but could potentially influence the way they interact with the building. The extent to which individuals interact with their visual environment depends in part on the adaptive opportunities that they can use to adjust lighting conditions (i.e. using blinds or lighting control systems) or to modify their behaviour (i.e. changing seating position or location). Through the use of adaptable opportunities available within the environment, an individual has the ability to control over the amount of daylight to better suit their needs.

The work described in this thesis focused on the behaviour of building occupants, behaviour in this context being how occupants select a seat in an open-plan library workspace where there is a free choice of seat location. A critical issue in the investigation of behavioural responses to daylight is how to devise methods to measure and evaluate behaviour and the daylight conditions. Two methods were used to quantify seating preferences: stated and revealed preference methods. To understand the relationship between daylight and seat choice behaviour, it is first necessary to understand what daylight is and how its characteristics can be quantified, these will be discussed in the next chapter.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter reviews the existing evidence for the effects of daylight availability on seating preference in open-plan spaces. The first part provides background about daylighting and an overview of current standards and metrics. The second part reviews existing theoretical explanations of how people choose their seat location in open-plan spaces and what factors influence their decision making. The third part presents a review of studies investigating the influence of daylight on seating behaviour of occupants and discusses methods for gathering evidence. The first studies reviewed are those in which observational methods were used to investigate actual seating behaviour and this is followed by investigations of perceived behaviour using questionnaire surveys. Finally, the chapter concludes by highlighting potential issues and limitations with the methods employed by previous studies.

2.2 Physical principles and characteristics of daylight

The principle characteristic of daylight is that its intensity, spectral content and spatial distribution vary as the sky conditions and the position of the sun change throughout the day and the year. This section gives a brief description of how varying illumination from daylight can be predicted for different sky and sun conditions as well as the methods of quantifying the effect of this by means of daylight performance metrics.

2.2.1 Sources of daylight

Daylight is a small portion of the entire spectrum of electromagnetic radiation originating from the sun, exceptional in that its wavelengths lie within the range capable of stimulating the visual system (~380nm to ~780nm) (CIE, 1987). The radiation outside the visible spectrum, such as those with longer wavelengths (infrared) or shorter wavelengths (ultraviolet), is not visible to the human eye and thus is not capable of creating a visual sensation. The theory of eye evolution is a scientific theory that essentially states that the structure of the human eye is very complex and that such complexity could be developed through a naturalistic process of evolution. The theory is based on the idea that the human eye has evolved gradually over long periods of time to detect light at wavelengths in the visible spectrum. Daylight has meaning only in terms of human vision, and the sensitivity of the human eye is a function of wavelength - which is greatest when the wavelength is within the visible spectrum (Tregenza and Wilson, 2011). Daylight has two components: sunlight and skylight. Sunlight refers to the direct light arriving at a point at the earth's surface directly from the sun. Skylight is diffused light from the sun, being scattered by clouds, air molecules, particles of dust or water vapour in the atmosphere before reaching the Earth's surface. The process of scattering of light tends to be wavelength dependent and in particular affects the colour of the sky. That is, the shorter wavelengths in visible light (violet and blue) are scattered stronger than the longer wavelengths toward the red end of the visible spectrum. It is these scattered lights that give the sky the blue colour during the day and the orange colour during sunrise and sunset (Hopkinson et al., 1966; Tregenza and Wilson, 2011). This process of selective scattering is also known as Rayleigh scattering.

Determination of sunlight and skylight availability is based on the sky conditions. Given that the presence of clouds introduces randomness, sky conditions are difficult to predict, although statistical data on cloud cover are available from observations at many weather stations (IPCC, 2007). To provide a framework for representing the actual sky conditions, the International Commission on Illumination (CIE) developed a series of mathematical models of ideal sky luminance distribution, of which the three most common are characterised as *overcast*, *partly cloudy* and *clear*. The overcast sky is defined as one in which the view of the sun is completely impeded due to the presence of dense cloud cover and there is little to no direct sunlight, whereas clear sky represents those sky conditions with a primarily direct sunlight component. Partly cloudy sky conditions lie between those of clear and overcast (Hopkinson et al., 1966; Reinhart, 2014; Tregenza and Wilson, 2011).

The experiments presented in this thesis were carried out in an open-plan space in a university library in Sheffield (A detailed description of the test room is given in Chapter 3). In Figure 2.1 actual sky conditions that correspond to clear, partly cloudy, and overcast skies are shown for the test location, Sheffield (53°22'57'' N, 1°29'18'' W).

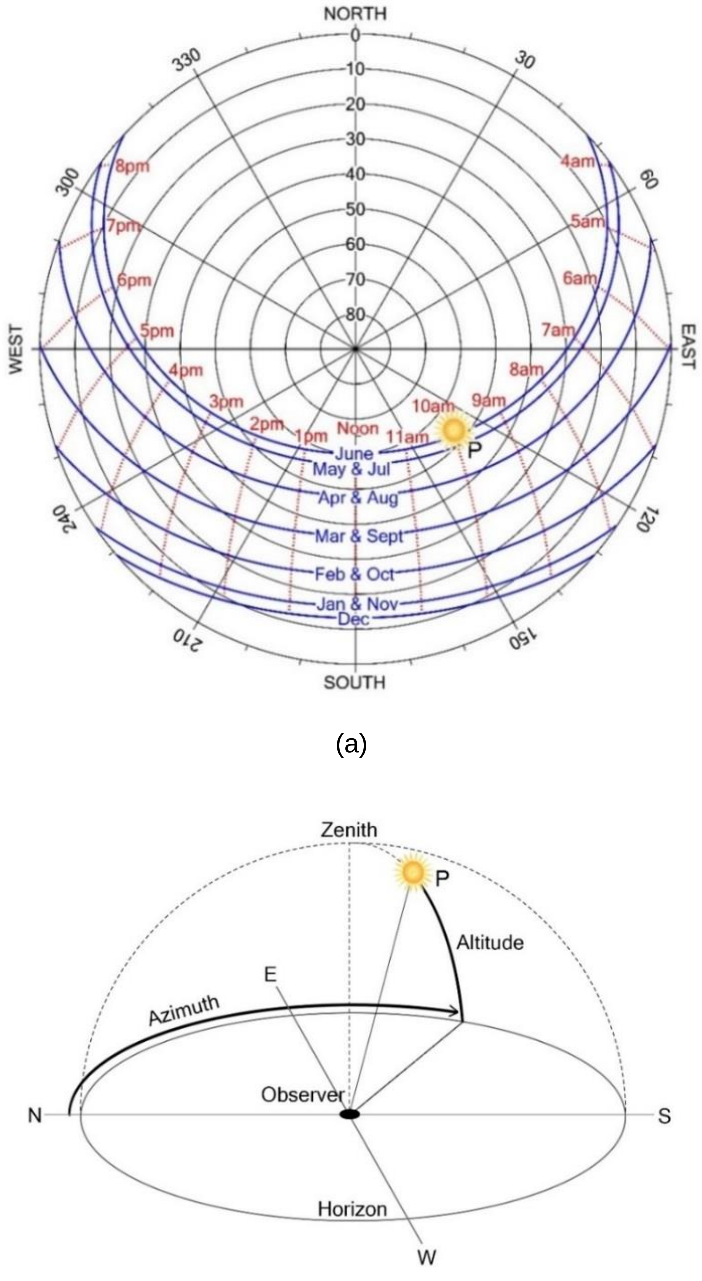
Figure 2.1. Fish-eye photographs of the three typical sky conditions, taken at ground level close to the library building, Sheffield, United Kingdom. Left: Clear sky. Middle: Partly cloudy sky. Right: Overcast sky.

As a result of these dynamic sky conditions, the amount of daylight entering a building cannot be determined with a high degree of accuracy, and design criteria are thus inevitably based on a statistical treatment of meteorological data (Lynes, 1968). In climates with predominantly clear sky conditions, as in southern Europe, it appears particularly important to maximize the penetration of diffuse skylight and block the direct sunlight as it causes discomfort through heating and glare. By contrast, in climates where overcast sky conditions predominate, as found in northern Europe, the design emphasis is usually on maximizing daylight penetration in a building. Yet, these are general responses to sunlight and skylight penetration, and daylighting design strategies depend on building performance requirements (Hyde, 2000).

2.2.2 Solar position

The variations in daylight are primarily due to the change in the relative position of the sun in the sky as a function of the time of day and season of year. The position of the sun throughout the year is highly predictable for any given location, unlike cloud cover which is subjected to calculation only on a statistical basis (Evans, 1981; Hopkinson et al., 1966). For any particular time, the position of the sun can be expressed in terms of its vertical angle above the horizon (altitude) and its horizontal angle, typically measured clockwise from north (azimuth).

Given that the angular relationship between the position of the sun and the observer constantly changes over the course of a day and through the changing seasons, it is important to get an idea of this variety of circumstances during building design. For convenience the solar geometry is often represented on a sunpath diagram, which enables projections of the sun's path across the sky. Figure 2.2a shows a stereographic sunpath diagram created for Sheffield using an on-line program at the web site of the University of Oregon Solar Radiation Monitoring Laboratory. Figure 2.2b illustrates the geometrical relation between the position of the sun at a given point P, the observer and the sky hemisphere.



(a)

(b)

Figure 2.2. Annual variation of the sun’s path for Sheffield (53°22'57" N, 1°29'17" W).
(a) Stereographic sunpath diagram, created using University of Oregon Solar Radiation Monitoring Laboratory Online Sun Path Calculator (accessed 12 January 2015); (b) Solar position angles for the precise location of the sun on 21 June at 10am.

The sunpath diagram presented in Figure 2.2a is based on the stereographic projection of the sky hemisphere. The concentric circles represent the solar elevation at 10 degree intervals, with its centre corresponding to the zenith and the outermost circle corresponding to the horizon (British Standards Institution, 2008). The path of the sun in the sky during an entire day is indicated by the long curved arcs (shown in blue), and the time of day is indicated by the shorter converging lines (shown in red). Note that the time indicated by the hour lines is solar time, and makes no allowance for daylight savings (when daylight saving is in operation, one hour must be added to each of the times indicated). It can be seen from the figure that in mid-summer, in Sheffield, the sun rises in the north-east just before 4am, and sets in the north-west after 8pm. At noon, the solar elevation is at its maximum of about 60^0. The position of the sun at 10am is represented by the point P on the sunpath diagram, and its geometrical relation to the sky hemisphere is illustrated in Figure 2.2b.

2.2.3 Basic daylight quantities

This thesis focuses on the amount of light and not on the spectral characteristic of that light (e.g. its spectral power distribution or colour properties). The quantitative approach to objectively evaluate the amount of light is essentially concerned with the two physical quantities, luminance and illuminance. Luminance is defined as the amount of light emitted from a source or reflecting surface (cd/m^2); and it depends on the direction from which the light reaches the surface, the direction from which it is viewed, and the material properties of the surface itself.

Once daylight enters a building through an opening, its further penetration depends on the material properties of the interior surfaces it passes through or strikes. The reflectance of a surface material is indicated by a reflectance factor, within the range of 0 to 1. A white surface, for example, has a reflectance factor of about 0.85, while a black surface has a value of only 0.05 (Lechner, 2015). It should be noted that the manner in which light is reflected by the material is highly dependent upon the surface characteristics. A perfectly smooth surface such as a mirror reflects light in a single direction (specular reflection), whilst a rough surface scatters light rays in different directions (diffuse reflection) (Nayar et al 1991). The transmittance factor describes the ratio of light that passes directly through the material (i.e. glass), and absorption factor describes the ratio of light absorbed within the material.

Illuminance, in contrast to luminance, is the total luminous flux that falls on a surface (lux) and is independent of those factors that luminance depends on, such as the viewing direction or the characteristics of the surface on which light falls. The external illuminance on the ground due to daylight varies depending on sky conditions, covering a wide range from 1000 lux on an overcast winter day to 100.000 lux on a sunny summer day (Boyce, 2014; Tregenza and Wilson, 2011). One important difference between illuminance and luminance is that when describing illuminance, the surface is considered as a receiver of light. When describing luminance, however, the surface is considered as a source of light which acts as the stimulus for vision. Illuminance therefore is an indicator of the flow of light within a space, whereas luminance is an indicator of the amount of light received by the viewer (Cuttle, 1971).

2.2.4 Daylight performance metrics

The dynamic nature of daylight presents a design challenge. In order to understand inherent characteristics of daylight and to use its potential benefits and attributes effectively within the design practice, a set of daylight performance metrics have been proposed (Mardaljevic et al., 2009; Reinhart, 2014). Quantitative evaluations by means of metrics enable relative comparisons between design alternatives as well as absolute comparisons against a benchmark value (Reinhart, 2014).

Daylight performance metrics are typically assessed for either a single sky condition (static) or a series of consecutive sky conditions (dynamic). Current metrics can be classified into two major categories, illuminance-based versus luminance-based metrics and static versus dynamic metrics. A description of each of these metrics classified according to the two categories is given in Table 2.1.

Table 2.1 Definition of typical daylight performance metrics and indices.

	Metric	Static or Dynamic	Description	References
Illuminance based	Daylight Factor (DF)	Static	The ratio of the daylight illuminance at a particular point on a horizontal plane to the simultaneously occurring external illuminance of the unobstructed overcast sky	Moon and Spencer (1942)
	Useful Daylight Illuminance (UDI)	Dynamic	The annual occurrence of illuminances across the work plane that are within a range considered useful by occupants (100-3000 lux*)	Mardaljevic (2015,2006); Mardaljevic et al. (2012)
	Daylight Autonomy (DA)	Dynamic	The percentage of the year when a minimum illuminance threshold is met by daylight alone	Association Suisse des Electriciens (1989); Reinhart (2002)
	Continuous Daylight Autonomy (cDA)	Dynamic	Similar to DA but partial credit is attributed to time steps when the daylight illuminance lies below the minimum illuminance level	Rogers (2006); Reinhart et al. (2006)
	Spatial Daylight Autonomy (sDA)	Dynamic	The percentage of area that meets a minimum illuminance level for a specified amount of annual hours	IES Daylight Metrics Committee (2012)
	Annual Sunlight Exposure (ASE)	Dynamic	The percentage of area that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year	IES Daylight Metrics Committee (2012)
Luminance based	Discomfort Glare Metrics	Static and Dynamic	The predictions of the occurrence of discomfort glare within the field of view. Metrics include, but are not limited to, Daylight Glare Probability (DGP) and Daylight Glare Index (DGI)	Wienold and Christoffersen (2005,2006); Jakubiec and Reinhart (2012)
	Metrics for Contrast and Variability	Static and Dynamic	Measurements of the positive impacts of luminosity within the space, such as the average luminance and luminance variation	Veitch and Newsham (2000); Loe et al. (1994); Rockcastle and Andersen (2013)

*UDI range limits were 100-2000 lux when the UDI scheme first published in 2005. The upper value of 2000 lux was revised upwards to 3000 lux later when new data from field research became available. The UDI range is further subdivided into four ranges: UDI fell-short (below 100 lux), UDI supplementary (100-300 lux), UDI autonomous (300-3000 lux) and UDI exceeded (above 3000 lux) (Mardaljevic, 2015).

Illuminance is the most widely applied measurement of daylight and is the foundation upon which most daylight performance metrics are based. The results of daylight analyses using static metrics are usually expressed in the form of illuminance values at certain points of interest in a building under a reference sky. One such metric is daylight factor, which is calculated under the CIE standard overcast sky. Daylight factor is the oldest and the most convenient way of expressing the quantity of daylight illuminance, and, as far as lighting practice concerned, it is one of the most widely specified metric by standards. It defines a constant relationship between the internal and external illuminance under overcast sky conditions. The luminance distribution of the sky is assumed to remain constant independent of absolute sky luminance. The rationale given for using the daylight factor method is that the reference overcast sky represents the worst case sky condition and that the method is primarily suited to calculating minimum values. Assuming that the total unobstructed illumination of an overcast sky is 5000 lux on the horizontal plane, for example, a daylight factor of 2% corresponds to an illuminance of 100 lux on interior work plane.

Understanding variations in local weather patterns is critical in determining the appropriate approach for daylight calculation. Daylight factor is most useful for locations where there are frequent overcast conditions, such as England, and is arguably less useful in sunny climates. The main concern associated with daylighting in sunny climates is that the direct sunlight make a significant contribution to indoor illumination and that the daylight factor approach becomes unrealistic for such climates (Tregenza and Wilson, 2011).

The limitations of daylight factor method can be summarized as follows: First, it excludes the contribution of direct sunlight. This presents limitations, especially in climates with predominantly clear sky conditions, as in southern Europe, where the direct sunlight makes a significant contribution to indoor illumination. Second, it considers only one sky condition, yet over a year, a building may experience many different sky conditions. The calculation of daylight factor is based on a standard overcast sky luminance distribution, however, real skies vary. This means the ratio of internal to external illuminance is no longer constant but varies as the pattern of sky luminance changes. The use of daylight factor is thus restricted in practice due to its lack of flexibility to estimate the dynamic variations in daylight illuminance as the solar position and sky conditions change.

Although the daylight factor method is capable of advancement by incremental means using the 'clear sky' evaluations, a more holistic approach is needed to evaluate daylight, particularly based on daylight availability determined from cumulative diffuse illuminance curves (Nabil and Mardaljevic 2005; 2006). Dynamic daylight metrics, also known as climate-based daylight metrics, have been introduced to overcome the limitations of the daylight factor method by providing a more comprehensive measure for a wide range of sun positions and sky conditions. There is considerable evidence to support the use of these metrics, such as the capability to predict the luminous quantities founded on standardised meteorological files specific to the locale for the building under evaluation. As a result, this approach enables a more realistic and location-specific evaluation of daylighting potential, and hence the design professionals rely more than ever on dynamic daylight performance metrics (Nabil and Mardaljevic 2005; Reinhart, 2011). Several dynamic metrics have been developed with the aim of capturing dynamic aspects of daylight; each describes different aspects of design. Of these, the two that appear to have been received a widespread acceptance are UDI and DA (IESNA, 2000). These metrics are typically used to estimate daylight availability over the year and throughout the space, and the consequences for the use of electric lighting and air-conditioning (Reinhart, 2014).

While there appears to be a consensus assigning importance to the implementation of illuminance-based metrics, there is also substantial research suggesting alternative ways to evaluate daylight performance that are based on luminance-based metrics. The point has been made that people are relatively insensitive to the absolute level of light in a room and that illuminance-based metrics are not capable of predicting spatial variations of daylight within an occupant's field of view. Luminance-based metrics are considered more capable than illuminance-based metrics in many ways, such as determining discomfort glare (i.e. Daylight Glare Probability and Daylight Glare Index) or the compositional impacts of luminance diversity within the field of view, the results of which are usually expressed in the form of renderings and/or photographs (Newsham et al., 2005; Rockcastle and Andersen, 2013). Providing accurate predictions with luminance-based metrics, however, is challenging. This is partly due to the wide variations in luminance distribution within the - many possible- fields of view, and partly due to limitations with the measurement equipment and method. Although it has become possible to analyse luminance distributions using high dynamic range (HDR) photography, there is still no clear consensus that such measures are capable of differentiating between visual comfort and discomfort as experienced by space occupants (Painter et al., 2009; Hirning et al., 2013; Van Den Wymelenberg and Inanici, 2014).

As a result, although the importance of daylight metrics is recognised, there is yet insufficient knowledge of which metrics are important in a given situation. Different metrics are based on different objectives. These include, but are not limited to, ensuring sufficient light to maintain wellbeing or productivity of building occupants, providing a visual environment that brings satisfaction to users, and reducing energy consumption. Boyce (2014) suggested that regardless of how it is predicted and quantified, daylight is highly regarded by people, at least in climates where daylight is limited for part of the year, and this in turn has an important effect on the design of buildings. Tregenza and Wilson (2011) suggested that the average daylight factor can be considered as a good indicator of the appearance of a room. Referring to this work, Boyce (2014) further argues that although dynamic metrics are important for estimating the energy consumption of a building, they tell us little about human response. For the human response, when and where sunlight occurs is much more important as it can cause discomfort (Boyce, 2014).

There is evidence from previous daylight studies supporting Boyce's idea. One study by Nezamdoost and Van Den Wymelenberg (2016) have investigated the ability of daylight metrics to predict occupants' subjective responses. They found that point-in-time illuminance was a greater predictor of occupants' subjective responses than the cumulative measure of daylight (e.g. total annual illuminance). Similar results were found in another study by the same authors (Nezamdoost and Van Den Wymelenberg, 2015) that looked at the relationship between daylight metrics and the qualitative evaluations of daylit spaces. Subjective space evaluations correlated well with point-in-time illuminance data. The subjects in these studies were in fact expressing a preference for adequate absolute daylight levels rather than temporal variations.

This discussion raises questions about how well daylight metrics address issues relating to adaptive behaviour (e.g. adjusting blinds, altering seating position). Dynamic metrics possess some potential limitations – not least of which is the inability to inform about the human response in the space or to predict adaptive behaviour of individuals at a particular point in time. This might be explained by the fact that dynamic daylight analysis involves predicting a cumulative measure based on long-term record of weather conditions. Daylight autonomy, for example, indicates the percentage of time that illuminance exceeds a specified threshold. It examines whether there is sufficient daylight in a space so that an occupant can work by daylight alone. Such specification might be necessary for energy analysis, but as a description of the experience of occupants, it is arguably inadequate. Ultimately, the value of any metric depends on how well it informs on the actual daylighting performance of the space, not only in terms of objective measurement, but also in terms of subjective experience of the space (Tregenza and Mardaljevic, 2018).

2.2.5 Current lighting standards for libraries

The physical setting considered in this thesis is a library reading room. What characterizes this type of setting is, firstly, the need to carry out a range of desk-based tasks, usually with a focus on reading and writing; and, secondly, that the people working in these spaces may remain static for periods of an hour or more (Reinhart, 2014; Tregenza and Wilson, 2011). With this in mind, what is good reading light, and what particular lighting issues the situation of reading/writing in a library environment raises deserve discussion.

The quantity of light required to perform a specific task is typically expressed as horizontal illuminance as it is one of the easiest and most relevant lighting terms to measure. Lighting standards, codes, and recommended practice documents usually specify the task lighting requirements for a workspace in terms of average illuminance on a horizontal plane at desk height, this being a surface on which a visual task is usually done (Cuttle, 2015; Rea, 2000). These recommendations do not identify the source that is required to provide these illuminances so the recommended levels may be met using either daylight or electric light. One thing to note, however, is that the use of daylight depends on the external daylight availability and the required illuminance can be provided by an electric lighting system even if the daylight provides sufficient light for most of the time (Boyce, 2014).

Two organizations for lighting professionals, The Chartered Institution of Building Services Engineers (CIBSE) and the Illuminating Engineering Society of North America (IESNA), had long been providing standards and guidelines for the lighting of indoor work places. Most recently, the Committee for European Standardisation (CEN) has produced European standards for lighting of work places, which subsequently have been adopted by the British Standards Institution (BS EN 12464-1). The recommended range for library reading rooms is between 300 and 500 lux (CEN, 2002a; CIBSE, 1999; IESNA, 2000).

Whilst most countries have adopted international standards, some others have developed their own national standards such as the Illuminating Engineering Society of Australia and New Zealand, and China Illuminating Engineering Society. There are, however, variations in these standards. For example, the recommended illuminance for library reading areas in Australia and New Zealand is 320 lux (Standards Australia, 2008), and in China it is 300 lux (China GB 50034, 2004). The process of setting lighting guidelines could possibly have been influenced by cultural and environmental considerations as well as political considerations, in addition to the state of knowledge of how illuminance affects task performance (Boyce, 1996; Lynes; 1968).

There appears to be general agreement that the optimal level of daylight can be achieved through the daylight performance metrics and the illuminance thresholds established, yet there is limited understanding of how building occupants respond to the changing illuminance distributions. The issue of providing 'good lighting' necessarily involves understanding peoples’ behavioural responses to, and interactions with, buildings they occupy (Steane, 2011). This distinction between the human (subjective) aspects and the physical (objective) measure of daylight is paramount in much of the discussion and an essential feature of the argument presented in the following sections.

2.3 Daylight and spatial behaviour

Daylight gives a sense of place in an otherwise less diverse and more homogenized visual environment, as the direction and intensity of illumination changes over time and space (Ander, 2003). This information enables the individuals to develop a judgement about the luminous environment and may potentially influence the way they orientate themselves within that environment (Boyce, 2014; Dubois et al, 2009). In a questioning of the circumstances that matter to human spatial behaviour, what this section aims to explore is the extent to which daylight informs decision making regarding the position of individuals within a given environment. First, the section examines the role played by the luminous environment in both guiding movement and influencing spatial orientation. Then it focuses on theoretical assumptions underlying current research in the field of seating behaviour and attempts to link those assumptions to specific research questions.

2.3.1 The potential role of daylight in spatial orientation

The way people respond to their environment may differ depending on the individual and the particularity of the environment they are exposed to. This is summarised by Boyce (2014), who suggests the idea that behavioural response to a physical stimulus is not in direct relationship to its magnitude, but depends on the information that people have in particular situation. Yet, the interaction of people with the space they occupy is a notion that has guided design since its earliest efforts. According to Bechtel (1977), who proposed to use a field observation method as a basis for architectural design, once the desired behaviour is identified, then design will follow; and it is necessary to ask two essential questions about design: “What behaviour does it encourage?” and “What behaviour does it inhibit?” (Bechtel, 1977). Similarly, Moos (1976) highlighted the importance of congruence and match between the behaviour of the people who occupy the space and the purpose of that space; and suggested that the physical environment imposes constraints, thereby limiting the possible behaviours that could potentially occur in it.

These ideas were elaborated in the study of Barker et al (1978) in which they observed that the individual behaviour of people was better explained by their current environment at the time of the observation than by their individual characteristics. These environments were identified as behaviour settings, each of which has an associated set of physical objects arranged (i.e. chairs and desks). According to Barker et al (1978), if a given individual enters a behaviour setting, he is influenced by it in ways dependent upon the nature of the setting and his position in it. This is not to deny the existence of individual differences in behaviour, but the variations themselves follow a form dictated by the structure of the setting (Cohen, 1985).

A typical behavioural response of an individual to the environment is to locate/orient themselves through movement. This is generally referred to as spatial orientation, and relies on the individual’s ability to use the information received through their senses to determine their position in relation to the surrounding environment (Hall, 1963; Sommer, 1969). Vision is typically the dominant source of sensory information, although inputs from other senses such as auditory or tactile senses may contribute (Posner et al., 1976; Rock and Harris, 1967; Rock, 1968). As the individual walks through the space, their brain continually interprets the changing retinal images, and updates the information of the physical environment, as well as their location and movement within it (Cuttle, 2008). This process inherently requires a decision to be made by the individuals based on the visual information received from the environment.

There are a number of reasons why daylight can be expected to have an effect on the spatial orientation of individuals in a given context. First, daylight is an important medium through which the individual receives visual information. It can give the individual directional information as well as idea of the sort of area they are in and hence may form a basis for decision-making when navigating through the space and choosing a location. Based on lighting conditions, individuals may either remain in some currently occupied location or alternatively move elsewhere, although this may depend on familiarity with the space (Flynn et al., 1988; Low and Altman, 1992). When the individual moves to another area, their orientation changes; and they may become aware of the dominance of a new luminous environment. This transition can be developed to provide a sense of continuity, in the sense that luminous influences are similar in the two adjacent spaces (i.e. similar amount of illumination), or, the transition can be developed to provide a sense of contrast and change (i.e. higher or lower amount of illumination) (Flynn et al., 1988). The end result is that on walking through the room, it is encountered as a sequence of alternating lighter and darker spaces.

Another reason for the influence of daylight is that it allows the visual task to be performed and this may encourage choosing a particular location and making the most of daylight. When engaged in tasks that demand higher mental processes, such as reading in a library reading room, for example, the ability to pay attention is most important and good lighting enhances the visibility of the task itself (Scherer, 1999; Steane, 2011; Steffy, 2002). Arguably though, in order to immerse themselves in reading, people may need to create a situation where they are focused more on the meaning of what they are reading and less on the external environment, which is usually expressed as 'being lost in the book'. In this situation a sort of withdrawal from the immediate environment may take place in order to achieve mental focus (Steane, 2011). When this concentration becomes dominant and individuals become less aware of sensory information stemming from their external environment, they may become less aware of their orientation in space.

Finally, it is important to emphasize that the choice of any particular location may be motivated by the desire to avoid visual discomfort. For example, individuals may locate themselves away from direct sunlight when it causes visual discomfort through glare. Yet, there is also a positive side to daylighting. As discussed earlier in this chapter, one aspect of daylighting that can be positive is its dynamic character which contributes to the creation of an exciting and attractive environment. Even if the most fundamental role of light is to provide the illumination necessary for a visual task to be seen, the scope is much broader than that; it can create an environmental impression, which in turn may affect the spatial behaviour of individuals.

2.3.2 Theoretical approaches to seating behaviour

The idea that people have ways of evaluating the physical characteristics of the environment when choosing a location and that these concepts exist in a form capable of being studied more or less systematically and related together to form a coherent system, has roots in psychology. Behavioural responses to the environment can be either conscious or unconscious. Kahneman (2011) and Eagleman (2011) argued that the awareness of our behavioural responses to the physical environment is limited and that most of our behaviour is not under our conscious control. In the context of people making seat choices, this would equate to not knowing what caused a particular action when choosing a seat, not knowing that they took a particular path to reach the preferred seat location, or not knowing that something they observed was causally linked to a particular action. Upon entering a room, for example, an occupant could identify alternative routes in order to avoid the crowded area. They may be unaware that they had noticed how crowded that area is, unaware that they adjusted their position/location in response to it, or unaware that noticing the crowded area caused them to adjust their position/location.

When it comes to decision making, Kahneman (2011) suggests the idea that people make choices intuitively rather than rationally. According to the argument developed by Kahneman (2011), people do not weight environmental variables equally but rather they tend to be more focused on one or more specific variables. Since it would be a labouring and time consuming process to consider all of those choices together and weight the value of choosing one variable over other every time people make a decision about where to sit, it is clear that they focus, instead, in those variables that respond to their immediate necessities. That being said, whatever is seen as a necessity will be highly weighted and other variables will be lightly weighted or disregarded (Kahneman and Tversky, 1979; Kahneman, 2011).

Another argument is based on the theory of rational choice. For example, Stone (2002) and Scott (2000) argued that whatever people do, their behaviour is largely the result of deliberate choices among alternatives, regardless of whether they make conscious or unconscious decisions. Much the same argument could be made about seat choice. The choice of being in a particular location may be rational and some form of cognitive process may occur prior to the selection of that location. It could be further argued that individuals define seating location before they arrive in a physical setting based on the experience they previously gained in that place, or they may consider the possibilities available upon entering the room. Once individuals collect relevant cues available to them either prior to or at the time, they may develop a preferred location.

The ability of individuals to choose their location is largely influenced by the degree of freedom of choice found in the environment. Hall (1966) explains this by arguing that what can be done in a space determines the way we experience it. The orientation depends for instance on the individual being able to walk freely from one side of the room to the other or move around in the room. What this means for an individual making a seat choice is that the process of choice is fixed by the accessible and available seats at the time that they enter the room. In other words, they can only choose among the seating options available to them. This suggests that any seating decision is dependent upon the decisions of other people who are already seated in the room, and thus cannot be taken as an absolute. This dynamic decision process may impact on individuals' choices. For example, individuals who enter a library reading room early in the morning are more likely to have a seat of their choice than those who enter later in the afternoon. Given the inherent sequential nature of the seat selection process, it is reasonable to assume that those individuals arriving late and desiring a seat near the window withdraw their first choice due to unavailability.

Further explanation for the discrepancies among the choices made by individuals may be attributable to differences in familiarity and previous experience. Someone who is familiar with the physical setting and the sort of activities that occur in it may make a very different seating decision to someone who is unfamiliar with the room. Likewise, previous experience may influence an individual's seating behaviour.

Human response to the physical environment is highly dependent on previous experience that influences expectation and establishes the basis for a response that is essentially comparative to what is familiar (Boyce, 2014). For example, choosing the same seat repeatedly can become second nature, and the individuals may find themselves retracing the same route and/or choosing the same seat out of habit, not thinking about how they arrived at that location. This raises the question whether there are differences in seating behaviour of first-time and repeat visitors. Repeat visitors are more likely to be familiar with the environment and they typically develop preferences based on previous experiences, while first-timers may need to rely on external sources of information (Kozak, 2001; Oppermann, 1999). Then there is the matter of emotional state of the individual. It is usually difficult to determine that a specific stimulus in the environment always provides focal information, since that depends on mental state, namely arousal, motivation and expectation (Boyce, 2014). That we have incomplete understanding of how these functions operate is not an overriding deficiency however, as we can employ observation to explore ways in which variations in the physical environment influence behaviour (Cuttle, 2008). The movements of individuals, and the subsequent seating decisions that occur in between these movements could provide a direct and measurable link to underlying processes of seating behaviour in a given environment.

While the early literature on seating behaviour was mainly concerned with theory, more recent research has developed methods to investigate the seating behaviours of individuals in response to a stimulus such as daylight. It could be argued, however, that this relationship between seating behaviour and a particular stimulus is a matter of probability rather than certainty, as people integrate multiple sources of information when making decisions about where to move and where to sit. Given that human behaviour is subject to many influences, the impact of light alone is likely to be masked by variations in other factors (Boyce et al, 2003). This implies that the importance of daylight is not always enough to override factors that influence seat choice behaviour. In fact, daylight is just one of the many factors affecting seating behaviour, and in many situations, it may be of minor or even negligible significance compared to other factors that influence the decision-making process. This raises the question of what evidence there is that daylighting, as currently practiced, can influence seating behaviour of occupants in spaces where there is a free choice of seat location. The next section reviews previous seating behaviour research, outlining what it can and cannot tell us about how daylight affect seat choice and what factors are likely to influence the decision making process.

2.4 Daylight and seating preference: A review of the evidence

Seating preferences of people can be inferred either from direct observation of their actual behaviour (revealed preference), or from their self-reported behaviour (stated preference). The former method involves observations of the seating behaviours and the physical setting in which the behaviours occur, while the latter method relies on individuals to express their preferences directly, i.e. in a survey. The following sections first describe how the laboratory and real-world settings are used to investigate seating behaviour, then provide a summary of the previous studies, these are divided into two categories: revealed preference studies and stated preference studies.

2.4.1 Real-world versus laboratory settings

Although laboratory settings offer greater control over the variables of interest, studies of seating behaviour are typically undertaken in real-world settings. There are several reasons for this. First, there are a wide range of environmental stimuli present in the real-world situations and it is difficult to reproduce that dynamic social context in laboratory settings (i.e. presence of other people, unpredictable events). The behaviours observed in laboratory settings may therefore be artificial and unrepresentative. Second, in laboratory settings it is difficult to recreate the tasks and goals an occupant is likely to encounter while choosing a seat, such as planning their route, searching available seats, walking, engaging in internal thoughts. It is thus likely that the behaviours observed in real-world environments differ from those laboratory conditions. Further concerns about laboratory studies arise from the fact that test participants know they are being observed, which may affect their seating behaviour and that the findings are often difficult to generalise to the real world (Sundstrom and Altman, 1976).

One important feature of observations in real-world settings is that they do not involve changing the environment or interfering with the behaviour of people being observed. This prevents people from changing their behaviour (they may behave differently when they know they are being observed), thus improves the reliability of the observations. The gathering of information (i.e. recording seating behaviour for a given period of time), however, requires systematic procedures and replicability. Visual methods such as video photography potentially enable more detailed information to be collected at the time of observation that would be possible by an observer working alone; but these should remain within the bounds of ethical considerations for personal privacy. Arguably, although such technology offers effective techniques for data collection, the naked eye provides information in 'human-sized units' that are at least equally important for the understanding of human-environment interaction as are other enhanced measures (Sussman, 2016).

As a result, studies of seating behaviour in real-world settings are required in order to develop a more accurate understanding of where people sit and why in normal situations. The key difference between the real-world and the laboratory setting is that in the second case there is no real environment stimulus and the subjects somehow cannot fully understand and be aware of the environmental factors that might influence the determination of their seating location. The review of previous literature on seating behaviour presented in this chapter did not find any studies carried out in laboratory settings. An important concern for the studies in real-world settings is the accuracy of data collected. Although video technology would appear to provide useful means of recording information on space use over time, the review did not identify any studies that have carried out observations using such technologies.

2.4.2 Revealed preference studies

The revealed preference method typically involves recording systematically what actually occurs in the physical setting, and as such is a measurement of actual behaviour rather than the perceived or intended behaviour. There are two approaches: record a snapshot of behaviour at certain intervals, or, monitor/observe ongoing behaviour. The first approach involves recording the behaviour of people at pre-determined intervals, either at fixed intervals (e.g. every 15 minutes) or random intervals. This method, also known as snapshot observation (Farbstein et al., 2016), allows the recording of peoples’ locations and how they are distributed in an entire space at a moment in time, with repeated snapshots (Ittelson et al, 1970; Sommer and Sommer, 2002; Bechtel and Zeisel, 1987). However, it does not allow recording sequences of behaviours since the observer takes into account only short sample intervals. The second approach, walk-through observation, involves continuous recordings of behaviour, specifically, tracking people while they choose their seats, noting what they do and where they go as they move through the space.

For both snapshot and walk-through observation methods, it is important to improve the accuracy and validity of data by establishing inter-observer agreement (two or more observers could independently record observational data and then compare them) (Sussman, 2016). Another way of evaluating the validity might be to use both methods jointly. For example, one observer may record individuals' seat choices at predefined intervals and supplement these observations with walk-through observation data gathered simultaneously by the second observer. These do not appear to have been the approaches taken by previous studies however.

Four studies were carried out using snapshot observation (Organ and Jantti, 1997; Kim and Wineman, 2005; Dubois et al., 2009; Wang and Boubekri, 2009) and two studies using walk-through observation (Carstensdottir et al., 2011; Othman and Mazli, 2012). A summary of the revealed preference studies reviewed is given in Table 2.2.

Table 2.2. Summary of revealed preference studies.

Study	Method	Location	Interval	Duration	Time of day	Time of year	Key Findings
Organ and Jantti (1997)	Snapshot	A library building	Three times a day: 10am, 1pm and 3.30pm	Daily over 5 months	10am to 3.30pm	June to October	The most popular areas were quiet, well-lit and adjacent to windows. Wall seating was preferred to the more exposed areas, with seats located adjacent to windows being the most popular.
Kim and Wineman (2005)	Snapshot	A university cafeteria and a library study area	10 min (cafeteria) 30min (library)	6 days (cafeteria) 8 days (library)	9am to 12pm and 2.30pm to 5.30pm (library) 11.30am to 1pm (cafeteria)	May and June (cafeteria) October and November (library)	Seat occupancy was higher in areas near windows with outdoor views. This difference was more pronounced in the cafeteria than in the library.
Dubois et al (2009)*	Snapshot	A university café	15 min	2 weeks	Not reported	October and November	The zones located near windows were noticeably preferred by occupants, in spite of the risks for highly variable conditions of daylighting.
Wang and Boubekri (2009)	Snapshot	A student union lounge	30 min	Three consecutive afternoons	1pm to 4pm	Mid-April	Participants preferred seats in sunlight. Away from sunny area, they preferred seats in more open spaces.
Carstensdottir et al (2011)	Walk through	A café and a restaurant	n.a	2 weeks	Not reported	Not reported	Tables located at the perimeter were more preferable than tables located near the middle.
Othman and Mazli (2012)*	Walk through	A library reading room	n.a	Not reported	10am to 12pm, 12pm to 2pm and 2pm to 4pm	Not reported	In the morning most people preferred to sit at the centre of the room to avoid excessive contrast in the window area. In midday there was a tendency to sit near windows, whereas in the afternoon when the room density becomes higher, there was no specific seating pattern observed.
Gou et al (2018)*	Snapshot	A library reading room	30 min	2 days	8am to 8pm	April	A sky view was preferred to a view of high-density trees. South-facing workstations had a higher occupancy rate on a sunny day while those facing east had a higher occupancy rate on a cloudy day.

* The three studies of Dubois et al (2009), Othman and Mazli (2012) and Gou et al (2018) used stated preference method as a complementary method.

The evidence from these studies is consistent in finding that there is a tendency to sit near the window when room density is sufficiently low to allow this choice. Examination of the results reported in four studies provides support for an effect of daylight on seating preferences (Kim and Wineman, 2005; Dubois et al., 2009; Wang and Boubekri, 2009; Othman and Mazli, 2012). Kim and Wineman (2005) recorded seat selection patterns of occupants in two types of settings, social (a cafeteria) and workplace (a library study area), the aim was to investigate how individuals choose their seats in relation to windows and views. For the purpose of the analysis, each room was divided into view and no-view zones based on proximity to the windows. For cafeteria setting, the first two rows of tables closest to the windows formed the view zone, whereas for the library room it was the north area which provided access to outdoor views, thus referred to as the view zone. A higher occupancy rate was observed in areas near windows (view zone) compared to those closer to the interior (no-view zone). For daylight analysis, the distribution of illuminance values was estimated through physical measurements in both the library and cafeteria. Illuminance levels were higher and more variable in the view zone than in the no-view zone, leading Kim and Wineman (2005) to conclude that the differences in the amount of daylight may have mediated any observed differences in seating occupancy between the two zones. These results suggest that the perceived value of daylight is at least in part related to the presence of an outdoor view: what is not known is the extent to which the change in daylight levels informed seating decisions, rather than the change in the availability of an outdoor view. Overall, the work of Kim and Wineman (2005) supports the idea that daylight is valued when choosing a seat, but it does not necessarily support the primacy of daylight over the provision of a view out.

Dubois et al (2009) observed seating behaviours in a university café and found that occupants had a higher preference for areas located near windows, where daylight levels experienced a high degree of variation, with fluctuating light conditions affecting the brightness of those areas across the observation period. The seating area was divided into eleven zones based on a regular grid. Seating locations were represented by codes superimposed on the floor plan according to their spatial references, that is, the locations of the respective zones (i.e. A2, B5). Occupancy was then calculated for each zone in the room. Daylight analysis was based on luminance rather than illuminance. In order to capture the luminance of the entire scene, digital photographs were taken at 15min intervals during which simultaneous occupancy observations were recorded. These photographs also enabled enhanced data collection during observations while also providing permanent visual records. The data produced by the seating observations and daylight analysis confirmed that the areas located near windows were much brighter than those away from windows throughout the observation period and that those brighter areas near windows were highly preferred by the occupants.

Wang and Boubekri (2009) observed seating behaviours of occupants in a student union lounge over a period of three consecutive sunny days. The results indicated that people tended to sit in areas with direct sunlight and that their seating behaviours were affected by the level of enclosure. Illuminance levels were measured on a regular grid across the room and from these data average illuminance values were determined. This corresponds well with the work of Kim and Wineman (2005) which has used illuminance as the metric of choice. The space was divided into five zones based on average illuminance level and the distance to the sun patches, which were defined as the areas where the sunlight directly falls on the floor, although the precise method for predicting the positions of sun patches was not reported. To analyse the effect of level of enclosure, Wang and Boubekri (2009) compared the seats for the presence or absence of enclosures around them, these included building elements that provide physical separation such as partitions and walls. The levels of enclosure were then categorized according to the number of enclosed sides around a seat. Each seat was given a value from 0 to 3, with 3 indicating that the seat is enclosed by three sides and 0 indicating the seat is fully open, that is, it has no enclosures at all. Results showed that among the seats in the sunny area, those that provide a high degree of enclosure were more frequently occupied, whereas away from the sunny area people preferred seats in relatively more open spaces. The authors concluded that individuals who exposed to high levels of sunlight would likely have experienced an increased physiological arousal and as a result tended to choose seats with high level of enclosure as a means of moderating their level of arousal. However, as noted by Wang and Boubekri (2009), further work is required to explore the assumptions about daylight and enclosure level.

In another study examining seating preferences in a library reading room, Othman and Mazli (2012) found that occupants tended to locate themselves away from windows to avoid high contrast caused by direct sunlight in the morning, whereas around midday, it was found that they preferred seats near windows. In the afternoon when there was not enough daylight and people had little option but to rely on artificial lights, they appeared to be more evenly distributed around the room. To estimate the variation of daylight levels, illuminance measurements were taken at representative points in the room. The results were reported as ranges rather than as absolute values. The highest illuminance range was recorded for areas near windows during the morning period. These findings suggest that even though occupants presumably sit in areas near windows in part because of the large quantities of daylight available, having too much daylight seems nonetheless to have reduced their motivation to sit in those areas in the morning. It could be concluded that people are willing to give up daylight when it causes discomfort, but just for a short period of time.

The importance of a view out is demonstrated by the work of Gou et al (2018). They examined whether there is a measurable effect of the information content of a view out on seat choice behaviour. The test space was an open-plan library room. The windows were identical except that at different seating locations the view content varied from views of shading devices to sky and natural scenes. The sky view factor was used as a proxy measure of the portion of sky visible from a viewpoint. For each seat position, sky view factors were calculated and the results were correlated with occupancy rates to test whether there was a relationship. The methods of calculating the sky view factor involved analysis of fisheye lens photographs as well as image processing. A digital camera fitted with a fisheye lens was used to collect data at the points where the occupants were located. The camera was mounted on a tripod at seated eye level. The post-processing of the digital images yielded values for sky-view factors. The results showed that seating areas overlooking the sky had higher occupancy rates than those overlooking dense trees and shading elements. The authors concluded that occupants preferred sky views as they contain multiple layers compared to other views that include only one or two layers. This research suggests that preferences for window seats may be related to the visual content of the view through the window, where multi-layered sky views are preferred over monotonous views such as those consisting of high-density trees. However, as noted by Gou et al (2018), one limitation of the study is that it examined only window seating areas, thereby neglecting the effect of occupancy patterns in other seating areas in the test room.

Conclusions from the above five studies about the effects of daylight on seat choice behaviour depend on the room layout. The layout of seating within a room, of which there are numerous possibilities, may affect occupants' experience of choosing where to sit. One possible difference between the test rooms is the regularity of the seating. If the test room had a different layout, for example the seats were arranged in a more regular/irregular pattern, different conclusions may have been drawn. The effect of seat regularity has been explored in further work (Keskin et al, 2015). Occupancy patterns were observed in two library reading rooms: one consisting of regular rows of study desks, while the other consisted of seats arranged in an angled configuration. The degree of correlations between daylight and seat use was much higher for the former than that for the latter room. This suggested that the prediction might be better for regular seating pattern than irregular. A comparison was also made between different seating areas in one room. For this data, the correlation was higher for regularly-placed seats, further suggesting seating regularity may be an important factor. Findings from this other work in relation to seating regularity are summarised in Appendix A.

In the studies reviewed so far occupancy has been recorded along with the prevailing daylight conditions. Daylight has been examined as a possible predictor of seating behaviour and estimated through physical measurements (the methods used to measure daylight are described in detail later in this chapter). In the remaining two studies (Organ and Jantti, 1997; Carstensdottir et al., 2011), it is not possible to draw a clear conclusion regarding whether or not a relationship between daylight and seating preference is supported, in part because these studies were not specifically designed to investigate such effects of daylight. Organ and Jantti (1997) examined space usage in a university library building; the aim was to identify the areas in the library that the occupants use heavily and those that they employ infrequently. They found that the most popular seats were those located along walls and adjacent to windows. The popular seats were reported as being well lit, though this impression was not based on any measured data. A similar result was found by Carstensdottir et al (2011) who recorded seating behaviour in two different social settings, a café and a restaurant. They reported tables located along the perimeter of the room were more preferred than those located in the middle. The authors did not report data regarding the level of daylight, but what they did indicate is that the availability of windows and outdoor views may affect seating preferences. However, since these studies do not observe seating behaviour with the specific goal of investigating the effect of daylight, it would not seem to be possible either to directly implement their findings nor to consider whether the amount of data collected by these studies were sufficient to expect an effect of daylight.

2.4.3 Methodological approaches used in revealed preference studies

An important question that arises from previous revealed preference studies is whether there is robust evidence that daylight does indeed affect seating preferences. While there is some evidence to suggest that the presence of daylight affects seating preferences, it is possible that the procedures used to collect data did affect the findings gained from a particular study. The information gathered from observations can vary widely depending on the function of the room in which the observation takes place, the interval for which observations are recorded, duration of the observation, time of the day and time of the year. Each of these will now be considered in turn.

Location: The way people locate themselves differs according to the physical setting. For example, when studying in a library reading room, an occupant might sit in a secluded area where she/he would be less likely to come into contact with others, but when encouraged to engage in social interaction in a café, she/he could choose more exposed areas. As these factors vary depending on where the observations take place, it may be beneficial to extend the research in other type of buildings. An example of how different settings influence where people choose to sit is highlighted by Kim and Wineman (2005), who recorded seat selection patterns of occupants in two types of settings, social (a cafeteria) and workplace (a library study area). Kim and Wineman (2005) only provide graphical data, with no summary statistics, but it appears higher occupancy rates were found in areas with outdoor views, and this difference was much smaller and less drastic in the library than in the cafeteria. This discrepancy between the two settings was explained by suggesting that view is less important in workspaces where people need a high level of concentration without distraction. Another concern is the generalizability of the results, so an important question to answer is whether room types of same use but in different buildings can be expected to show consistent results (i.e. two reading rooms in different library buildings). This was not examined in previous studies however.

Time interval: The interval for which recordings are made is another important factor to be considered when investigating seating behaviour. One limitation with periodical recordings is that they ignore seat occupancy changes between two observation points. If time interval matters for the snapshot observation approach, and if shorter interval duration is better than a longer duration, this might mean that while durations of 15 minutes lead to credible data (Dubois et al., 2009) the 2.5 hours or more adopted by Organ and Jantti (1997) do not. This could potentially influence the results of observations, especially those carried out in areas of high circulation where occupant density changes rapidly over time. Time interval may be a more significant factor for those observations carried out in a café where people typically tend to spend shorter periods of time, for example in comparison to those carried out in a library reading room where people remain static for longer periods of time. As would be expected, previous studies recorded data at shorter time intervals in social settings such as cafes and restaurants (Kim and Wineman, 2005; Dubois et al., 2009) compared to workplace settings (Kim and Wineman, 2005; Organ and Jantti, 1997). Most studies tended to record observations at fixed intervals (Kim and Wineman, 2005; Dubois et al., 2009; Wang and Boubekri, 2009), with the exception of one study by Organ and Jantti (1997), who recorded data at three times per day, with long intervals of time between them (around 2.5-3 hours).

The walk-through approach requires the observer to constantly monitor seating behaviour, which potentially overcomes limitations associated with periodical recordings, such as the loss of information relating to seat occupancy changes that occurs between two observation points. One thing to note, however, is that the use of walk-through observation may result in missing data in relatively large samples such as those found in areas of higher population density. Few previous studies have used this method to record seating behaviour. Two studies that did were Carstensdottir et al (2011) and Othman and Mazli (2012).

Duration: The information content of the observation depends on the length of the observation period. Observations of seating behaviours for shorter periods may introduce bias since the results tend to be more revealing of the random seating patterns than of typical patterns. Yet, it may be practically difficult to observe seating behaviour continuously over an extended period of time as it requires considerable time and effort. Although alternative methods such as video photography may allow continuous recording for longer periods, these were not used in previous studies, possibly due to the limitations with the recording equipment and method. The shortest observation period in previous studies was that of Wang and Boubekri (2009), who recorded data on three consecutive afternoons. The longest observation period was five months, and this was for the study of Organ and Jantti (1997).

Time of the day: Another factor that may influence the results is the time of the day when the observations are carried out. One study which investigated the relationship between occupancy patterns and the time of the day was carried out by Othman and Mazli (2012). They found that occupants tend to sit farther away from the window in the morning due to the excessive contrast in daylight levels, but they choose seating near windows to get more daylight in the afternoon. Kim and Wineman (2005) and Organ and Jantti (1997) recorded data both in the morning and afternoon, whereas Wang and Boubekri (2009) did so only in the afternoon. The other two studies (Dubois et al., 2009; Carstensdottir et al., 2011) did not report the time of day when the observations were made. There may be an advantage to observing seating behaviour also after sunset: if daylight does have significant influence on seat choice, and if this influence is greater than that of other factors such as access to view out, then seat choices observed after dark would be different from those observed during daylight.

An alternative argument of why one might choose to sit near windows is that high levels of daylight illuminance may lead to increased levels of thermal comfort, particularly in winter. By the same token, however, overheating may occur as a result of excessive solar gains in summer. The amount of light as it changes over the course of a day and through the changing seasons may directly affect seating preferences of individuals by increasing/reducing their thermal comfort. None of the previous revealed preference studies have explored these issues however.

Time of the year: The seating behaviour recorded at different times during a year may lead to different results. This variation could be caused by a number of factors. One possible explanation is that the solar position changes over the course of a year (i.e. different maximum altitude and different range of azimuths) and the occupants may have higher acceptance for sunlight penetration in the winter than in the summer, which may influence resulting seating behaviour. Another explanation could be how the space is being used at different times of year. For example, in a university library building the undergraduate students are not usually present during summer months, which results in a lower number of people encountered during the experiments. These possible effects of season were not explored in previous studies. Kim and Wineman (2005) carried out observations at different periods of the year (May, June, October and November), but for two different types of settings and so no comparison was possible. One study was carried out in autumn (Dubois et al., 2009) and one study in spring (Wang and Boubekri, 2009). Whilst the study by Organ and Jantti (1997) was carried out mostly during summer, other two studies (Carstensdottir et al., 2011; Othman and Mazli, 2012) did not report the time of year when the observations were made.

The primary limitation of the revealed preference method is the inability to infer individuals' motivation behind their seating behaviours. The question this raises is whether revealed and stated seating preferences lead to the same conclusions regarding the effects of daylight. Yet observation is only one of the methods used in the studies of seating behaviour, and it is sometimes complemented by other data collection methods such as surveys. The next section describes the way that stated preference methods were used in previous studies.

2.4.4 Stated preference studies

Another method of determining the seating behaviour of occupants is simply to ask them why they choose a particular seat or what factors influence their decision. This approach can provide insights into what aspects of the environment may affect their perceptions of the seating area they are in and any decision-making processes. Stated preference studies depend greatly on respondents' ability to remember their seating behaviour and report it without bias, thus potentially introduce a degree of subjectivity which could influence the end results (Wilcox, 2005). Given such potential for subjectivity in occupants' responses, some previous studies have used stated preference methods in conjunction with revealed preference methods to form more validated conclusions. Three such studies were Dubois et al (2009), Othman and Mazli (2012) and Gou et al (2018). In the first study, which employed a multiple choice questionnaire in a university cafe, daylight was reported to be the most influential factor in choosing a seat location, followed by ambient temperature. The next most influential factors reported by respondents were the view outside, the type of furniture and the distance from other occupants, which were of almost equal importance. The factors of least importance were noise and the odour coming from the food service area; and relatively fewer respondents chose the option 'other factors'.

In the second study, occupants were asked to evaluate daylight conditions and the quality of view from their sitting position on a five-point rating scale. The questionnaire consisted of two parts. The first aimed to determine whether seating preferences of occupants were affected by daylight and the second aimed to determine how satisfied occupants were with daylight conditions and the outside view. Concerning the effects of daylight, almost three-quarters of respondents agreed or strongly agreed that their seating preferences were affected by daylight. However, when asked whether daylight affected the amount of time they spent in the room, occupants disagreed or tended toward neither agreeing nor disagreeing with this statement. Another important consideration relating to daylight was how glare was perceived by occupants at different times of the day. Glare from the window was more frequently reported in the morning than in the early afternoon, and no glare was reported in late afternoon, suggesting that there is a substantive influence of time of the day on the level of perceived glare. This supports the finding from the same study reported earlier that people tended to sit away from windows to avoid high levels of contrast in the morning. As for the outside view, the majority of occupants reported that their view was either pleasant or very pleasant, and this trend was relatively consistent across different times of the day. The survey report concludes that most people agreed with the statements on behavioural effects of daylight, with the exception of the question regarding whether daylight was important for their length of stay in the room, which had little or no effect.

In the third study by Gou et al (2018), occupants were asked to indicate in their own words why they chose a particular seat location. Quietness was the most mentioned reason, followed by view out, privacy, less distractions, seclusion and lighting. In addition to the open-ended question, participants were also given a list of items and asked to rate the importance of each item on a five-point rating scale. In examining the reasons given by participants for choosing a particular seat location, the results were in agreement with those obtained from the analysis of open-ended survey responses, highlighting quietness as being the most important reason. In the latter case however, daylighting was the fourth highest rated reason after quietness, furniture and privacy. A factor analysis of the responses revealed three main factors. The first represented territoriality (furniture, privacy, quietness); the second reflected visual aspects (view out, daylighting, orientation) while the third reflected social interactions (friends, entrance, circulation). These results emphasize that daylighting cannot be examined in isolation and that interaction with other features of the built environment it could be an important factor when choosing a seat.

The fact that many aspects besides daylighting influence the choice people make about seating location is brought out in the three studies of Hygge and Loffberg (1999), Christoffersen et al (2000) and Parpairi et al (2000). They used post-occupancy evaluation surveys, and so measured perceived preference rather than the actual preference captured by observations. Although the data on which these studies are based was not acquired specifically for the purpose of investigating the effects of daylight on seating preferences, they were intended to facilitate an exploration of the relative importance of daylight and other factors regarding occupants' perception of the visual environment. The approach taken was to evaluate daylight within a wider framework within which respondents were asked a series of questions relating to their workplace. The analysis of subjective assessments paired with concurrent physical measurements was performed to identify the visual conditions preferred by occupants. These studies conclude that lighting is one of the most important factors in an occupant's assessment of physical environment (Hygge and Loffberg, 1999), and that it is highly desirable to be close to a window with a view, even though high levels of daylight in such areas could create glare problems (Christoffersen et al., 2000; Parpairi et al., 2000). A summary of the stated preference studies reviewed is given in Table 2.3.

Table 2.3. Summary of stated preference studies.

Study	**Location**	**Participants**	**Type of questions**	**Survey Items**	**Key Findings**
Hygge and Loffberg (1999)	5 office buildings	234 participants (varying ages)	Open-ended and closed questions	Daylight, artificial light, windows, view out, temperature, noise, ventilation, privacy, general environment (colours, carpets, decoration)	Good light was rated as the most important feature in a work place.
Christoffersen et al (2000)	20 Danish office buildings	1,823 participants (aged 18-34)	Closed questions	Direct sunlight, daylight, windows and view, electric light, noise, ventilation, temperature	Office workers had a strong preference for having their workplace near windows despite the presence of glare and screen reflections.
Parpairi et al (2000)	3 university library buildings	26 participants for each library (aged 20-29)	Open-ended and closed questions	Subjective feelings about daylight (Unpleasant–Pleasant, Gloomy–Cheerful, Dim–Bright, Tense–Relaxing, Glary–Non-glary, etc)	Occupants preferred higher levels of daylight even to the extent that too much direct sunlight caused discomfort and glare, as long as a landscape view was present.
Dubois et al (2009)*	A university café	Not reported	Open-ended and closed questions	Ability to choose a seat freely, task undertaken, importance of daylight, effect of other factors (view out, the type of furniture, proximity to other occupants, thermal conditions)	Daylight quality and high illumination were reported as the most important factors for seat choice.
Othman and Mazli (2012)*	A library reading room	114 participants (age not reported)	Closed questions	Daylight (availability, brightness, contrast, glare) and view out	Almost three-quarters of respondents agreed that daylight affects their seating preference.
Gou et al (2018)*	A library reading room	100 participants (age not reported)	Open-ended and closed questions	The reason of seat choice, view out, daylight, close to toilet/washroom, close to friends/mates, close to reference books, close to entrance/circulation, privacy, quietness, furniture, cleanliness and orientation	Daylighting and views were reported as the second most important factors influencing seat choice decisions.

* The three studies of Dubois et al (2009), Othman and Mazli (2012) and Gou et al (2018) used revealed preference method as a complementary method.

The work of Hygge and Loffberg (1999), undertaken as part of the Daylight Europe project, examined preferences for daylighting through a series of post occupancy evaluation surveys and reported the analysis of five office buildings. The method involved measuring and monitoring various aspects of the physical environment, and a parallel programme of subjective assessment to capture the experiences of occupants, and in particular the impact of both daylight and artificial light on visual comfort. One of the questions of interest in the study was what aspects of the physical environment were important. Respondents were asked to rank the three most important physical features of the workplace from a given list of ten items. Two environmental features were mentioned most frequently, with light (either daylight or artificial light) being the most frequent followed by temperature. Among other variables that have been identified as important are windows, view out, noise, ventilation, privacy and general environment (colours, carpets, decoration). Of these, ventilation was rated as relatively more important, and other factors were rated similar in importance by the respondents. The high level of importance given to light is suggestive of the value of good lighting in a workplace.

Another study carried out in 20 Danish office buildings by Christoffersen et al (2000) found a preference for working in the window zone in spite of the problem of glare, a result consistent with those reported by other studies reviewed in this chapter. This was studied using a post-occupancy evaluation survey of more than 1800 office workers. Responses were captured on a 5-point scale ranging from very unsatisfied to very satisfied; and on a 4-point scale ranging from never to always. While the former scale was used to measure the level of satisfaction with lighting conditions, the latter scale was used to measure comfort levels in the workplace. The physical measurements were made for representative offices in each office building, and included illuminance levels and daylight factors. For comparison purposes each room was divided into three zones: window zone, mid-zone and rear-wall zone. Results suggested that people working in the window zone had higher levels of satisfaction with daylight conditions than those working in the mid-zone or the rear-wall zone, a finding well correlated with the measured daylight factor. That is, higher daylight factor led to higher ratings of satisfaction with daylight. When it came to the outside view, the study found that satisfaction with the view from an office was greater for natural scenes than for artificial scenes. However, no relationship was found between the distance to the window from the work place and satisfaction with the view out.

Similar results to those found by Christoffersen et al (2000) have been found by Parpairi et al (2000). In an extensive study of occupant response to different daylight conditions in three Cambridge libraries, Parpairi et al (2000) found that occupants preferred areas close to the window where lighting levels were high and considerably more variable due to the presence of direct sunlight. They carried out a field assessment of a total of seven seating locations in the three libraries by a representative group of 26 students. The students were selected randomly from those who were using the library regularly and who were thus familiar with the spaces. The method involved recordings of subjective feelings of the students through a questionnaire and assessments of daylight conditions measuring illuminance and luminance levels. Daylight levels were calculated for predefined view positions and then compared against the survey data to draw conclusions about preferences. Data was collected under a clear sky in summer and winter, and under an overcast sky in autumn. The authors concluded that the areas with high levels of variable daylight, such as those found near windows, were highly appreciated by the occupants in all three library spaces. In addition, the occupants seated in these areas reported a high level of satisfaction in spite of glare. The reason for the tolerance to discomfort from daylight glare reported by the respondents was that the windows of their workspace overlooked a natural scene, which caused them to pay more attention to the view. This gives further evidence that seating behaviour is likely to be influenced by the outside view. The second reason reported was that whilst occupants were likely to suffer the effects of glare when they were close by the window, there was opportunity available to them if they preferred to move or adjust their position.

2.4.5 Methodological approaches used in stated preference studies

In the stated preference studies examined in the previous section it is apparent that daylight was explicitly considered among the set of attributes affecting choice. One particular concern raised with stated preference data is related to their trustfulness. It is not certain that a subjective response by a participant translates into actual behaviour. For example, if daylight conditions do influence the subjective assessment of visual environment this may not necessarily be reflected in actual behaviour. Objective measures of behaviour in conjunction with questionnaires could provide stronger evidence. However, very few studies employ both methods, and those that do, have collected data from those people who were seated in the test room at the time of observation. One possible criticism of this approach is the location of survey may have influenced the participant's responses. Once the seating decision has been made, the participant may seek to justify their decision by rationalization. This rationalizing may stem from a desire to appear more favourable to other people (generally known as social desirability bias). One way to reduce survey bias is to ask people to state their preferences before entry to the room as well as in the room.

2.5 Prediction of daylight: Review of the methods used in previous studies

The studies reviewed in the previous section are distinguished by the daylight measurement methods they employ– some determine illuminance levels at representative points while others attempt to analyse luminance variations using alternative methods such as digital image analysis. Two studies by Organ and Jantti (1997) and Carstensdottir et al (2011) did not specifically provide a quantitative measure of daylight, but rather presented it as a potential factor that might influence seating preference. Much of the evidence from these studies is based on observations of individuals seated in close proximity to windows, rather than any measured daylight data.

Those studies that did quantify daylight used physical measures rather than computer-based simulation techniques. Four studies measured illuminance, either on a regular grid across the room (Wang and Boubekri, 2009) or at reference points (Christoffersen et al, 2000; Kim and Wineman, 2005; Othman and Mazli, 2012), and one study (Dubois et al., 2009) considered luminance alongside illuminance and employed a digital image analysis technique to collect luminance data. Parpairi et al (2000) carried out a more comprehensive daylight analysis considering both illuminance and luminance-based metrics. A summary of daylight prediction methods used in these studies is shown in Table 2.4.

Table 2.4. Methods and tools employed in past studies of daylight and seating behaviour.

Study	Method	Measurement Tool	Output	Metrics/Indices
Christoffersen et al (2000)	Physical measurement	Not specified	Illuminance	Daylight Factor
Parpairi et al (2000)	Physical measurement	Illuminance meter and Luminance meter	Illuminance and luminance	Luminance Difference Index and Glare Indices
Kim and Wineman (2005)	Physical measurement	Hobo data logger	Illuminance	Average illuminance
Wang and Boubekri (2009)	Physical measurement	Not specified	Illuminance	Average illuminance
Dubois et al (2009)	Photography and digital image analysis	Mirror ball and digital camera	Illuminance and luminance	Brightness Ratio and Contrast Ratio
Othman and Mazli (2012)	Physical measurement	Illuminance meter	Illuminance	Average illuminance

Christoffersen et al (2000) measured daylight illuminances in representative offices in each building and from these data they calculated daylight factors at a point 2m from the window. Kim and Wineman (2005) used HOBO data loggers to collect illuminance as well as temperature and relative humidity readings for each test space. Three data loggers were placed at three different locations within the space – one near the window, the second in the mid-interior area, and the third in the far-interior area. Wang and Boubekri (2009) measured daylight illuminances across a 2m x 2m grid and determined average values for each of the five observation zones. Othman and Mazli (2012) measured daylight illuminances at representative points close to the locations of occupied seats. The measurements were taken during three time periods, at the exact hours of simultaneous observations.

Dubois et al (2009) have used luminance as the metric of choice and recorded luminance data using a digital camera and image processing. The camera was placed on a tripod, facing a mirror ball. A series of images taken at 15min intervals enabled a scene of wide luminance range to be recorded, numerical value of the pixels then made it possible to derive luminance data. Parpairi et al (2000) established a new method for measuring luminance diversity, called the Luminance Differences (LD) index. LD was calculated by taking eye-level luminance measurements in a 360-degree polar array across a horizontal plane and then calculating the difference in luminance levels across a range of angles corresponding to eye and head movement.

One question that arises is whether the metrics/indices used in previous studies are indeed appropriate and reflect what occupants actually need from daylighting when choosing a seat. The arguments given in favour of the use of work plane illuminance are that it correlates to quite a large extent with other measures of light in a room, and that it is consistent with the assumptions on which electric lighting is usually calculated (Tregenza and Wilson, 2011). The counter arguments include the view that people's behavioural response to daylight depends on several physical factors as well as subjective characteristics, so the information from a single measure of light quantity is not likely to provide evidence. Yet, physical parameters such as illuminance are important in terms of how people perceive daylight, without of course being the sole parameters affecting their perception and behaviour (Steemers and Steane, 2004). Rather than provide a quantitative measure for each seating location, past studies have tended either to divide the room into zones or to define representative points for illuminance measurements. The criteria used to define observation zones or representative points for illuminance measurements are somewhat arbitrary and the decisions about which daylight calculation parameters are met is likely to be subjective. It appears that no empirical evidence exists to justify the criteria used. The most common way has been to measure the illuminance at specific points and to determine the average illuminance over the specified surface. The rationale for averaging the illuminance values might be based on the hypothesis that single quantities are not very informative about the dynamic effects of daylight across the work plane.

Finally, it may be argued that, a prediction of luminance would be more appropriate than one of illuminance when considering the behavioural impact of daylight. Luminance-based metrics were considered by two studies (Dubois et al., 2009; Parpairi et al., 2000). One important finding from Parpairi et al's study was that subjects judge their daylighting environment depending on illuminance levels on the horizontal and vertical plane, while the daylight glare index was less successful in predicting subjects' responses. When calculations of indoor illuminance are intended to be used to asses both seating preferences of occupants and the general daylighting environment within the space, then horizontal illuminance, although perhaps less representationally accurate when predicting occupant behaviour, may have a wider acceptability and relevance. Given the uncertainty as to the behavioural effects of daylight, illuminance has been adopted as the most appropriate (and calculable) measure of daylighting for the purposes of computer modelling described later in this thesis. Luminance-based metrics were not considered in the current study, however, a discussion provided within the thesis focuses on motivations for using such metrics in the context of seating behaviour research.

2.6 Summary

The review of literature reported in this chapter highlighted that research on the seating behaviour of individuals is limited, and few studies have been carried out with the specific goal of investigating associations between daylight and seating preferences (Kim and Wineman, 2005; Dubois et al., 2009; Wang and Boubekri, 2009; Othman and Mazli, 2012). Other studies have tended to focus on subjective evaluations and overall satisfaction with the visual environment (Christoffersen et al, 2000; Hygge and Loffberg, 1999; Parpairi et al., 2000), but neither of these focused specifically on seating preferences. It is, however, possible to draw certain conclusions about the effect of daylight based on the evidence presented in these studies. A common finding in the stated preference studies is that daylight is perceived to be important when choosing a seat location. The samples included a range of different types of spaces and functions, such as offices, cafes and libraries. Questionnaires have been used for obtaining information about the reasons for the seat choice decisions. Further evidence comes from revealed preference studies, which suggest that people tend to sit in areas near windows where daylight levels are high, even to the extent that excessive levels produce glare.

Each study has tended to use a unique methodology in addition to a unique set of daylight metrics. This raises the discussion as to the method by which an individual’s seating behaviour was recorded (for example, snapshot or walk-through observation) or the procedure with which responses were sought (for example, before or after participants choose their seats). The current study aims to identify the effect of daylight availability on seating preference using a range of methods developed by identifying gaps in previous research. The questions for this study are summarised as follows:

What is the perceived importance of daylight when choosing a seat, and how do these perceptions of importance vary before and after the seat choice is made? Existing evidence, although limited thus far, suggests that daylight is perceived to be an important factor when choosing a seat in a space (Dubois et al., 2009; Othman and Mazli, 2012). The approach is based on asking people seated in the test space to state whether they think daylight is an important factor, selecting reasons for their seat choice from a list. One possible criticism of this approach is that the perceived influence of daylight on seat choice may depend on the context in which it occurs, for example, before or after the seat decision is made. Asking about reasons of seat choice behaviour within the test room may lead respondents to rationalize the choices they have already made before entering the room, resulting in inconsistent responses across the two situations. However, previous studies have neither assessed the relative importance of daylight before the decision is made nor provided data as to whether this relative importance varies after the decision. This study therefore includes alternative experimental methods that permit the comparison of responses of participants on the basis of their location (i.e. outside the room and within the room). A door-room survey method, surveying test participants before and after they enter the test room, was suggested to be a useful way of identifying potential contextual differences.

Do the actual behavioural data provide sufficient evidence to infer that there is a relationship between daylight and seat choice behaviour? Revealed preference studies have a number of inherent limitations in relation to what they tell us about actual seating behaviour in relation to daylight, primarily because there is no direct evidence that the daylight condition is actually being paid attention to, or is important to seat choice. One common finding in these studies is that people prefer to sit in areas near windows where daylight levels are high. However, this is only a proxy measure of preference for daylight. It is possible that seat choice is influenced by factors other than daylight. The conclusions drawn from the observations of actual seat choice behaviour should therefore be interpreted with caution. This study explored alternative explanations in a series of field experiments designed to assess whether daylight influences actual seat choice behaviour.

Do different observational approaches yield the same results? Previous studies of seat choice typically employ one of the two data collection methods, i.e. snapshot or walk-through approach. The snapshot approach involved recordings at different intervals in different time periods, and the walk-through approach involved continuous monitoring of seating behaviour over a specific period of time. Each method offers advantages and imposes limitations in terms of the accuracy of the data captured. The conclusion drawn from the observation of seating behaviour using one of these methods will therefore be more robust if supported by results obtained from the other method. For example, internal validation could be gained by employing walk-through approach in parallel to snapshot approach. These approaches have not been explored in previous studies. The current study evaluates the accuracy of the occupancy data by comparing results obtained with the two methods.

How well do daylight performance indicators predict seat choice behaviour?

Previous studies have relied on physical measurements taken in the test space. However, there are discrepancies between these studies in terms of the methods used for measurements. The majority of studies considered one characteristic, the amount of light, as determined by horizontal illuminances at desk (Christoffersen et al, 2000; Kim and Wineman, 2005; Othman and Mazli, 2012; Wang and Boubekri, 2009). In two studies, luminance was considered alongside illuminance (Dubois et al., 2009; Parpairi et al., 2000). However, differences may arise due to errors in physical measurement, for example, the precision of measurements used to specify illuminances, or by relying on a single metric such as daylight factor. Another limitation of these studies is that they have tended to divide the test room into somewhat arbitrary zones to determine measurement points, which means the measurements may not be reliable predictors of where an individual sit. What may be an improvement is to specify a range of metrics corresponding to the precise location of each individual seat in the test space. This is a more reliable method of collecting data regarding daylight conditions as the assumptions which are made for the location of measurements can be avoided. The simulation experiment reported in this thesis attempted to improve the accuracy of daylight availability estimates compared with previous studies of seat choice by exploring a set of metrics for each individual seating location. A comparison was made between the predicted daylight values and the results from observations using the snapshot and walk-through approaches. In the seat choice studies reported in this chapter, there appears to be no quantitative data by which to evaluate whether a relationship exists between daylight measurements and the records of occupancy.

The answers to these questions have potentially important implications for research on daylight and seat choice behaviour. The review of literature revealed that the number of studies on seat choice is limited and more studies are required in order to develop a more accurate understanding of where people sit in relation to daylight and why in open-plan spaces. The present research was designed to add to the existing body of knowledge in two distinct ways. First, it sought to investigate whether people think daylight affects their seat choice behaviour (stated preference method). This included an analysis of whether surveying at different contexts lead to same conclusions about the relative importance of daylight, by surveying test participants before and after they enter the test room. Second, the present research sought to determine whether any impact of daylight conditions on seat choice behaviour can be inferred from actual seating behaviour (revealed preference method). Specifically, seat occupancy was recorded over a certain period of time, and the results were subsequently correlated with those obtained from daylight simulations. The next chapter presents the first of these methods, stated preference method, and describes the approaches taken to conduct questionnaire surveys that were designed to address the above research questions.

CHAPTER 3. STATED PREFERENCE SURVEYS

3.1 Introduction

The literature review presented in Chapter 2 found a consistent preference to sit near windows in open-plan spaces but the lack of consideration given to other factors such as the proximity to other people or the view-out of the window means we do not know the relative importance of daylight nor how it interacts with these factors. This chapter reports an experiment carried out to investigate whether people think that daylight is an important factor in seat choice decisions amongst other possible factors. The first part of the chapter describes the test room where the experiments were carried out. The second part reports an experiment in which the participants were asked to indicate the factors they perceive to influence their choice of seat location in the test room. Responses from two groups were collected by opportunity sampling, one group being approached when they were about to enter the room and the other when they were seated within the room. Finally, the chapter concludes with a discussion of the results from the experiment.

3.2 Test Environment: Western Bank Library

The experiments were carried out in an open-plan reading room at the Western Bank Library (formerly the Main Library), the University of Sheffield (Sheffield, UK). The characteristics of the reading room were, first, that it had large double-glazed windows overlooking a natural setting of a park (Weston Park), these provided both daylight to the interior and a view-out, and, second, that there was a free choice of seat location so the occupants had the option to sit closer to the windows or move deeper into the room to avoid discomfort from direct sunlight (Figure 3.1).

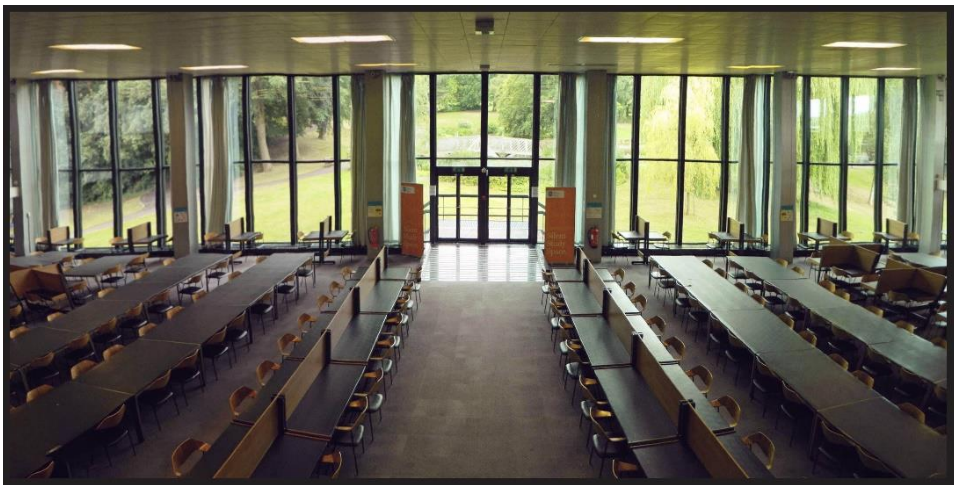
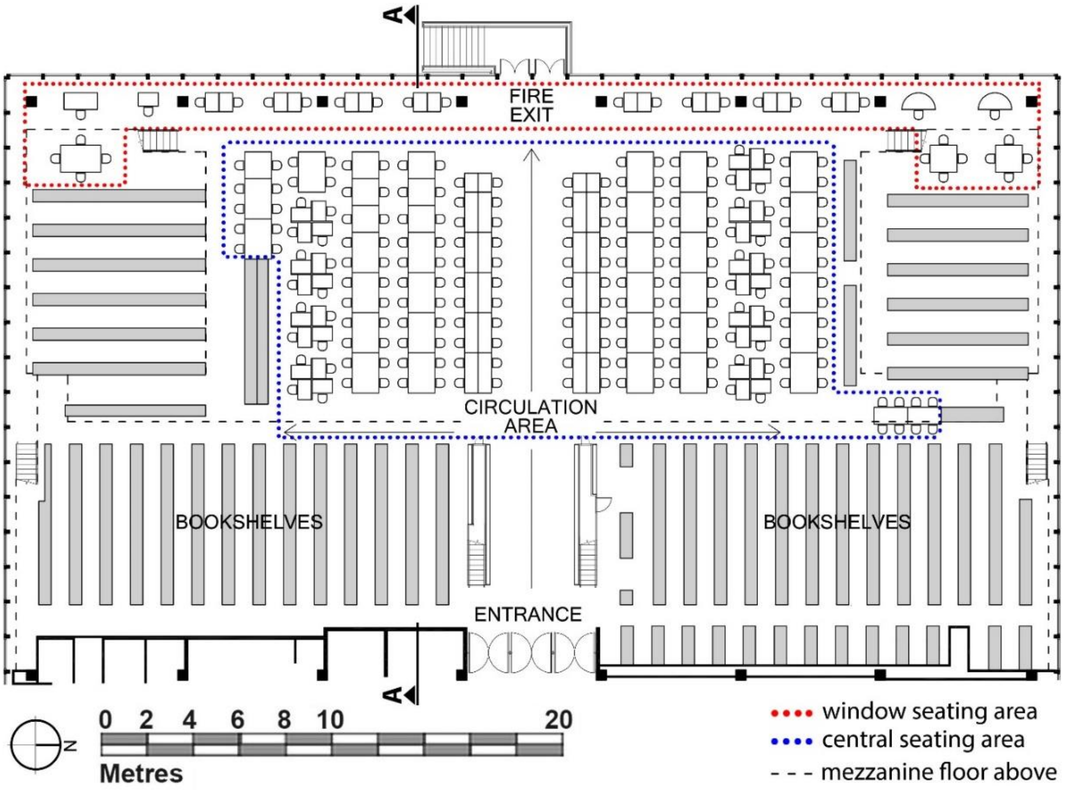
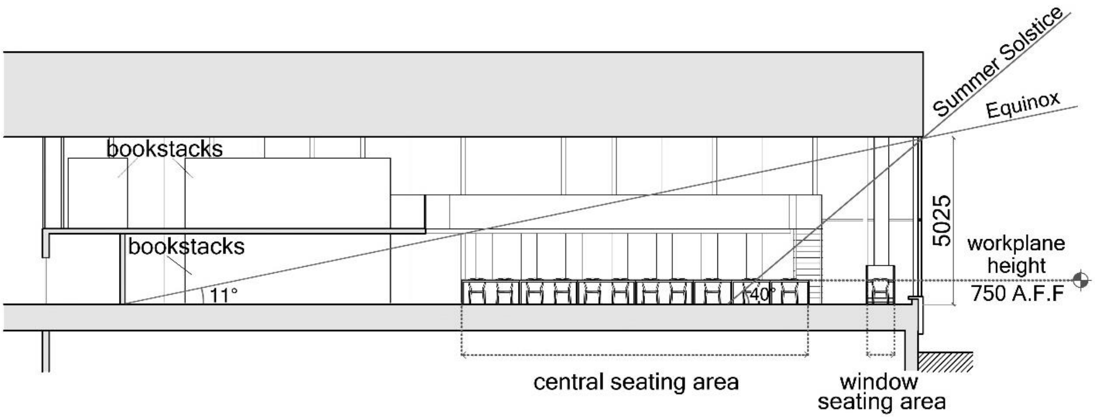


Figure 3.1. Interior view of the reading room from the mezzanine level, Western Bank Library, Sheffield. The space is oriented to a view looking west, towards Weston Park and the university buildings beyond (Photograph taken August 13, 2016).

The room has a rectangular plan measuring 45 metres long and 25 metres wide, with book stacks arranged around three sides of a central reading area (Figure 3.2). The room has a ceiling height of 5025mm and a window head height of 5000mm. The mezzanine floor is situated above the book stacks on the ground floor and contains additional book stacks, reading areas and office spaces. There is only one entrance to be used by the library users, which is located centrally on the east side of the room. Upon entering the room, one first passes between the book stacks and then reaches the central reading area, which has ten parallel rows of work desks. On the far side of the room from the entrance there are individual working desks along the west windows. This arrangement can serve to visually divide the room into two areas, a window area with open views through the west windows and a large interior area enclosed by mostly book stacks, with the exception of obstructed views of the Weston Park through the west windows. The central reading area has dimensions of approximately 25 metres long and 10 metres wide. The window area has a length of 42 metres and a width of approximately 1.5 metres.



(a)



(b)

Figure 3.2. Reading room geometric properties. (a) Floor plan; (b) Section A-A. Daylight enters directly through the double-glazed windows spanning the width of the room at the front (west facade) and at the two sides of the room (north and south facades). The seating area is separated for convenience into two areas, the window seating area and the central seating area. Materials from University of Sheffield Estates and Facilities Management, reproduced with permission.

The interior had been modified since its original construction and the decision was taken to extend the mezzanine to create an enlarged study floor with additional seats overlooking the lower level. Figure 3.3 shows how the reading room looked prior to refurbishment. Originally the book storage areas were tightly packed and devoid of daylight, while the seating areas were more formal with less variety in their arrangement (Worpole, 2013).

Figure 3.3. Interior view of the reading room before refurbishment (1959).
Image source: RIBA British Architectural Library.

The increasing number of students led to the expansion of the reading room and significant changes in how furniture was arranged. This was done by extending the mezzanine floor to create additional seating area above and storage shelving below. The emphasis now is on flexibility and a combination of individual and group study areas. The periphery of the room is now used for individual seating, with seats along the west windows, and the books being concentrated at three sides of the central seating area. As shown in Figure 3.4, there is a large variety of ways to sit in the room, for either as a single person at a private desk or in a group of people, and the total seating capacity is 250. The desks in the window seating area are arranged mostly for two facing people, separated by a 450 mm high partition, and with also some for individuals and for four people. The window seating area has 32 seats. In the central seating area, the desks are arranged both in linear rows and as four-person work spaces, and this area has 218 seats. The four person desks and the central two rows have partitions at 450 mm high.

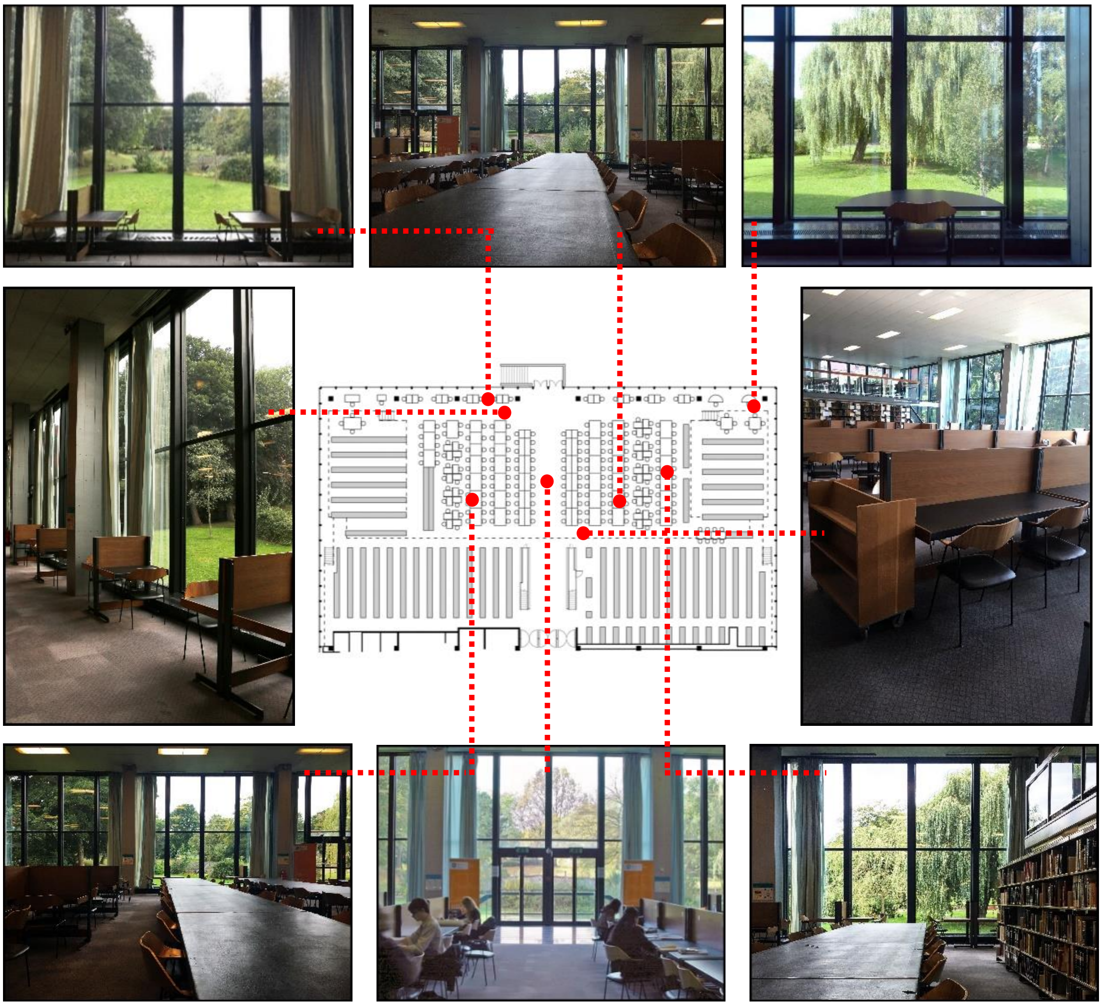


Figure 3.4. View out from different seating areas (Photographs taken August 13, 2016).

Artificial lighting, controlled automatically, is provided by single and twin luminaires installed at a grid of 120cm x 60cm and 180cm x 60cm, respectively (Figure 3.5). In order to evaluate the contribution of artificial lighting to the daylight levels in the reading room, horizontal desk top illuminances were measured, this being done after dark to ensure the measurements are electric lighting only. Illuminance was assessed using a Minolta T-10M illuminance meter, positioned horizontally on the surface of each working desk, chosen to enable representative sampling across the room. For this data, the mean desktop illuminance from electric lighting was 170 lux with a standard deviation of 61 lux, the minimum and maximum desktop illuminances being 11 and 264 lux, respectively. A simulation-based method was used to determine average daylight factor for the room (see Chapter 5 for the simulation method). The analysis has identified that the room complies with the benchmarks in terms of average daylight factor achieved: the average factor predicted for the room was 5.05%, which is above the recommended threshold of 5% for a well-daylit space (CIBSE/SLL, 2012). These data suggest that the room is predominantly lit by daylight and that the contribution of electric lighting in daytime is small relative to that of daylight.

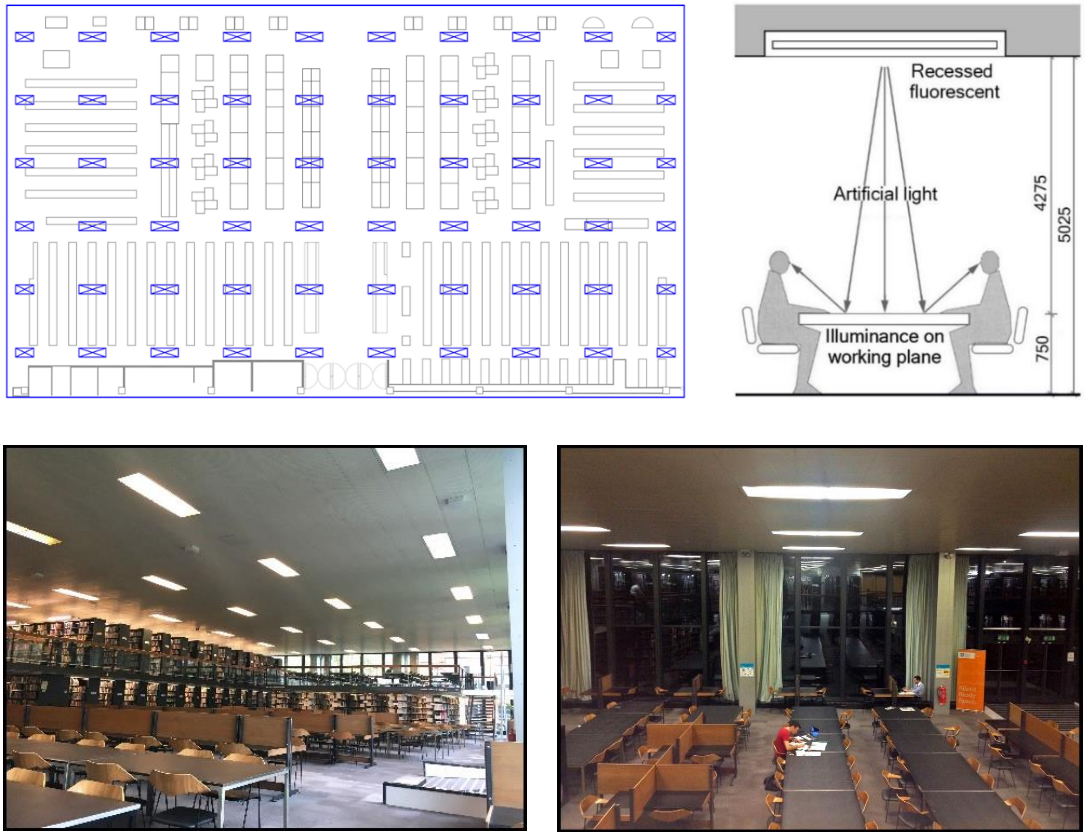


Figure 3.5. Schematic drawing (not to scale) showing the layout of the luminaires (blue squares) (upper left), the work plane illuminance from electric lighting (upper right), the views of the luminaires during daytime (lower left) and night time (lower right).

The shading devices in the reading room are automatically controlled and were fully open for every observation in this study. The automated blind control system does not enable occupants to adjust blinds to manipulate lighting environment (e.g. closing blinds to reduce glare or opening them to admit more daylight), which in this case eliminates uncertainty of occupant use of blinds. The system only allows the shading position to be either fully closed or fully open (Figure 3.6).

Figure 3.6. Shading position is limited to fully open (left) and fully closed (right). Automated control system does not allow the occupant to adjust shade positions, thus eliminating the uncertainty attributed to occupant control of shading devices.

As discussed in Chapter 2, the choice of control system affects how users can interact with the building, whether by reconfiguring building elements (i.e. drawing blinds to exclude sunlight) or by modifying their behaviour (i.e. moving from one place to another). The control systems of the electric lighting and window shading play an important role in seating behaviour. Active lighting and shading controls provide occupants with means for personally controlling their local visual environment in a way that enhances their comfort. An important aspect is that building occupants are no longer regarded as passive recipients of the visual environment, but rather play an active role in creating their own lighting preferences. In the current study, such active adaptive opportunities were not available to the occupants in the test space. That is, the automated control system does not allow the occupant to adjust lighting conditions through the use of shading devices and/or artificial lighting. What this lighting control system offers is the opportunity to explore the potential relationship between daylight availability and seat choice. As the occupants are not allowed to take active control of their environment, it is reasonable to assume that they respond to their visual conditions by changing their spatial behaviour (e.g. choosing a particular seat or changing seating position). The next section describes an experiment exploring the relative importance of factors perceived to influence seat choice decisions and whether response patterns differ across respondents before and after entering the test room.

3.3 Door - Room Survey

In the introductory chapters of this thesis, arguments were reviewed suggesting that the seating behaviour is essentially rational choice among a set of alternatives and that the means of arriving at a decision is by aggregation of preferences (Scott, 2000; Stone, 2002). In aggregating preferences, one obtains an order over a set of possible alternatives based on the degree of utility they provide. There is the counter argument, however, that even though people weigh the options rationally when they attempt to predict what they will do in a particular context, they tend to respond instinctively when they actually make a decision (Eagleman, 2011; Kahneman and Tversky, 1979; Kahneman, 2011). This suggests that choices about where to sit in a given environment are likely to be affected by the context of decision and therefore do not necessarily correlate with the higher-order preference.

The experiment presented in this section aims to provide further evidence in this debate by examining the perceived influence of daylight on seating preference in two locations, outside the test room and within the test room. The experiment was designed as a questionnaire survey, with responses being gathered by opportunity sampling – selecting those people who are available at the time – being those people about to enter the reading room, or who were already seated in the reading room. Surveying at these two locations allows discussion of the context in which the survey is conducted: The factors that people think should matter to their seat choice decision may not influence their behaviour in reality. This may lead people seated in the room to justify (or post-rationalize) the choices they have already made before entering the room.

In this section, ‘door survey’ refers to questionnaire responses sought at the entrance to the reading room, and ‘room survey’ refers to questionnaire responses sought within the reading room.

3.3.1 The questionnaire

Two surveys were designed to record responses, the door and the room surveys, each consisting of two parts. The first parts of the surveys were identical but the second parts were different: for the room survey the questionnaire was extended to record also feelings of importance of different factors affecting seat choice. To compare responses in the different locations the survey was designed following that used by Bernhoft and Carstensen (2008) in their study of factors which influenced pedestrians’ route choices. Rather than comparing responses from people in two locations, Bernhoft and Carstensen compared responses from two different age groups. In this method, respondents were presented with a list of ten factors that might influence their seat choice and asked to identify up to three of these that they consider to be the most important. Bernhoft and Carstensen (2008) asked “Which of the following conditions are most important for your route choice when walking/cycling in your hometown?” For the current study the questions were:

Door survey:	Where do you think you will sit in the reading room? Which of the following statements are the most important thing to you when choosing where to sit in the reading room? (Select the three most important factors)
Room survey:	Why did you choose to sit here? Which of the following statements were the most important thing to you when choosing where to sit in the reading room? (Select the three most important factors)

In addition to daylight, the available responses included nine additional factors, presented to participants in a multiple-option format. Previous research has used the method of asking respondents to choose options from a pre-selected list (Hygge and Loffberg, 1999; Christoffersen et al, 2000; Parpairi et al., 2000; Dubois et al., 2009; Othman and Mazli; 2012). The factors examined in the current work were guided by those used in previous studies. Though some of the previous studies were not necessarily designed with the intention of identifying factors associated with seat choice (Hygge and Loffberg, 1999; Christoffersen et al, 2000; Parpairi et al., 2000), the survey items have been used for this purpose.

Most of the categories used in the current survey were consistent with that reported in previous studies, with some exceptions, such as 'window size', which was considered by Hygge and Loffberg (1999) and Christoffersen et al (2000) when evaluating preferences for indoor environmental conditions in office spaces with different sized windows. As the current study was carried out in one single space and the size of the window was constant over the entire facade, this factor was not considered relevant to the survey. Items such as being near to power sockets or bookshelves were included to give a more specific and relevant context. The number of questions was restricted in order to ensure that the questionnaire was short enough to be completed within a reasonable time.

Although the survey was primarily concerned with daylight, other factors were also considered to allow the participant to rate the importance of daylight against other qualities of the physical environment when choosing a seat. A total of ten factors was included as a means of capturing the participant's perception of the physical and social environmental factors, the importance of which has been raised in previous research. The ten factors included in the room and door surveys were: “It is near power sockets”, “There is good daylight”, “There is good electric lighting”, “It is close to other people”, “It is distant from other people”, “There is a nice view”, “There are only a few people passing by”, “It is quieter”, “It was the closest available seat” and “It is near to the book shelves”. It should be noted that these factors are specific to the test space examined, for other libraries other factors could be important such as desks equipped with individual reading lights. There is no specific guidance as to what the survey should contain, since each building and lighting design is different. For example, the type of furniture may be worth considering when doing the survey in a space with a mix of different types of seats such as chairs, sofas, lounge chairs and carrels. Some occupants may also consider the availability of individual reading lights. In the particular library room investigated, these factors were not included as there were no individual reading lamps and the seats were physically identical.

The meanings of the ten factors were not defined to respondents and hence there is a risk of variations in interpretation. Of the stated preference studies examined, none have defined the meaning of the terms used in a survey. Giving definitions, either orally or in writing, extends the time needed for a survey: In the current work the aim was to obtain a large sample by using a purposefully brief survey form, and hence there were no definitions.

With ten items listed in order, there may also be an order effect, e.g. that the apparent importance of a particular factor is affected by the preceding factor(s). This may lead to subjective evaluations being misleading (Poulton, 1989; Ward and Lockhead, 1970). To counter an order effect five different versions of the list were established, each using a different order (see Table B1 and Table B2 in Appendix B for the five variations in which the ten seat choice factors were presented).

Describing the full description for each of the ten factors would be unnecessarily too long, therefore it was decided to use the abbreviated descriptions in the results section. The list of the abbreviated form of each of the ten factors used in results section is provided in Table 3.1.

Table 3.1. Abbreviated description of the ten factors used in door-room surveys.

Text used in questionnaire		**Abbreviated description**
Door Survey	**Room Survey**	
A place near power sockets	It is near power sockets	Power sockets
A place where there is good daylight	There is good daylight	Daylight
A place where there is good electric lighting	There is good electric lighting	Electric lighting
A place close to other people	It is close to other people	Near other people
A place distant from other people	It is distant from other people	Distance from others
A place where there is a nice outside view	There is a nice outside view	View out
A place where there are only a few people passing by	There are only a few people passing by	Few passers by
A place which is quieter	The noise level is lower	Quieter
The closest available seat	It was the closest available seat	Closest available seat
A place near to the book shelves	It is near to the book shelves	Near shelves

The door survey sought two further responses. The first asked:

> *In this room it is likely you will be reading and/or writing. For this task are you going to use: (Select as many as appropriate)*

Response options were:
paper-based media,
a laptop/PC,
other (please specify).

The second question asked:

> *If you have any additional comments that you would like to make about your seat choice, or general comments, please note them here.*

The room survey sought three further responses:

(1) *Is it your preferred seat?*

The responses available were:

    1. Yes, it is my preferred seat. I tend to sit here whenever possible.
    2. No, I sat here because my preferred seat was not available (e.g. someone else was sitting there).

(2) *During your visit to the reading room, did you change your seating location (did you move to another seat?)*

The responses available were Yes and No. If yes, a reason was requested.

(3) *In this room it is likely you will be reading and/or writing. For this task are you going to use: (Select as many as appropriate)*

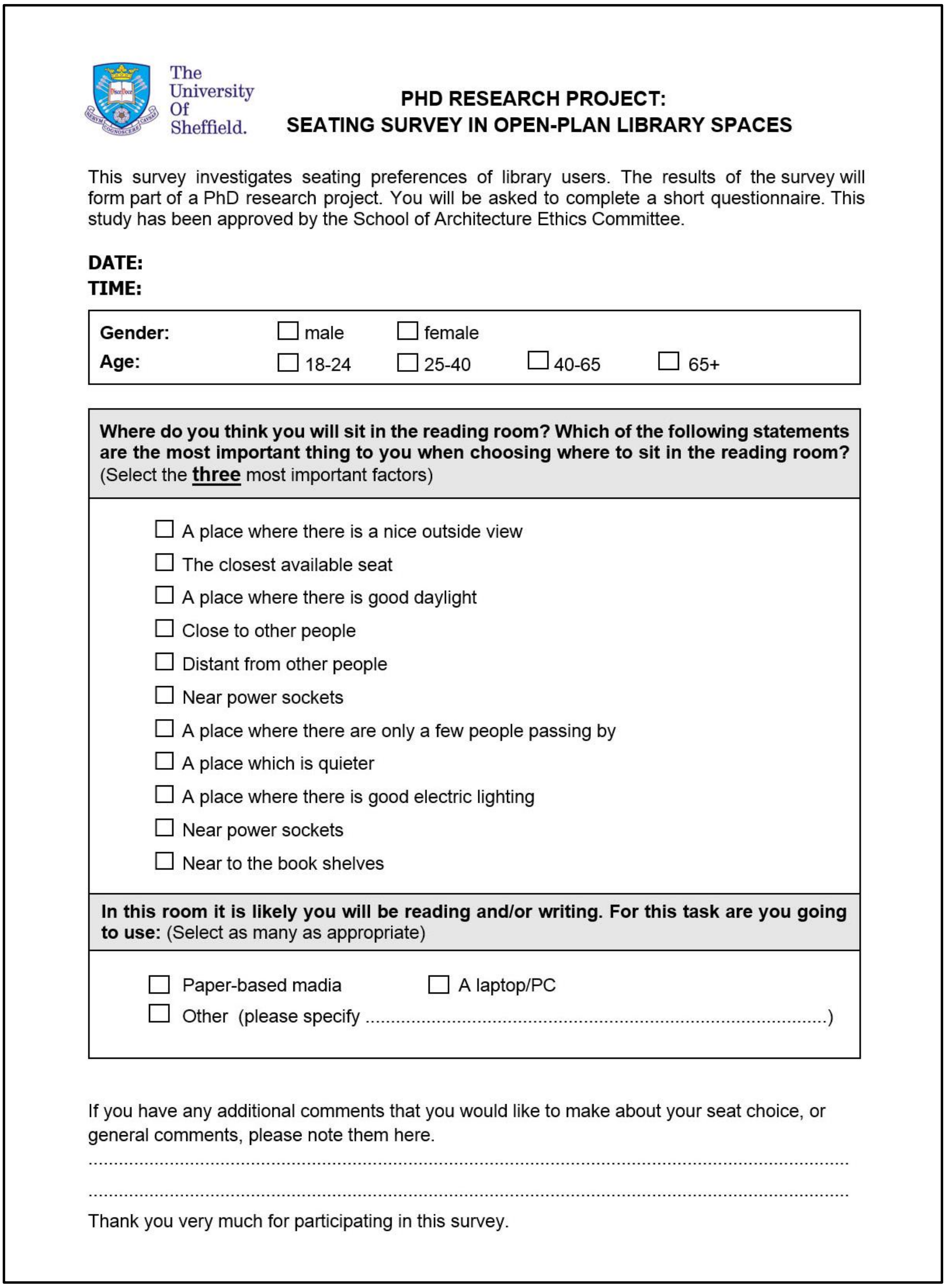
The response options were paper-based media, a laptop/PC, and other (please specify).

The room survey also included a short questionnaire which asked about importance and satisfaction of the ten items. For each item, there were three questions.

1. Is it important? A yes/no response was sought.
2. How satisfied are you with it? The response options were very satisfied, satisfied, dissatisfied and very dissatisfied.
3. Why did you express this opinion? Here respondents were invited to give their own response.

For the first two questions, participants were given the following instruction: "*Please indicate (by ticking your preferred option) whether the following factors are important when you decide where to sit*." The third question enabled respondents to add further comments to their responses.

The two questionnaires (door and room surveys) are shown in Figures 3.7 and 3.8. Note that these show only one version of the five which presented the ten factors in a different order.



The University Of Sheffield.

PHD RESEARCH PROJECT:
SEATING SURVEY IN OPEN-PLAN LIBRARY SPACES

This survey investigates seating preferences of library users. The results of the survey will form part of a PhD research project. You will be asked to complete a short questionnaire. This study has been approved by the School of Architecture Ethics Committee.

DATE:
TIME:

Gender:	☐ male	☐ female		
Age:	☐ 18-24	☐ 25-40	☐ 40-65	☐ 65+

Where do you think you will sit in the reading room? Which of the following statements are the most important thing to you when choosing where to sit in the reading room? (Select the **three** most important factors)

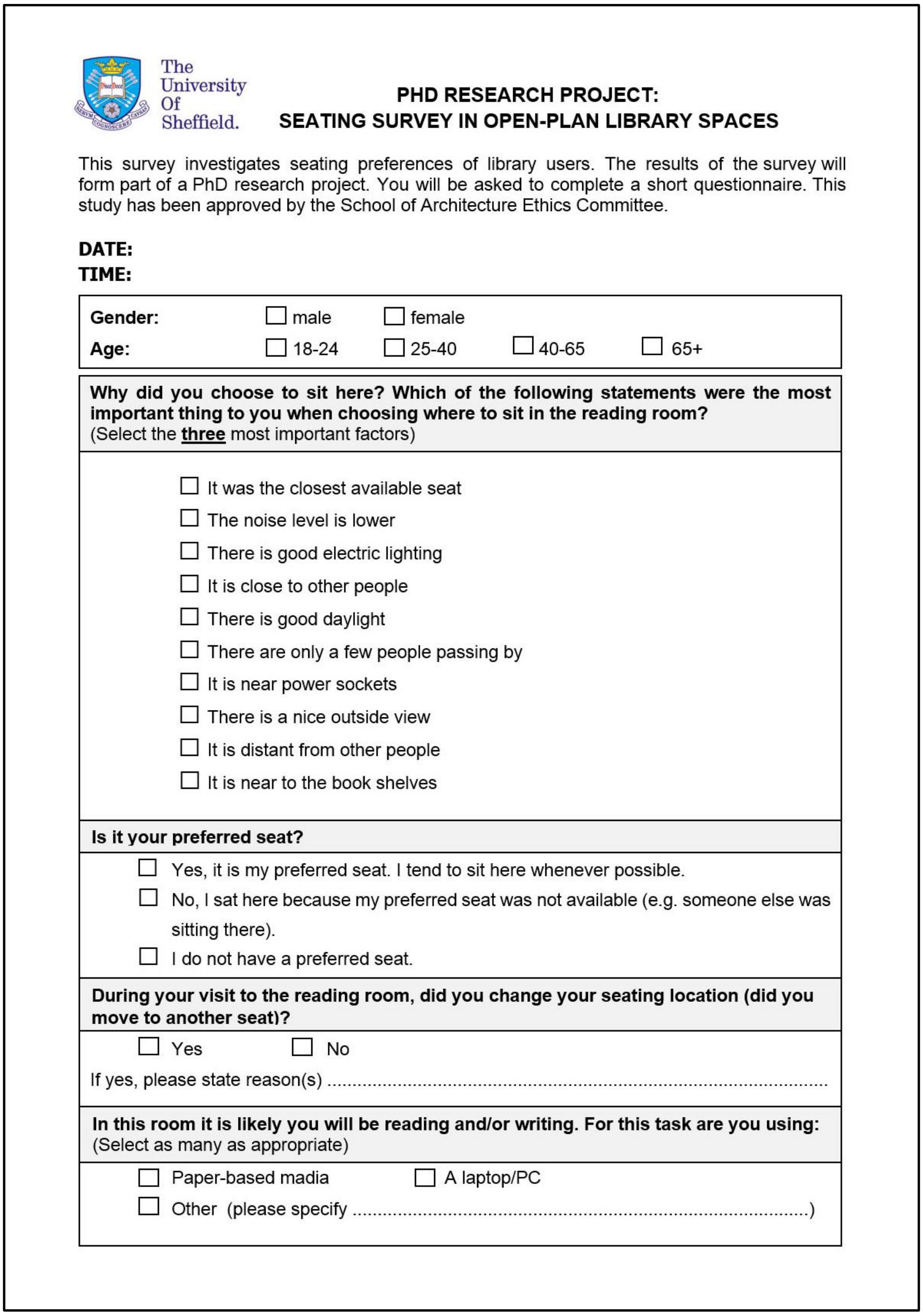
- ☐ A place where there is a nice outside view
- ☐ The closest available seat
- ☐ A place where there is good daylight
- ☐ Close to other people
- ☐ Distant from other people
- ☐ Near power sockets
- ☐ A place where there are only a few people passing by
- ☐ A place which is quieter
- ☐ A place where there is good electric lighting
- ☐ Near power sockets
- ☐ Near to the book shelves

In this room it is likely you will be reading and/or writing. For this task are you going to use: (Select as many as appropriate)

☐ Paper-based madia ☐ A laptop/PC
☐ Other (please specify ....)

If you have any additional comments that you would like to make about your seat choice, or general comments, please note them here.
....
....
Thank you very much for participating in this survey.

Figure 3.7. Questionnaire used in the door survey.



The
University
Of
Sheffield.

PHD RESEARCH PROJECT:
SEATING SURVEY IN OPEN-PLAN LIBRARY SPACES

This survey investigates seating preferences of library users. The results of the survey will form part of a PhD research project. You will be asked to complete a short questionnaire. This study has been approved by the School of Architecture Ethics Committee.

DATE:
TIME:

Gender:	☐ male	☐ female		
Age:	☐ 18-24	☐ 25-40	☐ 40-65	☐ 65+

Why did you choose to sit here? Which of the following statements were the most important thing to you when choosing where to sit in the reading room?
(Select the **three** most important factors)

☐ It was the closest available seat
☐ The noise level is lower
☐ There is good electric lighting
☐ It is close to other people
☐ There is good daylight
☐ There are only a few people passing by
☐ It is near power sockets
☐ There is a nice outside view
☐ It is distant from other people
☐ It is near to the book shelves

Is it your preferred seat?

☐ Yes, it is my preferred seat. I tend to sit here whenever possible.
☐ No, I sat here because my preferred seat was not available (e.g. someone else was sitting there).
☐ I do not have a preferred seat.

During your visit to the reading room, did you change your seating location (did you move to another seat)?

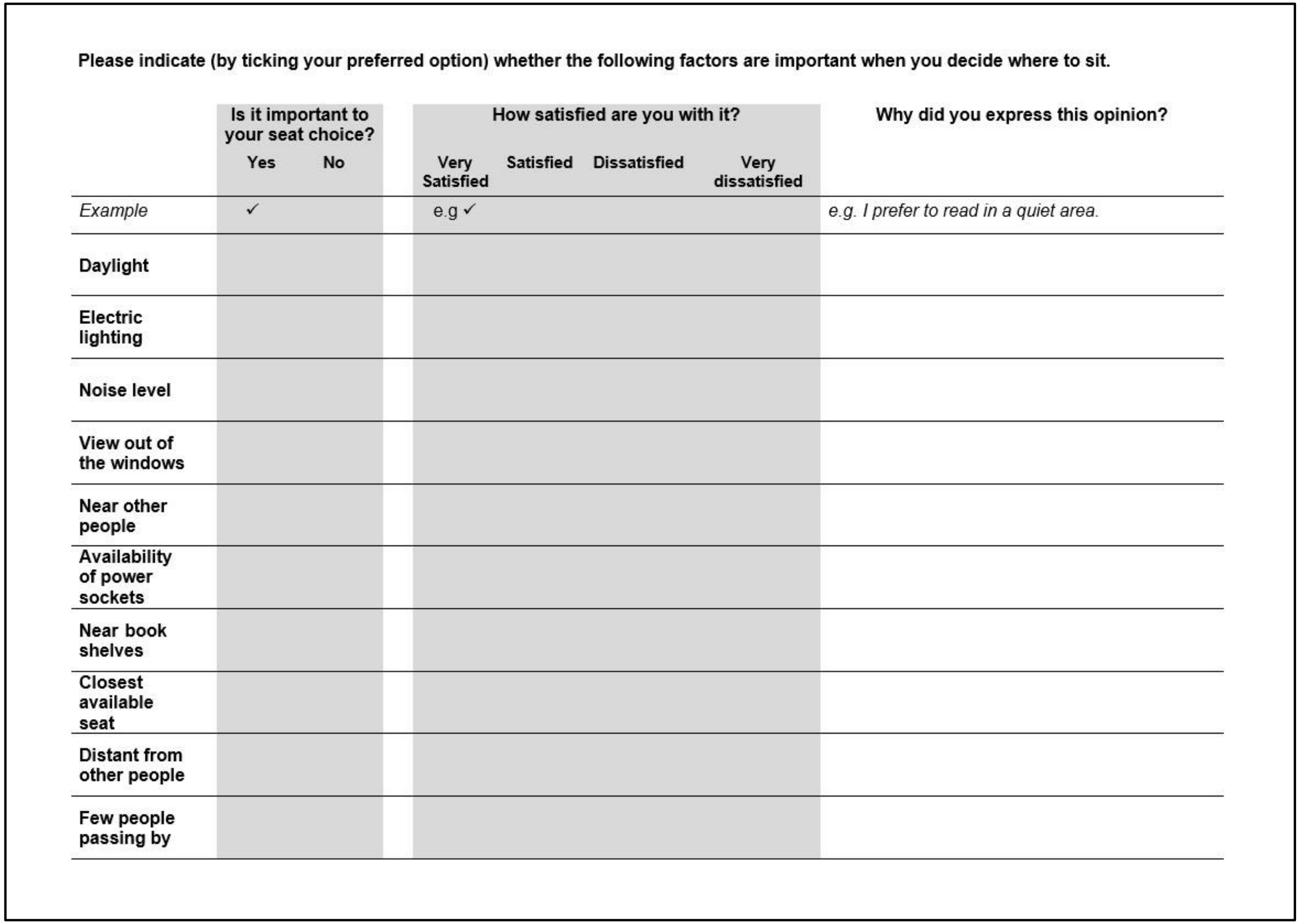
☐ Yes ☐ No

If yes, please state reason(s) ....

In this room it is likely you will be reading and/or writing. For this task are you using:
(Select as many as appropriate)

☐ Paper-based madia ☐ A laptop/PC
☐ Other (please specify ....)

Figure 3.8. Questionnaire used in the room survey.



Please indicate (by ticking your preferred option) whether the following factors are important when you decide where to sit.

	Is it important to your seat choice?		**How satisfied are you with it?**				**Why did you express this opinion?**
	Yes	**No**	**Very Satisfied**	**Satisfied**	**Dissatisfied**	**Very dissatisfied**	
Example	✓		e.g ✓				*e.g. I prefer to read in a quiet area.*
Daylight							
Electric lighting							
Noise level							
View out of the windows							
Near other people							
Availability of power sockets							
Near book shelves							
Closest available seat							
Distant from other people							
Few people passing by							

Figure 3.8. Questionnaire used in the room survey (continued).

3.3.2 Procedure

The two questionnaires were handed out personally in two different locations to users for completion. The two experimenters worked separately, with one located at the entrance door and the other within the room. For this task the author was assisted by an undergraduate student in the School of Architecture. Respondents were sought by approaching people either as they approached the reading room entrance door or people already sat within the room.

The first step in creating the room survey group was made by asking if any of those who had completed the door survey outside the room would be willing to participate again. After the respondent had entered and seated himself, the second experimenter approached the respondent directly and asked to participate. However, this was not always possible because the respondents were not always available and/or willing to participate in the room survey. Therefore, the data were collected randomly from those who were about to enter the room and those seated in the room, however aiming at the same group of respondents on both occasions. For those who agreed to respond there was no incentive such as a payment.
One potential limitation of the experiment is that the stated preference survey may have influenced the revealed preference of participants. Asking intentions or self-predictions regarding behaviour may have led to previously unaware participants becoming explicitly aware of their behaviour. This may have resulted in a consciousness about where they sat, as people often behave differently when they know they are being observed (McCambridge et al, 2012; Parsons, 1974; Sommer, 1968). This has to be accepted as one of the potential negative aspects of the field experiment, in which the role of consciousness in decision-making cannot be estimated.

In the previous stated preference studies reviewed in Chapter 2, few used more than 300 participants, with many using less than 200. The current survey was completed by 400 participants, this being 200 each for the door and room surveys. This sample size was larger than most other stated preference research and was estimated to be sufficient for the purpose of the study. Approximately equal proportions of male and female participants participated in the survey, but the age distribution was skewed towards younger people reflecting that young students were the primary users of the reading room. A detailed description of participants can be found in Table D1 in Appendix D. The survey was carried out in December 2015, over 3 days, with participants sought by opportunity sampling typically between 09:00 and 15:00. Ethical approval for this survey was confirmed by the school of architecture research committee on 06/08/2015. The full ethics application form can be found in Appendix C.

Weather observations were also recorded during the survey period. The instrumentation used included a SPN1 Sunshine Pyranometer. An algorithm was applied to the solar radiation data for classification of sky conditions (the basis for this is given in Chapter 5). The sky conditions ranged from partly cloudy to overcast, with the greater proportion of the data (97%) representing overcast sky conditions. Differences in data by the time of survey administration can therefore be hypothesized, simply by given differences in the weather conditions during the survey. It should be noted that the survey was carried out in winter when the exposure to daylight was limited. This raises a further question: How would the conclusions be affected if the weather conditions were different? Would we find a similar distribution of responses if the survey was conducted under different weather conditions, for example in summer instead of winter? It would be interesting to repeat the survey using the same methods but under different weather conditions. Future research could explore whether and the extent to which weather conditions can influence perceptions of respondents regarding the importance of daylight when making seat choice decision.

3.3.3 Results

This section presents and discusses the results of the door and room surveys. Analyses of the survey data did not suggest they were drawn from a normally distributed population and therefore non-parametric statistical tests were applied. Response data from two surveys were compared and a series of Pearson’s chi-square statistics was calculated to test for significant relationships between response rates. An alpha level (level of significance) of 0.05 was used throughout data analysis, unless otherwise noted. The results revealed no statistically significant difference between the two groups of respondents with respect to gender and age (see Appendix D for the test applied), thus eliminating the effects of such demographic differences among respondents.

Multiple-option data: what factors matter?

Figure 3.9 shows the frequencies by which each of the ten factors were chosen as the most important reasons for seat choice. This was determined by summing the number of times each factor was ticked, without applying any weighting or rank order to these ticks. When people were questioned at the door it can be seen that the availability of power sockets, low noise, daylight and view out were the four most important factors whilst electric lighting, closeness of seat and shelving and being able to sit close to others were the least important. A chi-square goodness-of-fit test was used (Coolican, 1994, p.453) and this suggested that the ten factors were chosen with significant differences in frequency ($\chi^2 = 259.56$, df = 9, $p < 0.001$).

Consider next when people were questioned within the room (specifically, when seated at a desk). The availability of power sockets was now of lesser importance; low noise, daylight and view out were still the more important factors along with being able to sit away from other people; the four least important factors were the same as found with the door survey, i.e. electric lighting, closeness of seat and shelving and being able to sit close to others. The ten factors were again chosen with significant differences in frequency ($\chi^2 = 211.85$, df = 9, $p < 0.001$).

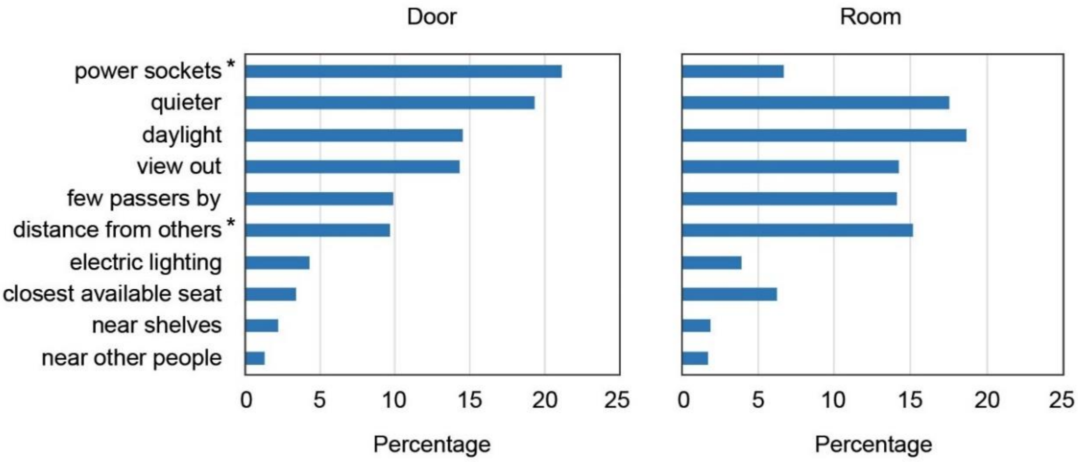


Figure 3.9. Frequency by which each factor was picked as being an important factor for seat choice. Asterisks (∗) denote statistically significant difference between door and room survey data.

What this analysis shows is that there were significant differences in the frequency by which a factor was considered to be important: it does not reveal a rank order or the difference between two specific factors. According to the trends shown in Figure 3.6 it is suggested that six factors were generally considered important:

- power sockets
- quieter
- daylight
- view out
- few passers by
- distance from others

Four factors do not appear to be important, these being electric lighting, closest available seat, near shelves and near other people. When choosing a seat, both groups found being close to other people the least important factor, this may be because most of the respondents were individuals rather than groups and they preferred not to sit next to other people.

The results suggest that daylight is either the joint third (door survey) or the most important (room survey) factor affecting seat choice. This supports previous studies that suggested daylight to be perceived as one of the most important factors that affects user satisfaction (Christoffersen et al, 2000; Hygge and Loffberg, 1999; Parpairi et al., 2000) and seat choice decisions (Dubois et al., 2009; Othman and Mazli; 2012). Further analysis was carried out to determine whether there were any statistically significant differences in responses between the two groups of respondents, as described below.

Multiple-option data: does survey location matter?

The survey was completed in two locations, door and room, and Figure 3.6 suggests some differences in perceived importance of the factors. Specifically, when asked at the desk, there was a decrease in importance of power sockets and an increase in importance of passers-by and distance from others. A chi-square test suggested that there were significant differences between the two groups for some of the statements, these being power sockets ($\chi^2 = 35.5$, df = 1, $p < 0.001$) and distance from others ($\chi^2 = 4.37$, df = 1, $p < 0.05$) (Coolican, 1994, p.453). The test results did not suggest a significant difference between rooms for the other factors: quietness, daylight, view out, electric lighting, distance from other people, near to shelves, few passers-by and near other people. Table 3.2 shows the results of the chi-square two-tailed test.

Table 3.2. Differences in responses between door and room surveys.

Factor		**Observed Frequency (O)**		**Expected Frequency (E)**		**X² ∑(O-E)²/E**	**df**	**Level of Sig.**
		Door	**Room**	**Door**	**Room**			
Power sockets	Ticked	118	36	77	77	35.50	1	p<0.001
	Did not tick	82	164	123	123			
Quieter	Ticked	108	95	102	102	0.85	1	**n.s**
	Did not tick	92	105	99	99			
Daylight	Ticked	81	101	91	91	2.02	1	**n.s**
	Did not tick	119	99	109	109			
View out	Ticked	80	77	79	79	0.05	1	**n.s**
	Did not tick	120	123	122	122			
Few passers by	Ticked	54	82	68	68	4.37	1	**n.s**
	Did not tick	146	118	132	132			
Distance from others	Ticked	55	76	66	66	2.50	1	p<0.05
	Did not tick	145	124	135	135			
Electric lighting	Ticked	24	21	23	23	0.11	1	**n.s**
	Did not tick	176	179	178	178			
Closest available seat	Ticked	19	34	27	27	2.45	1	**n.s**
	Did not tick	181	166	174	174			
Near shelves	Ticked	12	10	11	11	0.10	1	**n.s**
	Did not tick	188	190	189	189			
Near other people	Ticked	7	9	8	8	0.13	1	**n.s**
	Did not tick	193	191	192	192			

Chi-square analysis comparing the response data from the two surveys revealed that a significantly larger percentage of respondents found the presence of a power socket important for their seat choice in door survey than those in the room survey. It may also be a sampling bias of this procedure: if people were asked for their opinion at a desk without a socket it was probably not important to them. The following sections expands these results by examining whether significant differences exist in survey responses as a function of different types of tasks.

Multiple-option data: effects of task

Respondents were grouped into two categories in order to explore the effects of task being undertaken: laptop users and non-laptop users. This involved breaking down the responses by the task group and analysing the data for only those respondents who had access to power sockets (i.e. that were sat at a desk with a power socket in immediate proximity). Power sockets for laptop computers are provided only on some of the desks located in window seating area (see Chapter 4 and Appendix G). Figure 3.10 shows the frequency by which each factor was picked as being an important factor for seat choice, with respondents being those having access to power sockets. From this figure it appears that seating preferences of laptop-users was influenced by two factors other than daylight, these being availability of power sockets and the view-out. For non-laptop users who chose to sit by the window, however, seating preference was not stated to be affected by the availability of power sockets but instead by daylight, view out and few passers-by. It is apparent that if people want to use their laptop then power sockets is an important factor, but if they do not wish to use a laptop then power sockets plays no role.

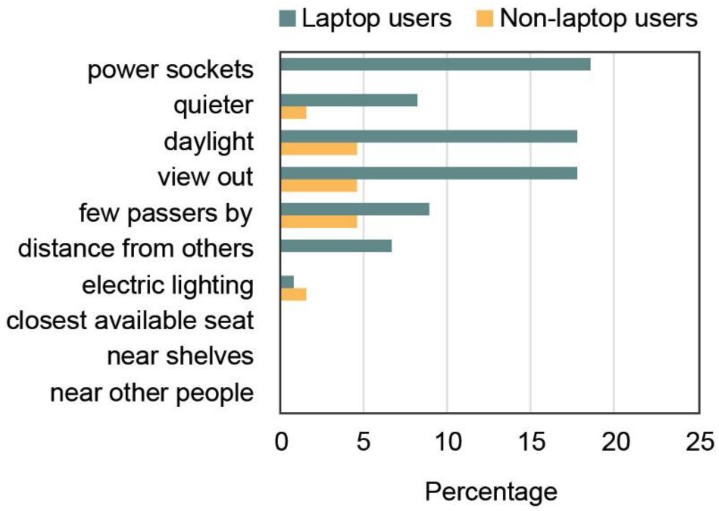


Figure 3.10. Room survey: Differences between laptop users and non-laptop users in their preferences for the ten factors (analysed for seats having access to power sockets).

Seating changes

The room survey was expanded to include a set of questions aimed at collecting data from the respondents who changed their seats during their visit. A majority of respondents (89%) reported that they did not change their seats during their visit to the room. For the remainder who did change seats (11%), the reasons of seat change included to be close to power sockets (40%), to avoid noise distraction (25%), favourite seat was not available (20%), to have a nice view and different environment (10%), and to be close to the shelves (5%). These results provide some support for the importance of power sockets, although it should be noted that the data were obtained from a small number of respondents (n = 22).

The survey also included questions to determine whether the seat was chosen as a preferred and/or favourite seat. Almost half of the respondents (44%) reported that they don't have any preferred seat, while more than a third of the respondents (35%) reported that they were sat in their preferred seats. The remaining respondents (21%) stated that their preferred seat was not available.

Factor importance

Respondents in the room survey were next asked to state whether they think the ten factors were important for their seat choice. This provided an alternative to multiple-option approach and allowed robust conclusions to be made based on the results of both approaches. In this section respondents were offered a Yes/No response option, followed by an additional question asking them to explain why they answered the way they did (e.g. why did you express this opinion?). The results of both importance and multiple-option analysis are shown in Table 3.3.

Table 3.3. Room survey: Importance analysis and multiple-option analysis results. Factors listed in order of importance.

Factor	**Is it important?**		**Multiple-option results**
	Yes	**No**	
Power sockets	56.5 %	39.5 %	6.7 %
Quieter	88.5 %	8.0 %	17.6 %
Daylight	70.0 %	17.0 %	18.7 %
View out	55.0 %	40.5 %	14.2 %
Few passers by	52.5 %	38.0 %	14.1 %
Distance from others	57.5 %	36.0 %	15.2 %
Electric Lighting	56.0 %	36.5 %	3.9 %
Closest available seat	58.5 %	39.0 %	6.3 %
Near shelves	9.0 %	84.5 %	1.8 %
Near other people	8.5 %	76.0 %	1.7 %

A comparison of responses to two survey questions indicated that the three items (daylight, quieter and distance from others) were chosen as most important in both questions. Figure 3.11 shows a scatterplot of the relationship between two datasets. Similar conclusions were drawn using both procedures, with increases in multiple-option scores tending to be associated with increases in the importance scores. Pearson’s test suggests the correlation to be significant (r=0.76, p = 0.01). This association between results from the two approaches to examining the importance of the ten factors means the conclusions can be considered as more robust.

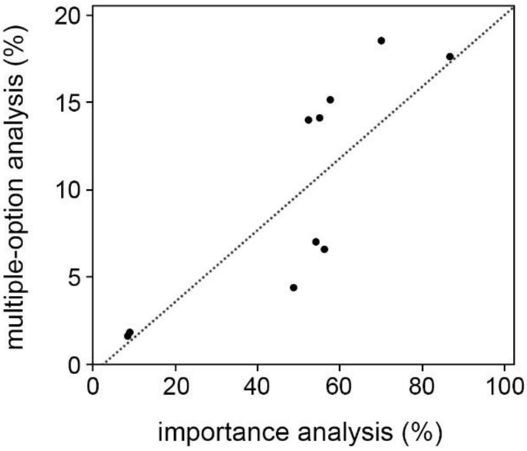


Figure 3.11. Room survey: Importance analysis results plotted against multiple-option analysis results.

The survey also asked respondents to comment on their answers, giving reasons why they chose a particular response option. The reasons that participants gave for the importance of each factor were divided into a set of categories, defined by the researcher. This was done by highlighting reasons given by participants, sorting them into clusters of the same fundamental concerns. For example, "I like a lot of desk space" was put into the increased desk space category, and "I prefer to be able to spread my stuff out" was also placed in the same category as it addresses the same underlying concern. Similarly, "reminds me of outside world" was included in the connection to the outside world category, and so was "I like to see the real world". The categories were defined based on words and phrases that appear in the text and that refer to a certain theme.

The categorization process is important because bias may occur when subjectively interpreting responses given to each factor. To increase the validity, the analysis was performed separately by two researchers and then the results were compared (Burnard, 1991). For this task the author was assisted by a postgraduate research student in the School of Architecture, whose background was outside the field of lighting. The ten factors and the categories into which reasons were sorted are given in Table 3.4.

Table 3.4. Room survey: The reasons given by participants for why they think each factor is important, categorized into common themes.

Factor	Reason given by the participant
Power sockets	Laptop charging
Daylight	Improved task visibility (reading and writing), preference for natural light rather than electric light, relaxation and good feeling
Electric lighting	Improved task visibility (reading and writing), provision of sufficient lighting when it gets dark
Near other people	Preference for sitting close to a friend, working with friends
Distance from others	Reduced distractions and interruptions, improved concentration and focus on work, preference for working alone, increased desk
View out	Relaxation, reduced stress, connection to the outside world, nice view of the park
Few passers-by and Quieter	Reduced distractions and interruptions, improved concentration and focus on work
Closest available seat	Preference of sitting near the door, avoiding walking past people
Near shelves	Convenience and easy access to books

Respondents were also asked to indicate how satisfied they were with the ten items on a 4-point scale ranging from very satisfied to very dissatisfied. The data from this part of the survey dealing with the occupant satisfaction were excluded from the analysis as they do not directly contribute to the aim of investigating whether people think that daylight is an important factor in seat choice decisions. The method was however identified as an alternative method of investigation that could be used in further research. At the end of the questionnaires, respondents were given the opportunity to mention the issues which they felt were not covered by the options given. Most respondents used this section as an opportunity to reinforce the views they had stated for their seating preference in the earlier sections of the questionnaire. Some also raised issues that were not included in the survey, including temperature and the habit of choosing the same seat.

3.4 Summary

The experiment described in this chapter investigated the perceived importance of daylight when choosing a seat location. An approach similar to that used by Bernhoft and Carstensen (2008) was taken, asking respondents to identify the three most important reasons for their choice from a given list of factors. The aim was to explore differences in the perceived importance of daylight across two groups of participants, those about to enter the room and those seated in the room. The door survey, which asked participants outside the test room to indicate factors that influence their seat choice, found that daylight was the third most important factor after the availability of power socket and quietness. When asked the same questions about the seat choices they made in the room, the importance of daylight increased, and it was the most important factor in this latter case. One possible explanation for this difference is that at the entrance respondents are likely to state what they perceive to be important, whereas in the room they may seek to post-rationalise their seat choice. The data collected with the survey questions were the frequencies of the responses to each pre-defined category. Differences in responses between the two groups of respondents were tested for statistical significance. Significant differences were found between the two groups in their responses to two items, these being the availability of power sockets and the distance from others. Although the perceived importance of daylight differed between the two groups, this difference was not statistically significant.

In door survey, two approaches were used to test importance of various factors including daylight: multiple-option and importance analysis. The former approach asked participants to pick the three most important factors from a list of ten. The latter asked for each of ten items to be defined as important or not important in terms of seat choice. Results from the multiple-option and importance analysis both suggested daylight to be perceived as one of the important factors. The two approaches are different: the first may encourage three factors to be picked when fewer were considered relevant, and also prevents more than three from being picked. The latter approach allows any number of factors to be highlighted as important. That the results of these two approaches agree suggests the findings are important. Age and gender did not influence stated preferences in this investigation.

The overall aim of the survey was to determine what factors are likely to influence where an individual sits in the test room. A comparative method was discussed for producing this evidence, based on the perceptions of respondents regarding the importance of daylight before and after making seat choice decision. From the evidence provided by door-room survey, it can be concluded that daylight is an important reason for choosing a particular seat. The survey also raised other factors that may affect seat choice, including noise, proximity to power sockets, and the preference to sit apart from others for privacy. The study relied on self-report measures instead of actual seating choices. Further research is needed to determine how space is actually being used and occupied. This is what the revealed preference study, described in the next chapter, addresses.

CHAPTER 4. REVEALED PREFERENCE SURVEYS

4.1 Introduction

This chapter describes four experiments carried out to examine actual seating behaviour in the test room. The aim of these experiments was to quantify the probability of a seat being occupied, this being assumed as an expression of preference. Following a review of previous research presented in Chapter 2, this was done by recording which seats were occupied at a series of regular intervals (the snapshot approach). To validate the findings, the experiment was repeated at different observation intervals, at different times of year, and at different times of day to permit a night versus day analysis. A second procedure was developed to provide some measure of the robustness of the conclusions drawn using snapshot observation. This latter procedure included tracking individuals' movement as they choose a seat, and was included as 'walk through approach'. The observations were compared against daylight metrics and the simulations carried out to determine these are described in Chapter 5.

4.2 Methodological approaches to the experiments

The observations were carried out in a large open plan, hot-desking space in Western Bank Library at the University of Sheffield (see Chapter 3 for a detailed description of the room). Seating behaviours were mostly recorded with the experimenter standing on the mezzanine floor overlooking the reading area on the ground floor. Two data collection methods were used, recording actual seating occupancy at fixed intervals (snapshot observation) and monitoring the behaviour of a single person over a period of time (walk-through observation).

Snapshot observations means that at specific instances, a record was made of which seats were occupied. This is essentially a detailed snapshot of who is where in the entire space at a point in time, with repeated snapshots captured over a number of days. Observations were recorded at hourly and sub-hourly intervals. A limitation of any given observation interval is that it fails to capture temporal variations in seating behaviour between the two successive observation points. The snapshot method may thus be considered weaker if conditions are not controlled and favourable for recording occupant movements, with data loss between two successive observation points sometimes being considerable. This can be due to differences in length of stay among occupants. For example, an occupant may tend to choose a seat and then remain at the same location over long periods of time; or they may be displaced from their prior seat of choice. A further limitation is that for any observation interval, there is a possibility of excluding the seat choices of those people who arrive and leave between successive observation points. To overcome such limitations associated with the snapshot recordings, walk-through observations were carried out simultaneously (Experiment 3b). Table 4.1 shows a summary of the data collection methods used in the four experiments.

Table 4.1. Summary of data collection methods for four experiments (EX: Experiment).

EX	Method	Season	Duration	Start Date	End Date	Time period	Interval
1	Snapshot	Summer	2 weeks	11-08-2014	22-08-2014	09:00-17:00	60 min
2	Snapshot	Autumn	2 weeks	10-11-2014	21-11-2014	09:00-15:00 18:00-21:00	60 min
3a	Snapshot	Summer	1 week	10-08-2015	14-08-2015	09:00-17:00	15 min
3b	Walk-through	Summer	1 week	10-08-2015	14-08-2015	09:00-17:00	n/a

Note: Data collection for Experiment 3a was carried out by Victoria Spencer, an undergraduate architecture student at the University of Sheffield for the purposes of a final-year dissertation. The student was advised by the author.

4.3 Snapshot approach

This section presents an overview of the procedures used in collecting snapshot observation data and this is followed by an explanation of key findings. The main approach to analysis is correlation, e.g. regression of seat occupancy on daylight factor, the latter being obtained from the simulations reported in Chapter 5. Further analyses are presented to explore questions of methodology, i.e. the effect of observation interval and season.

4.3.1 Procedure

To record seat occupancy, the experimenter held a numbered seating plan and ticked those seats that were occupied at that instant. The proportion of observations in which a seat was noted to be occupied was used to estimate the probability of a person choosing that seat. This is the method that was used by Dubois et al (2009), Kim and Wineman (2005), Organ and Jantti (1997) and Wang and Boubekri (2009). In these studies, the observation intervals were 10 min (Kim and Wineman, 2005), 15 min (Dubois et al 2009), 30 min (Kim and Wineman, 2005; Wang and Boubekri 2009) to over one hour (Organ and Jantti, 1997). The question of observation interval has not been raised in any of these studies. Observations recorded at 15 min intervals, for example, may give a more precise measure of occupancy than hourly observations. In experiments 1 and 2, a 60 min interval was used; in experiment 3a, a 15 min interval was used to enable analysis of the influence of time interval.

Another question being addressed by this study was whether there were any differences in seat choice behaviour at different times of the year. There are at least two reasons why the time of year can be expected to influence the seat choice behaviour. First, the intensity and duration of daylight changes throughout the year. Second, the number of students and their activity changes throughout the year. Therefore, observations were carried out in two different seasons of the year when daylight and student attendance would vary: summer (experiment 1 and 3a) and autumn (experiment 2). In summer it is expected that daylight intensity would be higher and there would be fewer students; in autumn it is expected that there would be a lower daylight intensity but more students.

Regarding the time of day for which observations were recorded, this was chosen to cover the period for which daylight was expected (Table 4.2). Daily surveys of seat occupancy were carried out between 09:00-17:00 for experiment 1, 3a and 3b; and between 09:00-15:00 for experiment 2; these being well within the period of daylight availability. In experiment 2, further observations were recorded between 18:00 and 21:00, for which time it was dark outside. It is assumed that if observations in the period 09:00 to 15:00 suggest different seat choices to those in 18:00 to 21:00, the cause is more likely to be daylight.

Table 4.2. Seasonal variations in the length of the daytime period.

Season	**Experiment**	**Length of the daytime period***		**Observation period**	
		Sunrise	Sunset	Start	End
Summer	1, 3a and 3b	05:39	20:45	09:00	17:00
Autumn	2	07:22	16:19	09:00	15:00
				18:00	21:00

* Length of the daytime period was calculated using online sun position calculator at http://suncalc.net, accessed at 15/06/2014. Sunrise and sunset times are given for each of the observation period: the earliest sunset and latest sunrise times are reported.

The primary data gathered were frequencies of seat occupancy; specifically, the proportion of observation points for which a particular seat was occupied. Each seat was scored as either occupied (1) or unoccupied (0), and for each seat these scores were summed and the sum was expressed as a percentage of the total number of observations, with a rating of 100% indicating that the seat was occupied for every observation carried out. This value is called the occupancy rate, and is defined by the National Audit Office (NAO) in the UK as “the number of hours a room is in use as a proportion of total availability” (NAO, 1996). For the current work, which investigates seats rather than rooms, the definition was amended to:

> *The proportion of observations for which a seat was occupied*
> *at the instant of a given observation point.*

The method of calculation, illustrated in an example calculating occupancy rate for seat 1 (experiment 1) is shown in Table 4.3.

Table 4.3. Example calculation of occupancy rate for seat 1.

Time Interval	Time period	Duration	Number of observations	Number of observation points when seat was occupied	Occupancy rate (%)
60 min	09:00 17:00	10 days	9 times a day (Total=90)	78	(78/90) x 10= 86.66

4.3.2 Overall results of snapshot observations

The results and analyses presented in this section are based on individual seats (see Appendix E for occupancy rate values for each individual seat); however, for the purpose of graphical presentation of data and for ease of interpretation, the data were separated into groups. This explanation makes use of daylight factor, which is a simpler measure of daylight, used in the study of Christoffersen et al (2000), and further explored in this study. The range of variation in daylight factor over the plan area of the room under consideration is divided into five bands; then the area is divided into five zones, defined by the band of daylight factor exhibited; and the seats in each zone are grouped together and collectively identified by zone number (Figure 4.1).

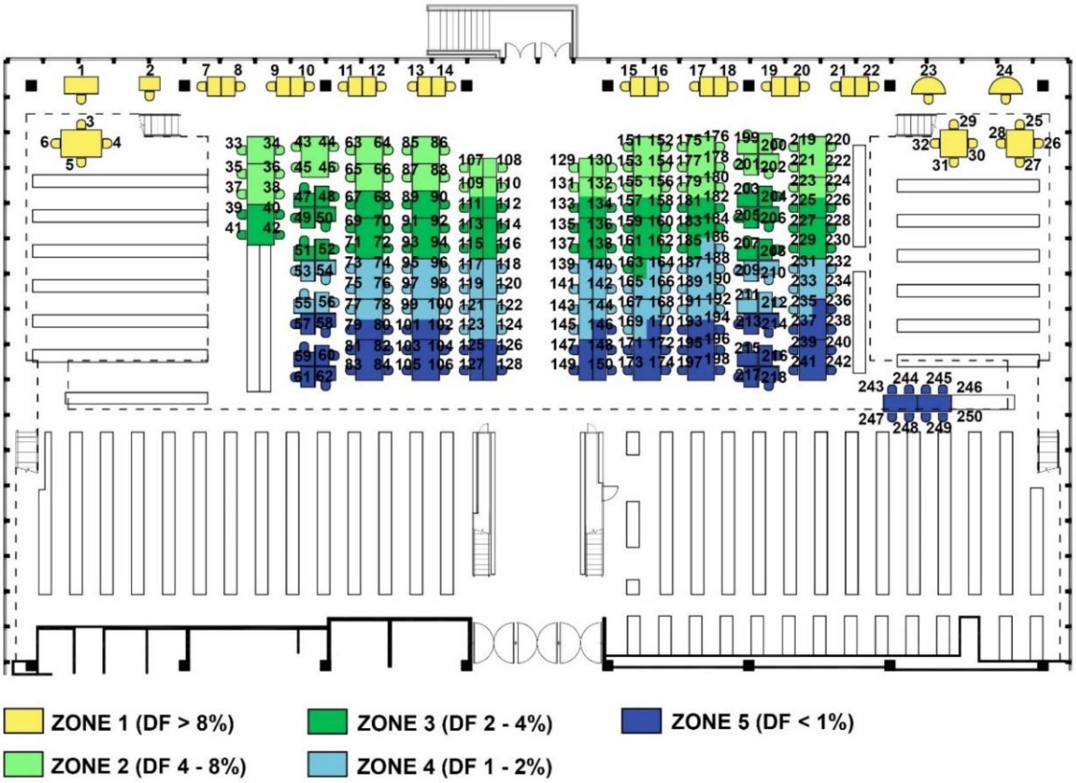


Figure 4.1. Seating plan with zones colour-coded according to values of daylight factors.

Having defined the zones within the reading room, average occupancy rates of each individual seat within each zone were calculated over the course of the observation period (typically one-week or two-week periods). This process was repeated for each experiment: EX 1, EX 2 and EX 3a. For EX 3a, which explored the effects of different observation time intervals, only the hourly data were used to assure data values are consistent with the data obtained from other two experiments. Table 4.4 gives a range of daylight factor values defined for each zone, the corresponding seat numbers and the average occupancy rates. Figure 4.2 shows average occupancy rates calculated for the five zones and makes comparison between the three experiments.

Table 4.4. Average occupancy rates for the three experiments (EX 1= Experiment 1, EX 2= Experiment 2, EX 3= Experiment 3a). Data were separated into five zones according to the range of daylight factors.

Zone	DF (%)	Seat no	Total number of seats	Average occupancy rate (%)		
				EX 1	EX 2	EX 3
1	> 8	1-32	32	37	69	24
2	4 - 8	33-38, 43-48, 63-66, 85-88, 107-110,129-132,151-156, 175-180,199-202, 219-224	50	2	24	3
3	2 - 4	39-42, 49-52, 67-72, 89-94, 111-116, 133-138, 157-163, 181-185, 203-208, 225-229	55	3	22	2
4	1 - 2	53-56, 73-78, 95-100, 117-124, 139-145, 164-169, 186-192, 209-212, 230-235	54	3	24	2
5	< 1	57-62, 79-84, 101-106, 125-128, 146-150, 170-174, 193-198, 213-218, 236-250	59	2	18	1

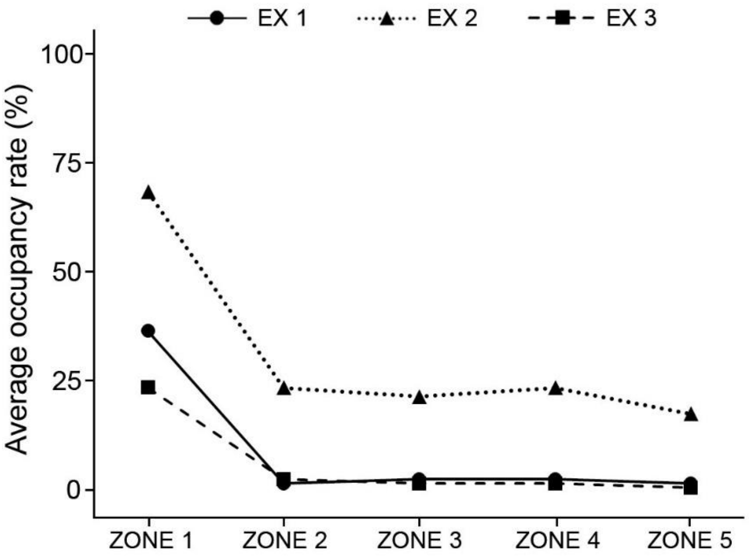


Figure 4.2. Average occupancy rates of each zone for the three experiments (EX 1= Experiment 1, EX 2= Experiment 2, EX 3= Experiment 3).

The results suggest that average occupancy rate varies over a similar range for all three experiments: the average occupancy rate is relatively high for Zone 1 (window seating area), where seats are placed individually, compared to the other four zones (central seating area), where seats are placed in groups. It can be concluded that occupancy rate decreases from Zone 1 to Zone 2 where there is a significant decrease in daylight factors, and then remains relatively stable across the remaining three zones, suggesting that further decrease in daylight factor does not have a significant effect. There is a significant difference, in both the daylight character and the physical environment, between Zone 1 and the other four zones. This should be in mind when interpreting data. Given that daylight varies substantially from Zone 1 to Zone 2, the interior can be treated as two separate spaces – a window area where daylight factors exceed 15%, and a central area where the daylight factor drops below 8% (A contour map of daylight factor is given in Chapter 5). The result is that, daylight factor varies dramatically between Zone 1 and Zone 2, then it tends to vary relatively little across the central area. Data for the two areas are therefore treated separately in the following chapters.

The findings suggest an effect of distance to windows on occupancy rates but do not demonstrate the effects of daylight alone due to the lack of control of other variables, although the analysis allows to see at a glance the way that daylight factors and occupancy rates are distributed throughout the room (a detailed daylight-occupancy rate analysis based on individual seats is presented in Chapter 5).

A limitation of overall analysis of snapshot observations is that the total number of people observed in the reading room is not the same in each experiment. One possible reason why average occupancy rates calculated for Experiment 2 (EX 2) differ greatly from those for other two experiments is that more people were observed during autumn period (EX 2) compared to summer period (EX 1 and EX 3).

To demonstrate avoidance of the influence of occupant density, a method should show little or no correlation between its measure and the number of occupants observed during the experiment. Therefore, to make comparison between the three experiments more explicable, average occupancy rates calculated for each experiment were transformed into standardized average rates. This was done by the method of adjustment based on weighted averages in which the weights were chosen to provide an appropriate basis for the comparison (i.e., a standard) (Fleiss, 1981). The overall occupancy rate (the total number of observations when a seat was occupied divided by the total number of observations) was considered as a robust measure of scale for this analysis since it takes into account the duration of the observation (total number of observations) and the total number of people observed (total number of observations when a seat was occupied). To determine the weights for each dataset (EX1, EX2 and EX3), an overall occupancy rate was calculated for each experiment and then the proportion to the lowest value across all three datasets (4.8%) was specified (Table 4.5). The standardized occupancy rate was then computed by multiplying each data value by its weight (e.g. 37 x 0.7 = 26 for Zone 1 in EX1 dataset) and the results are presented in Table 4.6.

Table 4.5. Overall occupancy rates for each experiment and the corresponding weights.

	Total number of observations	Total number of observations when seat was occupied	Overall occupancy rate (%)	Weight
EX 1	22500 (90 hour x 250 seat)	1540	6.8	0.7 (4.8/6.8)
EX 2	12500 (50 hour x 250 seat)	3464	27.7	0.17 (4.8/27.7)
EX 3	11250 (45 hour x 250 seat)	537	4.8	1

Table 4.6. Weighted occupancy rates for the five zones, each calculated by multiplying by its relevant weight. Each dataset was normalized based on the minimum value in the dataset.

Zone	DF (%)	Seat no	Total number of seats	Weighted average occupancy rate (%)		
				EX 1	EX 2	EX 3
1	> 8	1-32	32	26	12	24
2	4 - 8	33-38, 43-48, 63-66, 85-88, 107-110,129-132,151-156, 175-180,199-202, 219-224	50	1	4	3
3	2 - 4	39-42, 49-52, 67-72, 89-94, 111-116, 133-138, 157-163, 181-185, 203-208, 225-229	55	2	4	2
4	1 - 2	53-56, 73-78, 95-100, 117-124, 139-145, 164-169, 186-192, 209-212, 230-235	54	2	4	2
5	< 1	57-62, 79-84, 101-106, 125-128, 146-150, 170-174, 193-198, 213-218, 236-250	59	1	3	1

Transformation to standardized average occupancy rates results in the data from all three experiments weighted proportionally to the lowest overall average occupancy rate (4.8%). In other words, the average occupancy rates are scaled so that the values in the EX3 dataset remain constant with the rest expressed as a proportion of this dataset. This approach eliminates the amount of variability that exists between the three datasets due to difference in occupant density (total number of people observed during the experiment). The effect of the standardization procedure is shown in Figure 4.3.

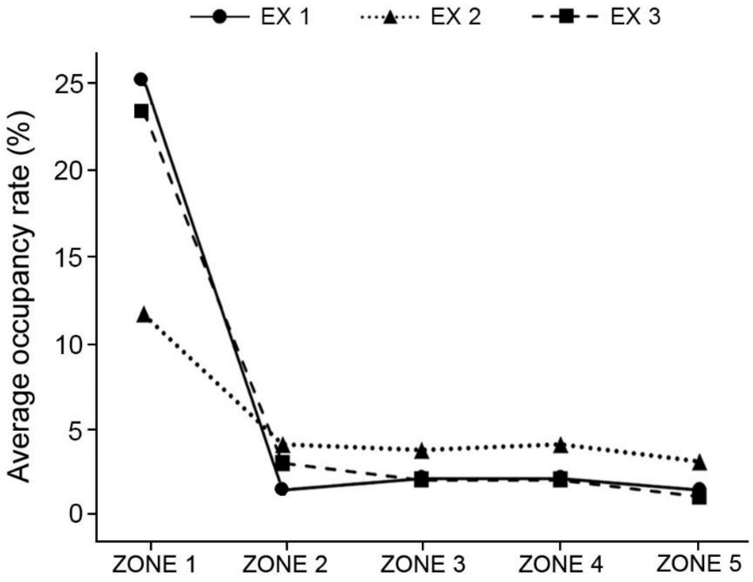


Figure 4.3. The effect of the standardization procedure as applied to the occupancy data. Average occupancy rates of each zone for the three experiments after standardization (EX 1= Experiment 1, EX 2= Experiment 2, EX 3= Experiment 3a).

These results confirm to some extent the tendency to sit near windows as reported in previous studies (Carstensdottir et al., 2011; Dubois et al., 2009; Kim and Wineman, 2005; Organ and Jantti, 1997; Wang and Boubekri, 2009). Observation period (i.e summer or autumn) seems to be informative about the occupant seating behaviour as it is indicative that the occupants choose their seats on the basis of other factors, one identified is related to the number of other occupants in the room.

4.3.3 Visualization of snapshot data using heat maps

One approach to visualising the occupancy rate variance between individual seats is to use heat maps. This approach was used by Khoo et al (2014; 2016) to visualise seat occupancy in an academic library. The resulting heat map generated by the researchers was a graphical representation of data from 112 observations, where the average occupancy rates of each predefined zone in the room were differentiated by colour. In the current study, occupancy data obtained from the snapshot observations captured the number and location of occupied seats in the reading room at regular intervals. These were represented in a heat map format, with a colour range from blue (lowest data values), through green, yellow and orange, to red (the highest data values) (Figure 4.4). The heat map format has the advantage of allowing a reader to see at a glance the distribution of occupancy rates throughout the room and is derived from data representing the observation period (see Appendix E for numeric data).

The data visualized through heat maps indicate that occupancy rates decreased sharply from the window seating area to the central seating area, and the decrement was greater for the summer period when occupancy rates are close to zero in the central seating area (EX1 and EX3), compared with the autumn period when occupancy in the central seating area was higher (EX 2). Representative heat maps of occupancy during autumn and summer periods revealed no significant pattern of change in occupancy rates across the central seating area, indicating that the occupancy variation was random. A possible explanation for the observed patterns of occupancy is that the proximity to the window plays an important role in the choice of a place to sit, but becomes less influential as the number of occupants increases and fewer seats are available in the window seating area and occupants are thus ‘forced’ to sit in the central seating area.

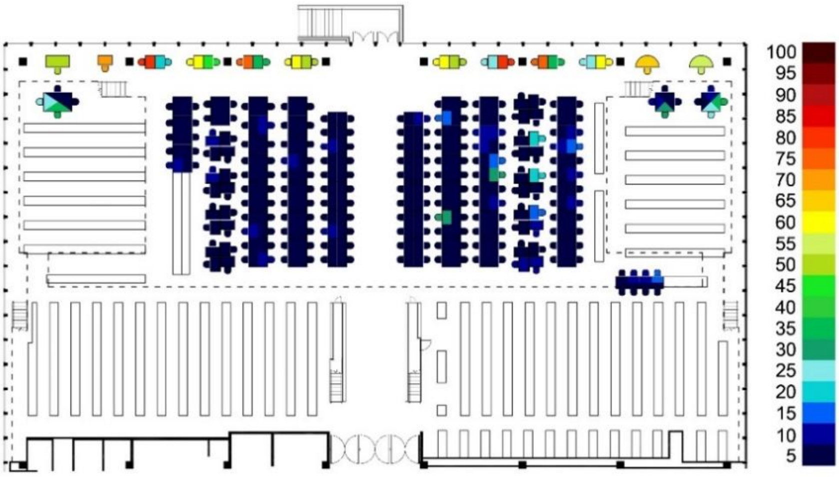
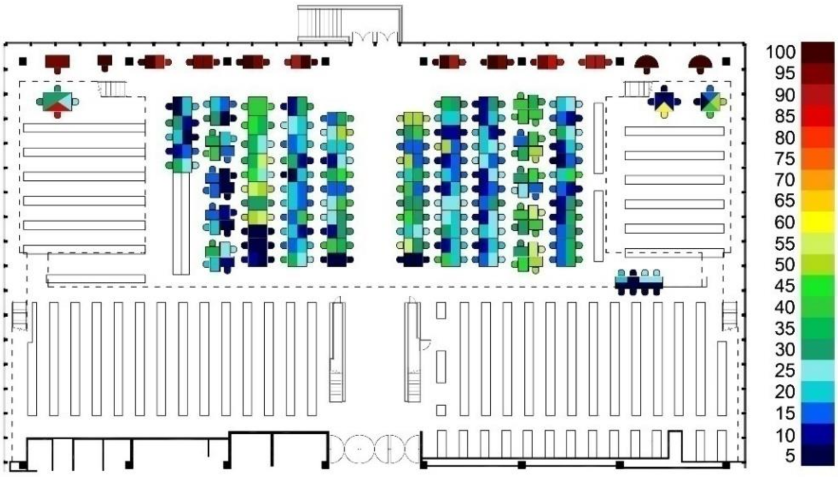
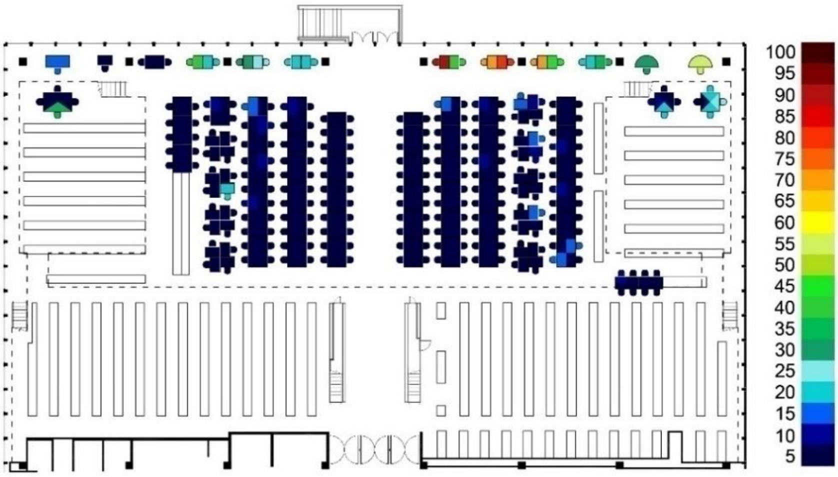
Experiment	Heat map based on individual seat occupancy
EX 1 Summer 09:00-17:00	
EX 2 Autumn 10:00-14:00	
EX 3 Summer 09:00-17:00	

Figure 4.4. Heat maps for the three experiments, with colour scale representing average occupancy rate data.

When entering the room, occupants tend to sit in the window seating area, possibly due to daylight, the unobstructed view, and the relatively high level of privacy provided by individual seating. However, when most or all of the seats in the window area are filled and occupants have to choose the remaining available seats in the central area, these factors appear to be less important, and other contextual factors such as physical proximity to other occupants may become a determining factor, which results in an occupant distribution more evenly spread throughout the central seating area.

These data seem to support the hypothesis that people prefer to sit near windows, since higher occupancy rates were observed for the window seating area. It is, however, important to note that the influence of proximity to a window and its related attributes (i.e. admission of daylight and a view out) varies across the two seating areas. Occupancy rates would have been expected to decrease from Zone 2 to Zone 5, either continuously or discontinuously, if proximity to windows had equal importance for the occupants seated in window and central seating areas but this was not the case. In other words, occupants have a strong preference for window seating over central seating, but little or no preference for central seating nearer the windows over central seating further from the windows. This suggests further investigation may be required.

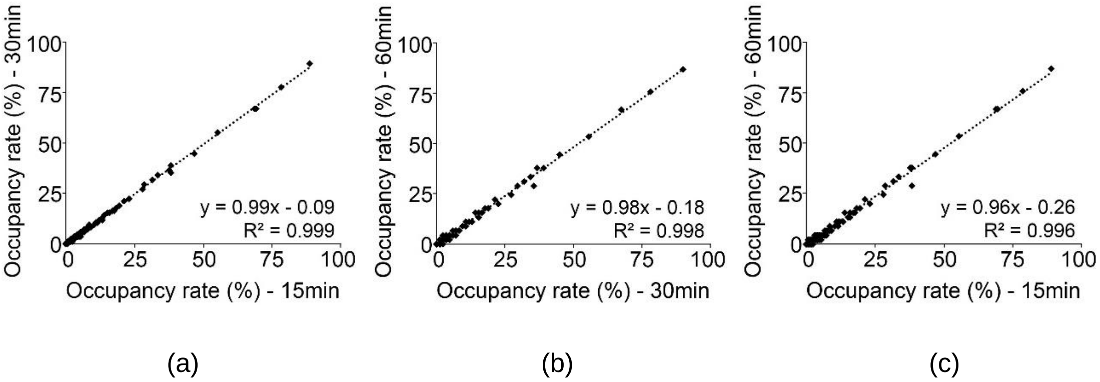
Observations recorded at different time intervals over different seasons may indicate experimental variations in the data. This was tested through a series of correlation analyses, described in the next section.

4.3.4 Analysis of experimental variations

This section investigates the effect of two experimental variables: (1) different observation intervals (i.e. 15min, 30min and 60min); (2) different months of a year (i.e. autumn and summer). The possible existence of a significant relationship between the variables was evaluated through a series of correlation tests conducted at different levels. Each of these experimental variations will be considered in turn.

To investigate the possible effect of time interval, observation periods in experiment 3a were divided into short time intervals during which the occupancy was recorded using a numbered seating plan. Whilst observations were made every hour during the observation period in experiments 1 and 2, in experiment 3a, a shorter interval was used (15 min) to allow two types of analyses: (1) If hourly and 15 min observations lead to the same results; (2) If hourly observations taken at different points lead to same results (e.g. 1000, 1100, 1200… vs. 1015, 1115, 1215 etc).

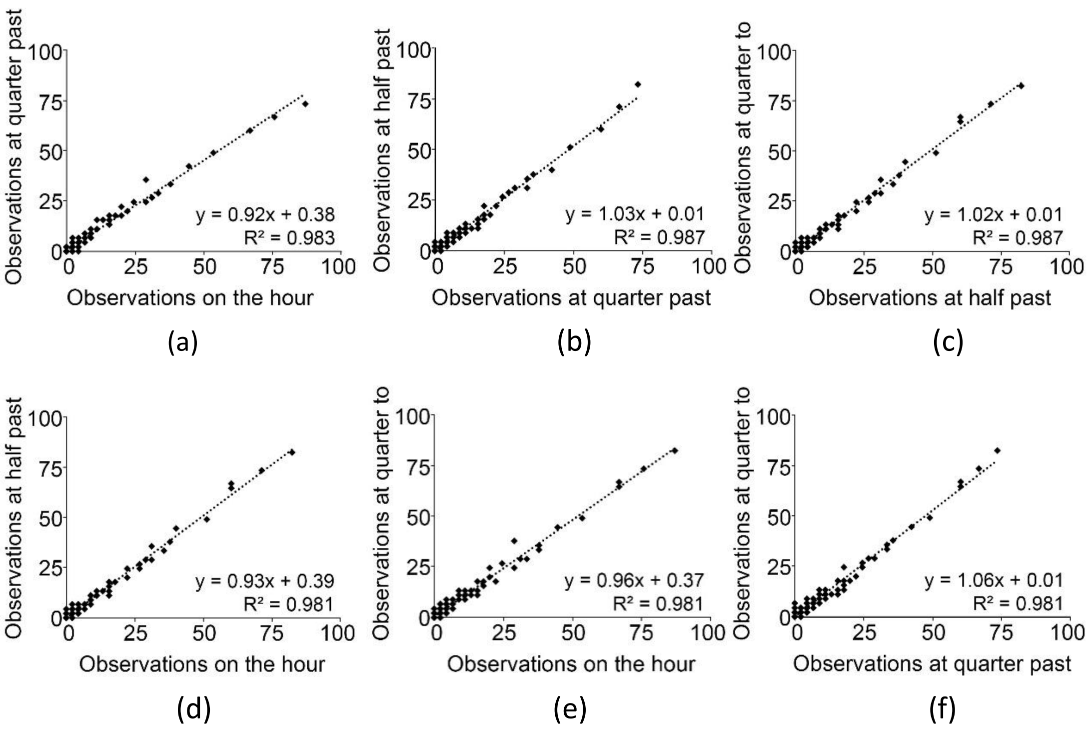
Three intervals were considered: 15, 30 and 60 minutes. For the 15-min data, these are the average occupancy rates for each seat. For the 30-min data these are the observations recorded on the hour and half past each hour. For the 60-min data these are the hourly observations. There does not appear to be any significance difference between the three intervals at which occupancy observations were recorded (Figure 4.5). This was confirmed by Pearson's correlation comparing occupancy rates at the 15, 30 and 60 min time intervals, each gives a p-value less than 0.001 (n= 250, p < 0.001). It was therefore concluded that observations recorded at hourly intervals lead to similar assessments of occupancy rate as those captured at 15 min intervals.



(a) (b) (c)

Figure 4.5. Comparison of the three intervals (a) 15min versus 30min dataset, (b) 30min versus 60min dataset, (c) 15min versus 60min dataset. Only data from experiment 3a are used.

Next consider different approaches to selecting the hourly interval. An analysis was carried out comparing the four different approaches to establishing 60min intervals: on the hour, at quarter past, at half past and at quarter to. These comparisons are shown in Figure 4.6. In all six comparisons the high degree of correlation is suggested to be statistically significant (p < 0.001). It was therefore concluded that observations taken at hourly intervals on the hour provide satisfactory representation of hourly observations taken at other points.



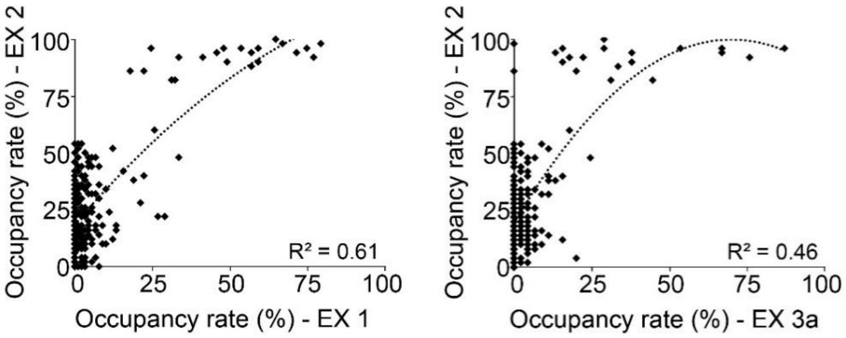
(a) (b) (c)

(d) (e) (f)

Figure 4.6. Comparison of the four versions of 60min dataset (a) observations on the hour versus observations at quarter past, (b) observations at quarter past versus observations at half past, (c) observations at half past versus observations at quarter to, (d) observations on the hour versus observations at half past, (e) observations on the hour versus observations at quarter to, (f) observations at quarter past versus observations at quarter to.

Considering the movement of occupants between two observation points, the time interval for which recordings are made is expected to be an important factor when recording seating behaviour. Yet, comparison of results from the observations made at intervals of 15min, 30min and 60min showed that occupancy rates vary within a very small range among the three time intervals. This could be explained by the duration of time an occupant spends in a seat. Though the time interval during which seating observations are carried out may be important in areas of high circulation or social areas where people spend shorter periods of time such as restaurants or cafes, it is less of an issue in library reading rooms where people may remain static for long periods of time. Therefore, this conclusion should be validated in surveys of spaces where occupancy tends to be for shorter periods, such as restaurants or cafes.

Another source of experimental variation could be the season during which observations were recorded. Two distinct different seasons were selected, autumn (EX2) and summer (EX1 and EX3a), each enables different conditions of observation such as daylight levels and occupant density. Note that the hourly data were used to assure data values are consistent among the three experiments. Figure 4.7 shows scatter plots of the relationship between the occupancy rates calculated for the summer and winter observation periods. A second order (quadratic) model has been used to create the best-fit curve for the data from the three experiments. As expected, the plots show similar relationships for EX1-EX2 and EX2-EX3a. Although the two summer experiments (EX1 and EX3a) were not identical in sample size (EX1 was carried out over a two-week period and EX3a over a one-week period), there is enough similarity between the two scatter plots (Figure 4.7a and Figure 4.7b) to expect reasonable similarity of changes in occupancy rates in summer and winter observation periods.



(a) (b)

Figure 4.7. Comparison of the occupancy rates in summer (EX1 and EX3a) and winter (EX2) periods. (a) EX1 and EX2, (b) EX2 and EX3a.

4.3.5 Daytime-night time analysis

In experiment 2 (EX 2), observations were drawn before and after dusk to enable comparison of seat choice in periods when daylight could, and could not, have a direct effect. Observations during hours of daylight were done between 09:00 and 14:00, whilst after-dark observations were done between 18:00 and 21:00 (see Section 4.2.1 for sunrise and sunset times for the observation period). It is assumed that if daylight has a significant direct influence on seat choice, then observations in these two periods would lead to different occupancy patterns. Figure 4.8 shows occupancy rates from the night-time observations plotted against the daytime observations. Pearson correlation suggests this degree of correlation is significant (n=250, p<0.001). This indicates that occupancy rates are similar in daytime and after dark, and hence that daylight has very little if any effect on seat choice. One confound to this analysis is that the occupants tended to arrive whilst it was still light, and were influenced by this, and then remained at the same location into the after-dark period.

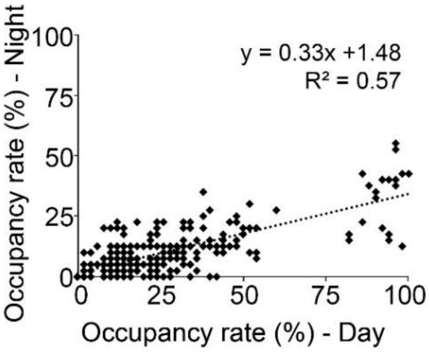


Figure 4.8. Occupancy rate observed at night time plotted against occupancy rate observed at daytime.

4.4 Walk-through approach

The experiments reported in this section attempt to measure the robustness of the results obtained from the snapshot data. This was developed in a second method in which the movement of individual people was recorded as they choose a seat. This procedure was employed in experiment 3 (EX 3) alongside the snapshot observations.

4.4.1 Procedure

Snapshot observations did not allow recording sequences of behaviours since the observer considered only short sample intervals and recorded behaviours at sample points in time. In the walk-through method, movements of occupants were recorded from when they enter the reading room until they choose a seat. This procedure involved tracking, rather than producing a static picture, and following the movement of one occupant at a time. As the tracks of multiple library users are overlaid a pattern may emerge that indicates desired seats and pathways.

One potential problem with the walk-through approach is that it might be impractical or unreliable as whilst the observer is recording one behaviour some other information is likely to be missed (Mills and Nankervis, 1999). One step towards addressing this problem is to use technologies that allow for automatically tracking the movement of occupants, thereby capturing things not noticed at the time of being present. Clips of occupant movements in the room could be recorded, either as a continuous motion video or as a sequence of still images taken and displayed in sequential order. These approaches have not been used in previous research (see Chapter 2). For the current study, audio or video recordings were not allowed due to privacy reasons. To overcome this limitation, walk-through observation was carried out during the summer period when room occupancy was low, allowing the researcher to record the behaviour of a single occupant and be available to observe the next occupant who arrives. The observed seat choices were then compared with the snapshot record for that same moment of time to ensure consistency between two datasets (note that the walk-through observation was carried out in parallel to the snapshot observation).

The pattern and direction of movement were traced on the floor plan and the seat number chosen was recorded. Visually overlaying the routes followed by occupants could help identify those paths/areas which are predominantly used when entering the room. A method of notation was developed using identification numbers and lines for locating recorded seating behaviours on the seat map (Figure 4.9).

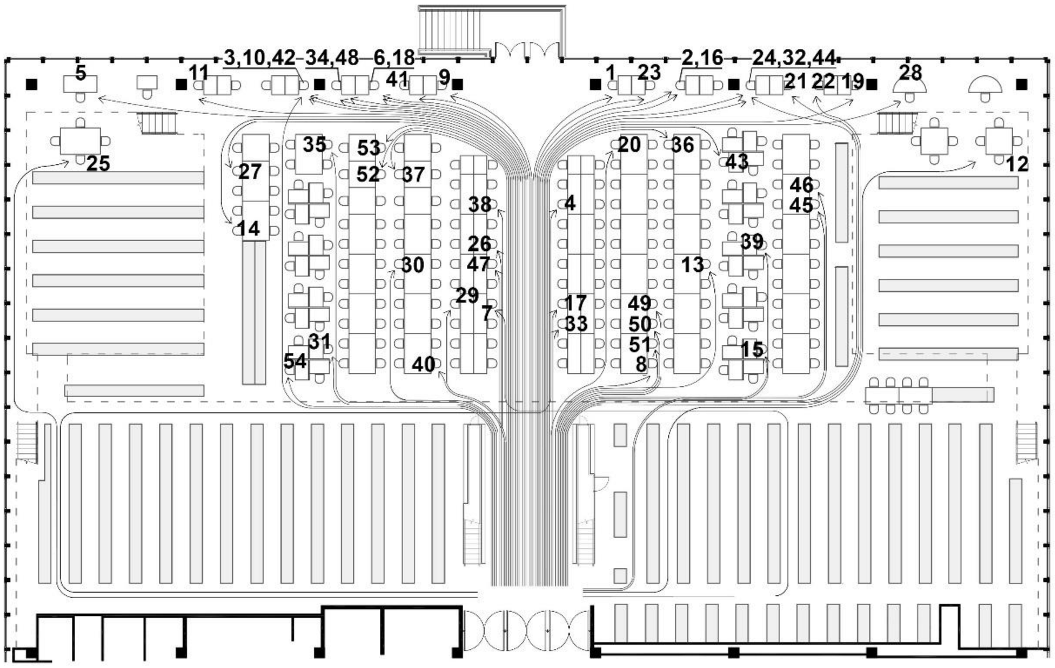


Figure 4.9. Seat map showing the direction and movement of each occupant (a single line with an arrow head) through the reading room. Each occupant was given an identification number to indicate the order of entrance into the room. Note that these data are for only one day (day 1).

Once the occupant had entered the reading room, the experimenter followed a short distance behind. As in the snapshot experiments, the occupants being observed were not made aware of the research being undertaken to avoid any influence this may have had on their movements and behaviour. For each observation, the route taken by the occupant was tracked and the amount of time they spent in the seating area was recorded. The activity they displayed while in the seating area was noted, including their use of power sockets. Additional data were also captured on each occupant, such as being or not being in a group, as these were expected to have an effect on outcomes. A total of 203 users' seat choice and walking path were recorded. The raw data was gathered using observation record sheets (see Appendix F).

4.4.2 Results: Group settings

There may be differences between seat choices made by individuals (people working alone) and by groups (people actively engaged with one or more people for a common purpose). When people are in groups, they may behave differently than they do when they are alone. For example, whilst individuals may prefer to sit away from others for privacy, a group of people may tend to sit in close proximity to each other, either next to each other or opposite each other to increase social interaction, this being some form of verbal or nonverbal communication among group members. This was analyzed at two levels: individual and group. The latter can be further broken down into two sub-levels: groups actively collaborating and groups sitting together but working alone. Because the experiment was carried out in a supposedly quiet area where social interactions among occupants are less likely to occur, however, these aspects were not considered and the analysis of group seating behaviour was intentionally kept fairly simple.

The data indicate that occupants sat individually (77%) more often than they sat in groups (23%). It should be noted that one-eighth of the room was designed for individual use (the window seating area), while seven-eighths of the room was designed to be more collaborative in nature (central seating area). The majority of observed group work (81%) was two people working together; only 19% of groups comprised three or more people. Often, two or more people occupied a table in the central seating area as it can accommodate larger groups. However, this doesn't entirely account for the very low number of groups working together in the window seating area since sometimes there were two people sitting opposite each other and there were tables that groups could use.

The results suggest that any preference for daylight may have been overridden by group settings. Seating behaviour cannot be explained only by daylight. A high level of privacy offered by individual seating in the window seating area or the presence of large tables for group work in the central seating area may also be influential, so an important question is whether there are any privacy considerations that might affect individuals' seating preferences. One approach might be to quantify the ratio of people in close proximity to determine local density. Further discussion of this is given in the next section.

4.4.3 Results: The local occupancy density

The density of individuals in the seating area, and thus how crowded people feel, could have an impact on their seating preferences. Occupants' seating decisions might differ when the seat next to theirs is already occupied by another person than when it is unoccupied. The theory of proxemics, originally proposed by Hall (1966), describes what interpersonal relationships are mediated by distance. The idea is that there is an optimal personal distance from others at which people feel comfortable, although this varies according to culture and social context (Hall, 1966; Patterson, 1976). Choosing a seat adjacent to already occupied seats means narrowing down personal distance. As discussed in the previous section, people may adjust their spatial relationships with others according to the activity they are engaged in, either individual work or group work. It was assumed that the distance sought from others is likely to be larger for those working alone than for those working in groups.

Considering proxemics interactions in a library room setting that accommodates fixed seating and tables, each seated person has a definite position and personal space, and their seating preferences are likely to have been affected by the presence of others. In the current experiment, sitting on two neighbouring seats places occupants at less than 75 cm apart, which apparently remains below the minimum public distance proposed by Hall (1966), a distance of 3.7 m (12 feet) at which an occupant would be able to take evasive or defensive action if threatened (Hall, 1966).

With the exception of Wang and Boubekri (2009), none of the previous seat choice studies have investigated the effect of presence of enclosures. In their experiments, Wang and Boubekri (2009) compared individual seats according to the number of enclosed sides around them, but did not provide any measure of proximity or occupancy density. The aim of this experiment is to take one step towards a more comprehensive approach which may lead to a more convincing conclusions regarding whether proximity to other people affects seat choice. The approach used in the current experiment is based on the conception of neighbourhood to determine the local occupancy density. This is expressed as the percentage of occupied neighbouring seats on arrival. The number of neighbour in the example presented in Figure 4.10 is set at eight (Coates, 2010).

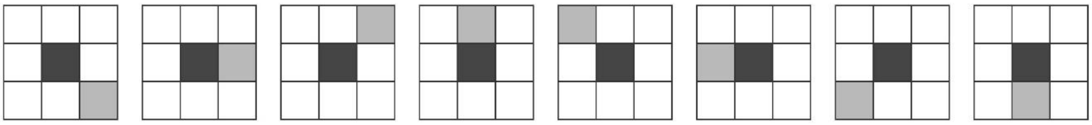


Figure 4.10. The eight different ways of having a single neighbour. Note that dark grey shading indicates the cell being updated and light grey shading indicates the neighbour of that cell.

Two common neighbourhood patterns are the Von Neumann and the Moore. Whilst the von Neumann neighbourhood comprises of four cells orthogonally surrounding a central cell, the Moore neighbourhood takes into account eight cells on a two-dimensional square lattice (Maignan and Yunes, 2013) (Figure 4.11).

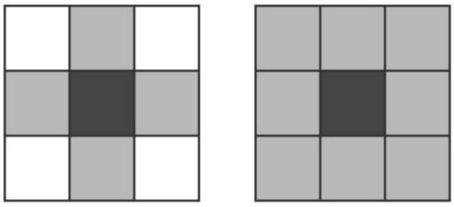


Figure 4.11. The von Neumann neighbourhood (left) and the Moore neighbourhood (right). Note that dark grey shading indicates the cell being updated and light grey shading indicates neighbours of that cell.

The definition of neighbourhood is somewhat arbitrary and in theory modifiable depending on the context. With regard to the layout of the room where the experiment was undertaken, it seems reasonable to assume that the seating preferences may not be influenced by the presence of other people outside the visual field, which extends up to about 100° laterally (Boyce, 2014). Hence, in the current experiment, the Moore neighbourhood concept has been extended to incorporate other factors rather than just possible neighbours in the area, such as the seating position and the inclusion of visual view angle. The number of neighbours of a seated occupant was calculated on the extent to which another occupant would intrude into the 100° field of vision. Along with the seats on both sides, this approach takes into consideration those seats directly opposite and diagonally opposite the person (Figure 4.12).

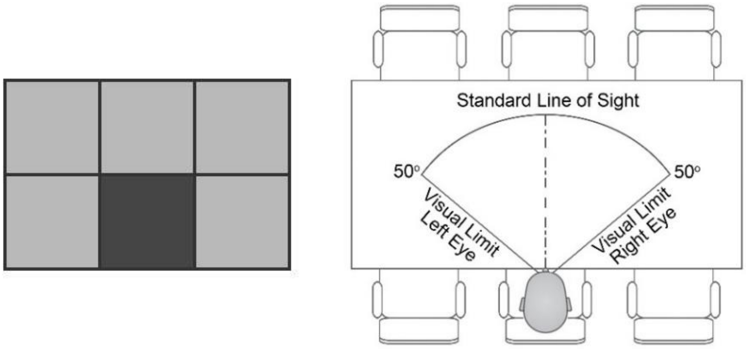


Figure 4.12. Around each seated occupant there exists a neighbourhood within occupant's field of view (Adapted from the neighbourhood concept proposed by Moore).

The local density was calculated for each seated individual by dividing the number of people in the modified Moore neighbourhood by the number of seats in that neighbourhood. Each individual was then assigned a value ranging between 0 and 1, with 0 indicating that there is no one sitting in neighbouring seats on arrival, and 1 indicating all neighbouring seats are occupied. The total number of seats surveyed was 250, of which 38.4% were partitioned and 61.6% were non-partitioned. The partitions were of 450mm height, providing visual separation between the seats. The occupants seated behind the partitions were not taken into account as they were outside the visual field of view. The example shown in Table 4.7 illustrates the calculation method for a partitioned and non-partitioned seat.

Table 4.7. Example calculation of the local density for the two occupants (day 3) (see Appendix F for the locations of the occupants). Note that the occupied neighbouring seat is not taken into account if there is a partition between the seats.

Occupant id no	Seat no	Partitioned/Non-partitioned	Number of occupied seats in the neighbourhood	Total number of seats in the neighbourhood	Local density
42	27	Non-partitioned	1	3	0.3
47	207	Partitioned	1	3	0

It was assumed that if physical proximity matters, people would tend to sit in a seat with a low local density score. Figure 4.13 shows the number of people for each density category. As expected, the plot shows that most people chose to place themselves in areas with a local density score of 0. For those people who sought privacy (i.e. local density score of 0), there was no apparent trend in seat location. In other words, people tended to sit some distance apart from others, regardless of whether they preferred window or central seating area.

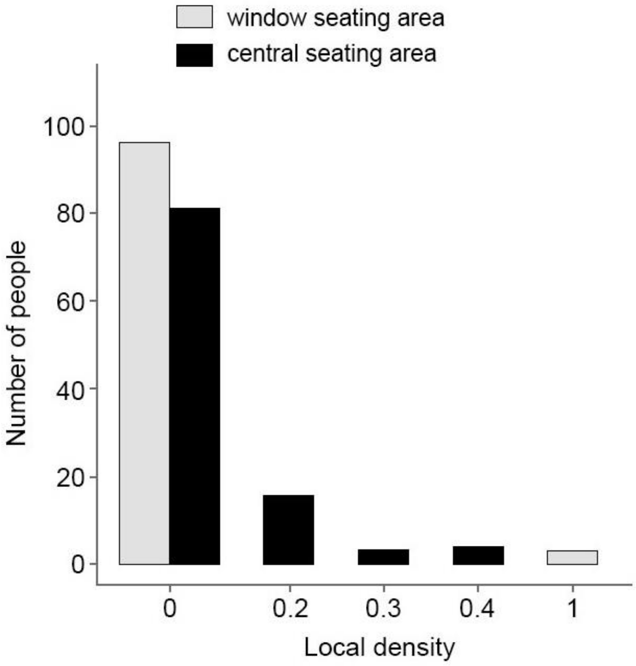


Figure 4.13. Local density in window seating area (Zone 1) and central seating area (Zone 2-5).

A potential alternative explanation for these results would be that seat availability may have limited occupants' choices. For example, occupants whose preferred seat is not available may be forced to sit next to an already occupied seat. In such cases, occupants may have little or no control over their proximity to others. That is to say, the close proximity of occupants to others may result from circumstances beyond their control, and it may be this difference in individual control that is responsible for the effects observed in the current experiment.

This section has explored a method that uses a modified Moore neighbourhood concept to determine the effect of local occupancy density on actual seat choice. Local density was estimated by the number of people seated within the visual field in the modified Moore neighbourhood. The results from this investigation suggested that occupants tended to sit apart from others, as the local density was low in most cases. The proposed method provided insight as to how occupants place themselves in relation to those already present. It should be noted however that the method provided only a proxy measure of individuals' proximity to others and different approaches can be taken.

4.4.4 Results: Length of stay

The snapshot approach used in previous experiments attempted to provide static pictures of seating behaviour of occupants at specified time intervals. Although no significant difference was found between the three time intervals used (15min, 30min and 60min), it is possible that this approach could still have been influenced by differences in the length of stay among occupants. Longer length of stay in the window seating area may have resulted in a higher occupancy rate while shorter length of stay in the central seating area may have resulted in a lower occupancy rate. Both these assumptions would in theory account for the higher occupancy rate observed in the window seating area compared to the central seating area and thus likely to influence resulting outcomes and bias the comparison. An alternative analytical approach that could address this limitation or confirm/refute conclusions drawn from the snapshot observations data is to examine the trends in length of stay among occupants.

Length of stay (duration) was defined as the amount of time a given desk is occupied, determined by the arrival and departure times as recorded by the experimenter. It should be noted that this record may not be a completely accurate measure of the exact number minutes spent at the desk (i.e. occupants may leave their desks temporarily), but it can provide a reasonable estimate of the time a desk is occupied. A series of arrival and departure times recorded for each occupant, with the difference between the two times being calculated to determine the length of stay. The overall mean length of stay across five zones was 2 hours and 35 minutes with a standard deviation of 1 hour and 57 minutes. The longest length of stay among occupants was 8 hours and 36 minutes and the shortest length of stay was 2 minutes.

The mean length of stay in each zone is shown in Figure 4.14, and was compared using one-way ANOVA. This suggested that the mean length of stay differed significantly between all five zones (F(4,198) = 11.114, p <0.001). A Tukey post hoc test revealed that Zone 1 (window area) produced significantly higher length of stay than Zone 2 (p <0.001), Zone 3 (p <0.05), Zone 4 (p <0.001) and Zone 5 (p <0.001). There was no statistically significant difference between the zones in the central area (Zone 2-5) (p-values range between 0.961 and 0.999).

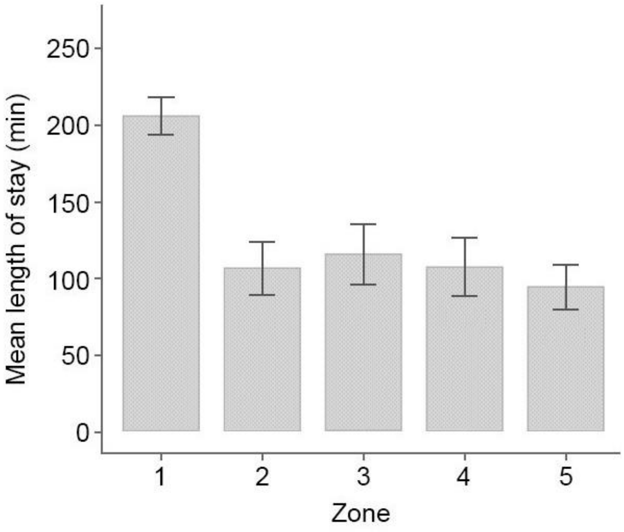


Figure 4.14. Mean length of stay by zone. Error bars show Standard Error of the Mean. (Zone 1= window seating area, Zone 2-5= central seating area)

These results suggest that the length of stay had an effect on the occupancy results: The amount of time spent at a desk was significantly longer in the window area (Zone1) than in the central area (Zone 2-5). This confirms the assumption that high occupancy rates can be due to longer lengths of stay rather than higher number of occupants occupied. This presents a limitation in the snapshot approach.

4.4.5 Results: Type of activity

An alternative explanation for the differences in occupancy rates observed in the reading room is the probability of an individual being focused on a particular task whilst limiting attentional capture by other stimuli such as daylight. That is, the difference in occupancy rates between seating areas could be attributed to the fact that some occupants were engaged in a computer-based task, which demanded greater attention to be paid to the presence of power sockets, and give evidence that seating behaviour is influenced by the task being undertaken. To examine how task and the availability of power socket influence seating preferences, occupants were classified in terms of the tasks they perform, these included computer and paper-based tasks. It was assumed that those who carry out computer-based tasks would need access to a power socket, while those who carry out paper-based tasks do not. Then there might be a third group, for which it is unclear whether the access to power sockets matters or not, such as those carrying out computer-based tasks but do not require external power supply. Table 4.8 presents a summary of power socket availability and usage for the two task groups.

Table 4.8. Availability and usage of power sockets for computer-based and paper-based task groups (n=203).

	Computer-based task	Paper-based task	Total
Power socket available and being used	40	n.a.	40
Power socket available but not being used	2	23	25
Power socket not available	46	92	138
Total	88	115	203

n.a. (not applicable)

The need for access to power sockets may have altered occupants seating behaviour and increased their tendency to sit close to a power socket if they were carrying out computer-based tasks. It should be noted that power sockets are not provided on all desks but only on some of those located in window seating area (Zone 1) (see Appendix G for power socket availability on each seat). The window seating area thus begins to represent a workspace that is designed to enable occupants to perform certain tasks (computer-based tasks), which may explain part of the differences in occupancy rates between seating areas.

When activity is examined separately for the two seating areas, findings have shown that occupants seated in the window seating area in which all power sockets are located include not only those who carry out computer-based tasks, but also those who carry out paper-based tasks (55% and 45% respectively). Likewise, occupants seated in the central seating area include those who carry out paper-based tasks (69%) as well as computer-based tasks (31%) (Figure 4.15).

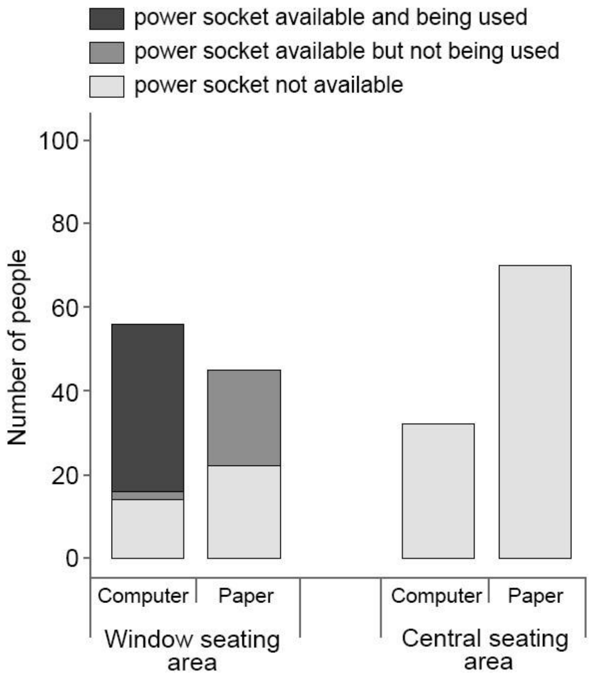


Figure 4.15. Type of activities and availability/usage of power sockets in window seating area (Zone 1) and central seating area (Zone 2-5).

The number of people performing a computer-based task observed in the central seating area with no available power sockets suggests that the sequential process of seat choice may have introduced bias and that the seat choices may have resulted from the absence of available seats with power sockets in the window seating area, though these are difficult to confirm with observational data. These do not undermine the implications of the results however, as regardless of whether the decisions about seating location were task-relevant or task-irrelevant, the point is that there was no clear evidence of an association between availability of power sockets and seat choice.

4.5 Summary

This chapter has described the methods used to investigate actual seat choice behaviour in the test room. Three experiments were carried out, one in the autumn and two in the summer, to account for seasonal variations in daylight and occupancy. Seat choice behaviour was assessed using two methods: snapshot and walk-through. While the reliability of data collected with one particular method may be questioned, confidence can be drawn from the convergence of results obtained with both snapshot and walk-through methods. Snapshot approach included recording data at regular intervals, with each record representing a snapshot of the use of the seats at a particular time. In this approach occupancy rates were calculated using a formula adopted from National Audit Office (NAO) to provide a quantitative basis for seating preferences. The results showed a general preference in all experiments to sit near windows: occupancy rates were higher in window area compared to central area. In the central area where occupancy was low, there was no significant change in the occupancy as a function of the distance from the windows. It appears that proximity to windows has little effect on those who sit in the central area.

One potential problem with carrying out field observation studies in natural conditions as in this case is the difficulty in controlling the environmental conditions so that specific variables such as daylight can be isolated for investigation. An attempt to address this was done by recording seating behaviour of occupants during the daytime and after dark. A comparative analysis of data revealed that a relationship existed between daytime and after-dark occupancy rates, suggesting that the effect of daylight may be small. However, these data should be interpreted with caution because of the effect of length of stay: Occupants arriving during daytime may have remained in their seats after dark. This may have resulted in overestimation of occupancy rates after dark.

Walk-through experiment explored seat choice behaviour not as a snapshot of specific occupancy patterns captured at a particular instant but in terms of sequential movement. Observations were made by a second experimenter in parallel to snapshot observations. The experimenter kept watch over the room from some distance away and recorded the movement of people entering, where they sat, what they do, and how long they remained at their seats. The collected data suggested that there is a tendency for the individuals seated in window seating area to remain in their seats for longer periods of time, a preference for individuals to sit apart from others for privacy, and a preference for groups to sit in close proximity to each other. These findings support the conclusion that occupants prefer to sit near windows and raise issues of privacy and the length of stay.

Next chapter describes and discusses a simulation framework that quantifies daylight levels in the test room. The first part provides a description of the simulation model and the second part presents an analysis of the ability of a range of illuminance-based metrics to predict seat choice behaviour.

CHAPTER 5. SEAT OCCUPANCY AND DAYLIGHT

5.1 Introduction

This chapter examines methods for prediction of daylight performance metrics by means of simulation. The first part of the chapter describes the simulation framework devised to investigate these metrics, and summarizes the results. The second part presents the statistical analysis used to correlate the metrics derived from the simulations with the results from revealed preference surveys presented in Chapter 4. Finally, the chapter concludes with a discussion of the limitations of the simulation method and suggestions for future research.

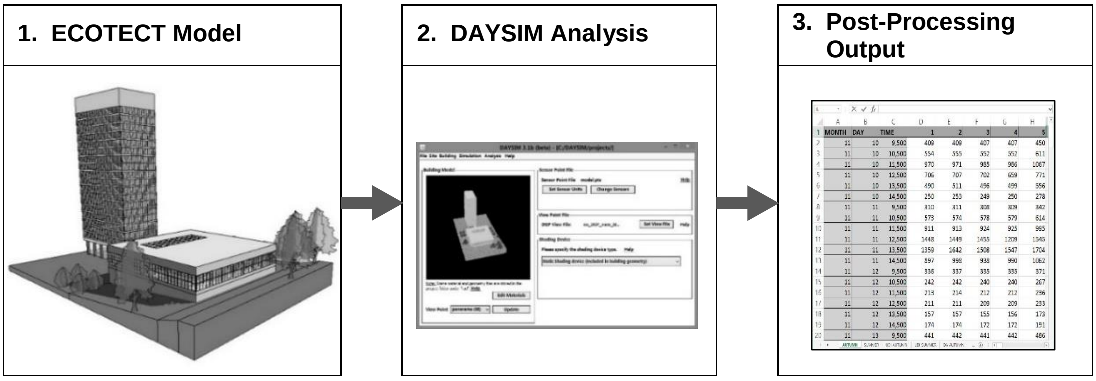
5.2 Daylighting analysis: A simulation-based approach

Daylight performance was evaluated through simulation to gain a reasonable estimate of the variation in daylight illuminance in the test space. This section describes the steps taken in the simulation process, the weather data used for the simulations and the parameters and indicators considered for the analysis. Finally, a discussion on the validation of the simulation method and the results of simulations are presented.

5.2.1 Simulation method

Simulations were carried out for the test room using the RADIANCE-based daylighting analysis tool DAYSIM within Autodesk ECOTECT. This method resulted in the following simulation procedure (shown schematically in Figure 5.1) being made in the sequence outlined below:

1. Setting up a three-dimensional model of the building in ECOTECT.
2. Importing this model to DAYSIM which determines the illuminance due to daylight at a series of grid points.
3. Calculation of daylight metrics from these illuminances using a spreadsheet.



	A	B	C	D	E	F	G	H
1	MONTH	DAY	TIME	1	2	3	4	5
2	11	10	9,500	409	409	407	407	450
3	11	10	10,500	554	555	552	552	611
4	11	10	11,500	970	971	985	986	1067
5	11	10	12,500	706	707	702	659	771
6	11	10	13,500	490	511	496	499	556
7	11	10	14,500	250	253	249	250	278
8	11	11	9,500	310	311	308	309	342
9	11	11	10,500	573	574	578	579	614
10	11	11	11,500	911	913	924	925	995
11	11	11	12,500	1448	1449	1455	1209	1545
12	11	11	13,500	1359	1642	1508	1547	1704
13	11	11	14,500	897	998	938	990	1062
14	11	12	9,500	336	337	335	335	371
15	11	12	10,500	242	242	240	240	267
16	11	12	11,500	213	214	212	212	236
17	11	12	12,500	211	211	209	209	233
18	11	12	13,500	157	157	155	156	173
19	11	12	14,500	174	174	172	172	191
20	11	13	9,500	441	442	441	442	486

Figure 5.1. Simulation process flow chart. ECOTECT (2011) was used as the modelling interface from which the DAYSIM (version 3.1) program was launched; the subsequent output was then modified in EXCEL to extract data of interest and to match recommended simulation parameters (i.e. 3000 lux upper threshold of UDI).

A similar procedure was used by Pechacek et al (2008) who combined annual daylight simulation with photobiology data to evaluate circadian efficacy of daylight in interior spaces. They built a three dimensional model of the space in ECOTECT and then exported to DAYSIM to then have the files necessary to carry out post-processing using a MATLAB-based script. For the current study, the numerical data obtained from the simulations were post-processed in Microsoft's EXCEL and the resulting data were subsequently imported into MATLAB for visualization purposes.

The RADIANCE calculation engine used in DAYSIM applies backward raytracing simulation method, where rays are emitted from the point of interest and traced backwardly until they either hit a light source or another object (Larson and Shakespeare, 1998). DAYSIM uses the RADIANCE algorithm combined with the daylight coefficient approach (Tregenza and Waters, 1983) and the Perez sky model (Perez et al., 1990, 1993) to predict the annual time series of interior illuminance values at each sensor point over a specified area (Larson and Shakespeare, 1998; Reinhart and Walkenhorst, 2001). The daylight coefficient method, originally proposed by Tregenza and Waters (1983), divides the sky into 145 sky segments and calculates coefficients using backwards ray tracing methods to relate the luminance of each sky segment to a point inside the space. It describes how much light a point on a surface receives from a certain sky segment compared to all the other segments, and a complete set of daylight coefficients for all sky segments then defines the relationship between a point within scene and celestial hemisphere.

The computed daylight coefficients are then coupled with the weather data, the results of which serve as input to calculate the annual time series of interior illuminances. DAYSIM uses the Perez all-weather sky model, which extends beyond the relative distributions of the standard CIE sky models to provide customized luminance distributions based on direct and diffuse irradiances taken from the weather file. (Perez et al., 1990, 1993; Reinhart and Walkenhorst, 2001). In other words, Perez all-weather sky model uses irradiance values as inputs to generate the sky luminance distribution patterns for all sky conditions from overcast to clear, through partly cloudy. In doing this, a representative sky for each time step in the weather file is created and sampled over the same sky discretization pattern as used for the daylight coefficient generation. Then a matrix multiplication operation is performed to compute the daylight illuminance (Reinhart and Walkenhorst, 2001).

Daylight illuminances were determined for a set of pre-defined sensor points at specified intervals across the given time period. The resulting time series of illuminances were post-processed with custom algorithms that determined the performance metrics for each sensor point. The entire simulation process, as illustrated in Figure 5.2, implies a series of stages.

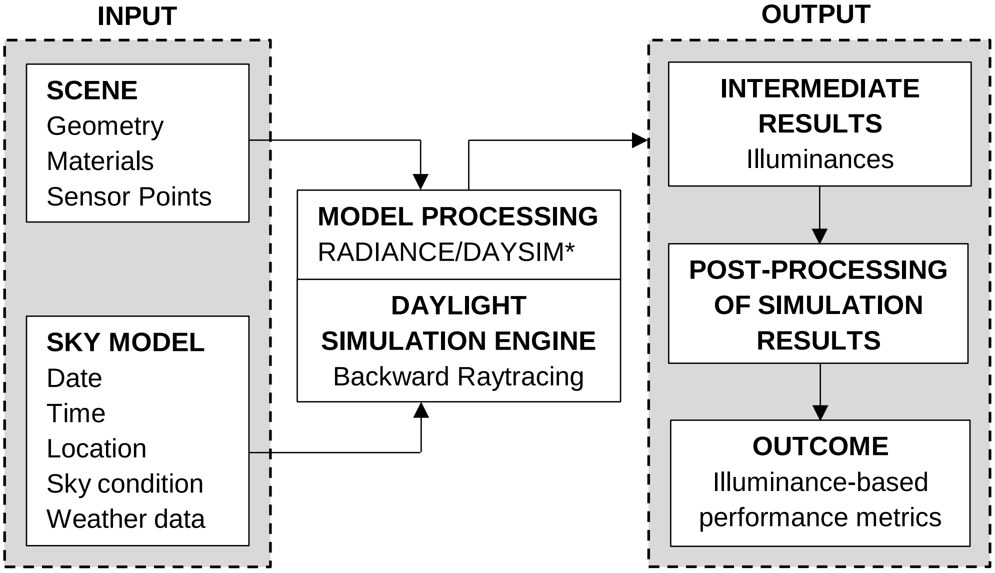


Figure 5.2. Schematic diagram of simulation process.

* DAYSIM uses the Radiance algorithm combined with a validated daylight coefficient approach and the Perez sky model to simulate time series of indoor illuminances (Reinhart and Walkenhorst, 2001).

The simulation procedure shown in Figure 5.2 is summarized below:

1. A three-dimensional model of the test space was generated in Autodesk ECOTECT. The model contains information on the geometry of the building with immediate surroundings as well as the surface material properties (The building geometry for the simulations was provided by the Department of Estates and Facilities Management in an AutoCAD format). A survey of the reading room was also carried out to obtain all relevant information relating to the interior space, to be inserted into the three-dimensional model produced by software, as described in IES LM 83 (IES Daylight Metrics Committee, 2012). A grid of sensor points was specified in the horizontal plane on the surfaces of individual desks where illuminances were to be determined.

2. A weather file for the building was imported that includes irradiation data (As described previously, DAYSIM uses the Perez all-weather sky model, which require direct and diffuse irradiances as input for each time step). These data were obtained from the solar radiation measurement station located on a nearby building (see Section 5.2.2). The weather file was generated based on the irradiation data for the period of observation, this was done by extracting the corresponding data from the database, the details of which are discussed later in this chapter.

3. Model geometry and simulation settings were then exported into Radiance/DAYSIM format. The output from DAYSIM was a data file containing the illuminance values for pre-defined sensor points in the space, located at work plane level (0.75m from the floor). Some of these sensors were singled out as ‘core work plane sensors’, that is, sensors close to where the occupants are located (Nabil and Mardaljevic, 2005). This approach makes it possible to calculate the illuminance profile for those individual sensor points on the horizontal grid that corresponded with the location of each individual seat in the model.

4. Simulation results were post-processed in Microsoft’s EXCEL in order to determine daylight metrics for each seat separately, these included horizontal work plane illuminance as well as dynamic performance metrics such as daylight autonomy and useful daylight illuminance. This step involved identifying which times of the year to consider as a time basis for

daylight performance metrics (i.e. two-week period in August for Experiment 1), extracting data of interest from the annual indoor illuminance data sets, and, finally, setting the ranges with which the results will be evaluated (i.e. 100-3000 lux range for UDI).

5. The illuminance profiles determined separately for the two observation periods were coupled with the occupancy pattern. Note that the choice of using illuminance-based metrics as opposed to luminance-based metrics is linked to the decision under Chapter 2 to use work plane illuminances as a basis to judge whether the daylighting is 'adequate', which is assumed to be an important factor when choosing a seat. Further investigation with regard to using luminance-based metrics is proposed for future study (see Chapter 7).

5.2.2 Weather data

The study is based on instantaneous measurements of irradiance data collected at the solar radiation measurement station located on the roof of the Hicks Building, within 200m of the test building (53°22'52" N, 1°29'11" W) (Figure 5.3). The station was put into operation in 2010 and has been in use ever since. The data is being collected as part of the Sheffield Solar Project, which is funded by the EPSRC (Solar Energy for Future Societies: EP/I032541/1; Wise PV: EP/K022229/1) and the University of Sheffield.

The weather station is equipped with a SPN1 Sunshine Pyranometer from Delta-T Devices, which measures both direct and diffuse radiation (W/m^2), and a data logger (Delta-T Logger), which initiates the readings, controls the sensors and stores data related to 2 minutes range. The manufacturer specifies an overall accuracy for both the direct and diffuse radiation of ±8% (±10 W/m^2) for individual readings (Delta-T Devices, 2007). Performance classifications of pyranometers are defined by the International Standard ISO 9060/1990, which are also adopted by the World Meteorological Organization (WMO, 2008). According to the specified standards, the SPN1 Sunshine Pyranometer matches or exceeds the ISO First Class standard and the WMO Good Quality standard for a solar pyranometer in all respects apart from the spectral response, which is accurate to ±10% over 400 x 10^{-9} m to 2700 x 10^{-9} m (exceeds the standard accuracy limit of ±8%) (Delta-T Devices, 2007).

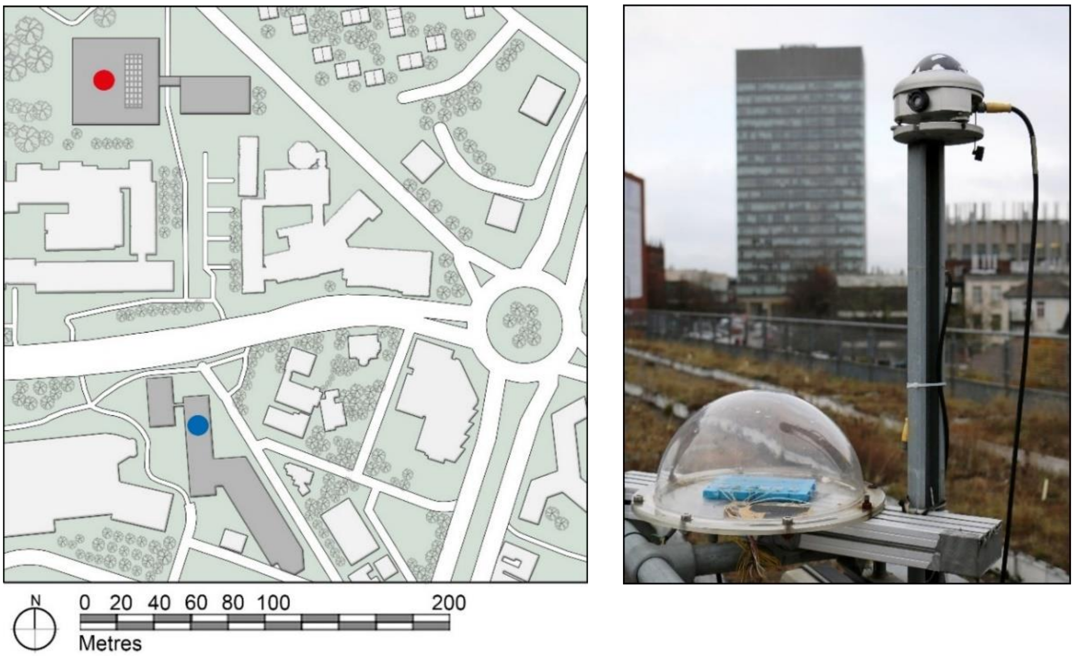


Figure 5.3. Solar radiation measurement station. Left: Location of the library building (marked with a red dot) and the solar radiation measurement station (marked with a blue dot). Right: Measurement equipment (Pyranometer, type SPN1).

The pyranometer uses multiple sensors and a computer-generated shading pattern that ensures some sensors are exposed to direct sunlight and some are in the shade. This allows inferring the global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI); and subsequently the output enables calculation of direct normal irradiance (DNI) using Equation 5.1 (Delta-T Devices Ltd, 2007).

$$\mathrm{DNI} = (\mathrm{GHI} - \mathrm{DHI})/cos(SZA) \qquad \textit{Equation 5.1}$$

where SZA is the solar zenith angle calculated at a given time.

The method was to select daily courses of instantaneous illuminances collected over the observation periods from the Sheffield Solar database, where instantaneous illuminances are 1-second recordings taken at 2-minute intervals, programmed in MATLAB with MySQL database storing data. The instruments are regularly calibrated by comparison against a Kipp CM 21 secondary standard pyranometer, which is traceable to the World Radiometric Reference (WRR) – the accepted worldwide standard for solar radiation (Delta-T Devices, 2007; Gueymard and Myers, 2008). A description of the dataset used in simulations is given in Table 5.1.

Table 5.1. Weather dataset used in simulations. The data were generated based on a measurement period from 2014 to 2015. Separate datasets were created for each year.

Station	Period of measurement	Latitude	Longitude	Time Step	Calibration Reference Standards
Sheffield	2010-present	53.38 N	1.48 W	Two minute instantaneous	World Radiometric

The final dataset contains time series of direct normal and diffuse horizontal irradiance at 2 minute intervals. It should be noted that daylight simulation studies generally use hourly irradiation data and thus tend to neglect the short-term dynamics of daylight, which eventually lead to underestimation of indoor illuminance (Walkenhorst et al, 2002). For the current study, the measured weather data from the solar radiation measurement station compromise irradiation data at intervals less than one hour - a typical time step between records for standard weather files such as Test Reference Year (TRY) - thus enabling the observation of typical changes in shorter intervals. By using the weather data for the precise periods of the observation with a shorter time step removes one source of uncertainty in the analysis that might have been present if instead a standardised or averaged hourly weather data set had been used.

Global horizontal irradiance data recorded at the weather station for the year 2014 are plotted in a temporal map using MATLAB, as shown in Figure 5.4. The shading in the figure represents the magnitude of the irradiance with zero values shaded in dark blue, indicating the hours of darkness. Figure 5.5 illustrates the mean daily global and diffuse solar radiation data for the two observation periods, summer and autumn. These figures reveal daily/seasonal variations of irradiance, with shorter periods of daylight in the winter months and longer in summer.

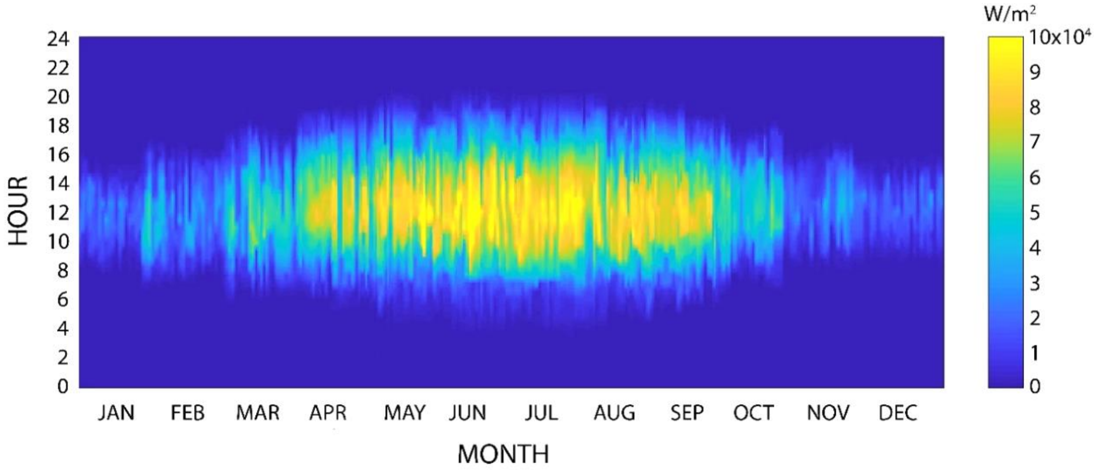


Figure 5.4. Temporal map of the global radiation recorded with the SPN1 pyranometer. The graph shows the 2014 dataset.

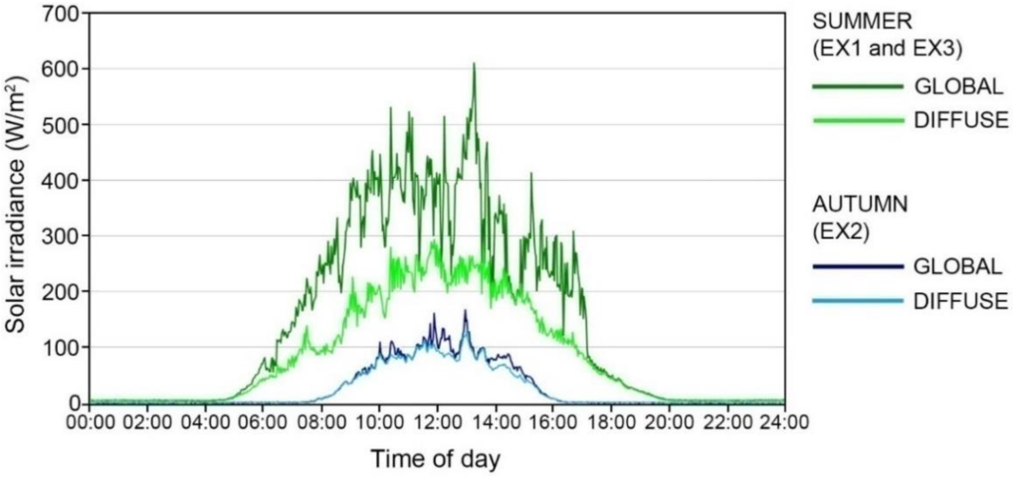


Figure 5.5. SPN1 readings at 2 minute intervals as recorded over the two observation periods: Summer (EX1 and EX3) and Autumn (EX2). For the summer period, the mean values of the two data sets are displayed.

To create a weather file to be used with the simulation model, an approach similar to that used by Matterson et al (2013) was taken, using the standard weather data integrated into ECOTECT as the baseline. The baseline dataset consisted of hourly values of solar radiation data for Sheffield. The study then applied the modified Skartveit-Olseth method implemented in DAYSIM to create 2-minute irradiance data from the hourly data (Skartveit and Olseth, 1992; Walkenhorst et al., 2002). The stochastically generated short time-step solar irradiance data file was adjusted manually by modifying the values of direct and diffuse horizontal radiation according to data obtained from the weather station.

5.2.3 Simulation parameters

The surface reflectance properties were determined through physical measurements. The measurements were taken for the surface under investigation and for a reference surface with a known reflectance (a grey test card of 18% reflectance) using a handheld LS-110 luminance meter. The reflectance of the test surface was then determined by comparison with the reflectance standard available in the form of the 18% grey card, as in Equation 5.2 (SLL and NPL, 2001; Tregenza and Loe, 2014).

$$p_t = p_s \frac{L_t}{L_s}$$ *Equation 5.2*

where p_t is the reflectance of the target, i.e. the unknown surface
p_s is the reflectance of the standard (in this case the grey test card)
L_t is the luminance of the target surface
L_s is the luminance of the standard surface

The method was to measure the luminance of the material (target surface, Lt) and then the luminance of the sample card (standard surface, Ls) placed immediately beside it. The paired measurements were repeated ten times for each surface (floor, walls and ceiling), changing the target spot around the room each time. Table 5.2 reports the measured reflectance values corresponding to each element.

Table 5.2. Measured reflectance values. Mean and standard deviation determined from 10 individual measurements.

Surface	Description	Measured value	
		Mean	Standard deviation
Floor	80/20 carpet tile	0.08	0.01
Wall	Plaster	0.72	0.04
Ceiling	Metal tile	0.59	0.02
Bookshelves	Metal	0.04	0.01

Measurements to determine the transmission of the existing low-emissivity double glazing were carried out using two illuminance meters (Minolta T-10M). The method involved measuring the percentage reduction between the incident light levels under the same target spot. In order to minimize errors due to temporal variations, the measurements were taken under overcast sky conditions where the luminance distribution of the sky is relatively stable. The glass dirtiness was not taken into account, assuming that the cleansing effect at regular rainfalls in the area was adequate to keep the reduction in transmission due to dirt within acceptable limits (less than 10%) (Sharples et al, 2001). Five paired readings were taken, changing the target spot on the glass surface each time. The meters were interchanged during each sequence of measurements to eliminate inaccuracy from meter error, as was done by Tregenza (1998) when investigating calibration methods. The mean transmittance was 0.58 with a standard deviation of 0.06. This measure of transmittance appears relatively low compared with the typical transmittance value of low-emissivity double glazing, which is given as 0.69 in CIBSE guidance (CIBSE, 2006b). This lower transmittance of glazing may be due to the type of coating applied. A special coating may have been applied to improve thermal performance of existing windows. This may have decreased light transmittance. The reflectance value of the grass outside of the library building was estimated to be 0.25 (CIBSE, 1999).

The Radiance simulation parameters that determine the accuracy and precision of the predictions were presented in Table 5.3. These parameters were chosen based on recommended values from earlier DAYSIM validation studies and correspond to ‘scene complexity 1’ as defined in the DAYSIM tutorial (Reinhart, 2006) (i.e. the model does not have any dynamic facade elements) (Larson and Shakespeare, 1998; Reinhart, 2006). For example, the simulation considered up to 5 ambient reflections from the environment (ambient bounces, *ab*); and, for each sensor point 1000 rays were cast to sample the ambient environmental conditions (ambient divisions, *ad*) (Larson and Shakespeare, 1998; Reinhart, 2006).

Table 5.3. Radiance simulation parameters.

Parameter	Description	Value
ab ambient bounces	The number of diffuse interreflections which will be calculated before a ray path is discarded	5
ad ambient divisions	the number of sample rays that are sent out from a surface point during an ambient calculation	1000
as ambient super-samples	the number of extra rays that are sent in sample areas with a high brightness gradient	20
ar ambient resolution	the density of ambient values used in interpolation	300
aa ambient accuracy	the error from indirect illuminance interpolation	0.1

There were no system dynamics such as electric lighting or shading control considered in the simulations. The two options ‘Blind Use’ and ‘Blind Control’ were not changed (assumed as ‘Passive’ and ‘Static’ respectively) as there was no shading device taken into consideration in the calculations. It was recorded that the electric lighting was switched on for the entire period investigated. However, the contribution of electric lighting to the overall illuminance was small relative to that of daylight, and therefore not considered in the analysis.

5.2.4 Performance indicators

Daylight performance was assessed by considering horizontal illuminance on the work plane, following the approach taken in previous research (Christoffersen et al, 2000; Kim and Wineman, 2005; Othman and Mazli, 2012; Wang and Boubekri, 2009). The locations of the core work plane sensors were defined according to the precise seating configuration such that each sensor point corresponds to the position of each individual seat (Figure 5.6).

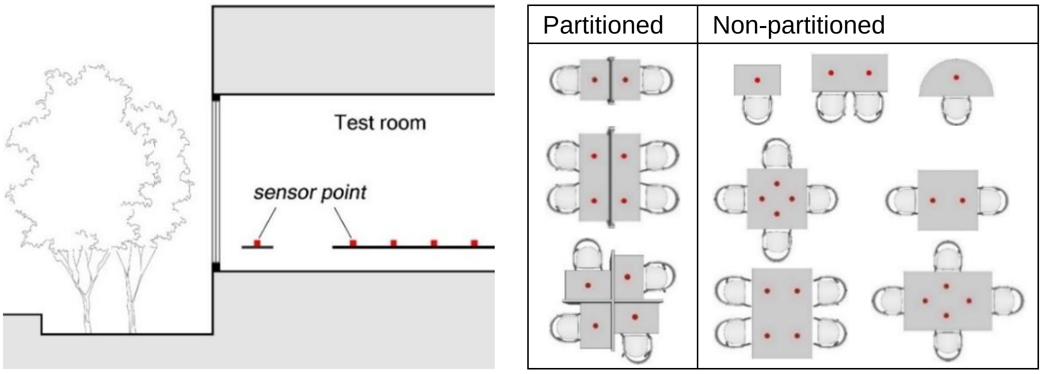


Figure 5.6. Section through the test room showing sensor points for which daylight indicators are calculated (left); seating plans with marked positions of sensor points (right). Each sensor point corresponds to the geometrical centre of the desk (or desk portion) surface.

Given the measured solar irradiation data within the observation time period, a representative illuminance value was determined for each sensor point at each 2-minute time interval. It should be emphasized that dynamic daylight simulations are generally performed for the entire year to analyse daily or seasonal variations in daylight (Mardaljevic, 2006; Walkenhorst et al, 2002). Such cumulative methods are typically used for calculation of energy consumptions or the determination of seasonal dynamics of daylight at the early design stage (Mardaljevic, 2006; Reinhart, 2001). When the purpose of the simulations is to investigate the finer dynamics of daylight over a specific period of time, as in the simulations carried out in this study, the use of average illuminance is recommended instead of point-in-time illuminance (Athalye and Eckerlin, 2009; Ibarra and Reinhart, 2013; Matterson et al, 2013). This is because DAYSIM calculates solar contributions using an interpolation approach, which relies on a predefined set of sun positions (65 sun positions at 10° angular separation in azimuth and altitude). In doing this, each actual solar contribution is determined by averaging the results from four neighbouring predefined positions. Such an interpolation algorithm used by the DAYSIM simulation engine leads to uncertainty of the sun's position, which in turn leads to discrepancies in the instantaneous results at any single point in time (Bourgeois and Reinhart, 2006; Reinhart and Walkenhorst 2001). A comparison was therefore made for the average values of illuminance rather than point-in-time illuminance, as was done by Athalye and Eckerlin (2009) and Matterson et al (2013) when investigating the relationship between measured and simulated illuminance data.

Daylight levels within the test space were evaluated using daylight factor (DF), and a further investigation was carried out in order to determine dynamic daylight performance metrics, these were generated from large sets of illuminance results with different reduction techniques with respect to the observation period. Among the several dynamic metrics which have emerged, the Daylight Autonomy (DA) and the Useful Daylight Illuminance (UDI) as defined by the Illuminating Engineering Society of North America (IESNA) have received a widespread acceptance, and thus were chosen for this study (see Chapter 2 for a description of daylight performance metrics). Both DA and UDI profiles were generated through post-processing illuminance datasets derived from the simulations. Records that contain null values were excluded from the analysis. The three approaches to quantifying daylight used in this thesis are summarized as below.

- Horizontal illuminance on the desk (as used by Kim and Wineman, 2005; Othman and Mazli, 2012; Wang and Boubekri, 2009)
- Daylight factor at the desk (as used by Christoffersen et al, 2000)
- Dynamic daylight metrics at the desk (these have not been previously used in seat choice studies). Two metrics were considered: DA with a threshold at 300 lux, and UDI with thresholds at 100 lux, 300 lux and 3000 lux. The thresholds were derived from current guidelines (see Chapter 2).

5.2.5 Validation of the simulation method

Previous validation studies demonstrate that the RADIANCE-based DAYSIM simulation method achieves a high accuracy (Reinhart and Herkel, 2000; Reinhart and Walkenhorst, 2001; Reinhart and Andersen, 2006). The approach taken by these studies is to compare computer predictions with measurements taken simultaneously in the test space. The two validation metrics employed by these studies are mean bias error (MBE) and root mean square error (RMSE). These metrics provide a quantitative estimate of the differences between two data series. The former measures the tendency of one data series to be larger or smaller than the other, and the latter represents the standard deviation of the differences between the two data series (Burkholder, 1978; Marriott, 1990; Steiger and Lind, 1980). It is shown by comparing simulated and measured data that the RADIANCE-based DAYSIM simulation method provide valid results that accurately replicate real world conditions with a relative MBE below 20% and a relative RMSE below 32%, and these values were considered sufficient to produce reliable simulation results (Reinhart and Andersen, 2006; Reinhart and Breton 2009).

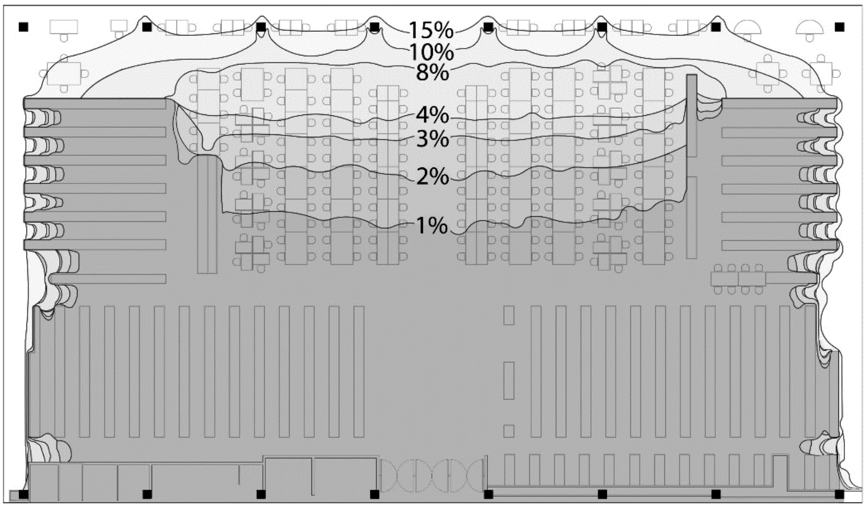
One potential source of error could come from the underlying simulation algorithm of DAYSIM. As noted in the previous section, DAYSIM uses interpolated sun positions and this interpolation could cause a large deviation for a single time step. In its original form, RADIANCE simulates indoor illuminance under one sky condition and at one point in time. This approach gives a more precise accounting of the sun’s position at a given time, thus capable of achieving a higher degree of accuracy. When time-series of illuminance values are considered, however, this approach becomes inefficient, or requires enormous computation time. DAYSIM tends to produce very similar results to RADIANCE under overcast sky conditions, but divergence can occur under sunny sky conditions (Reinhart and Breton 2009). Although the absolute error in a single time step was determined to have minimal influence on annual simulation results (Reinhart and Breton 2009), it may have substantial effects when considering variation of illuminance within shorter time periods. In an attempt to reduce such errors caused by the interpolation algorithm, average values were used for comparative evaluation rather than absolute values. Other sources of error could result from the inaccurate input parameters in the simulation model. It is also worth noting that there is some uncertainty inherent in any daylight prediction, as they are data samples taken from a field of energy which varies continuously over time and space (Tregenza, 2017).

It is worth noting that other methods for determining daylight availability exist, such as point-in-time simulations or physical measurements, rather than dynamic simulation. Dynamic simulation is essentially a process of constructing a mathematical model at every given time interval. One criticism is that as the study relied on computer simulation rather than physical measurements, it is not known whether the daylight performance predictions are related to real conditions. Future research efforts could be directed at providing evidence to support the reliability of data produced by the simulation. A more precise approach might be to compare daylight performance predictions with physical measurements taken in the test space. This may ultimately provide insights into what degree the simulated dataset is representative of the naturally occurring daylight conditions in the test space.

5.2.6 Simulation results

This section presents simulation results of indoor illuminance distributions for the test room, calculated with the simulation method described in previous sections. The large body of results calculated by DAYSIM was aggregated in order to provide an overall view of the daylight availability within the space. For this purpose, contour maps were created with MATLAB using the data points calculated by DAYSIM - one for every 2-minute interval during the observation period. Two sets of plots were generated for the three experiments. The first is based on displaying data from two summer experiments, with each data point representing the mean value from EX1 and EX3. The second displays data collected from autumn experiment (EX2). The data contained within the plots throughout this section are intended simply for illustration purposes. The numerical results for each individual seat are presented in Appendix I and the graphical output of the produced data in the form of contour maps is shown in Figure 5.7 – Figure 5.11, these are described in turn below.

Figure 5.7 illustrates the distribution of daylight factor (DF) across the entire room. The results show an increasing DF distribution in the central seating area varying from 0.5% to 6%, whilst in the window area the values exceed 20%. The DF levels appear to be fairly high in the window seating area compared to those found in the central seating area and the circulation areas that do not have direct access to daylight due to the rows of bookshelves. It is evident from the data that with increasing distance from the windows, daylight factors decrease rapidly to 6% over a distance 0 to 4m from the windows, then more gradually reaching a minimum at around 0.5%.



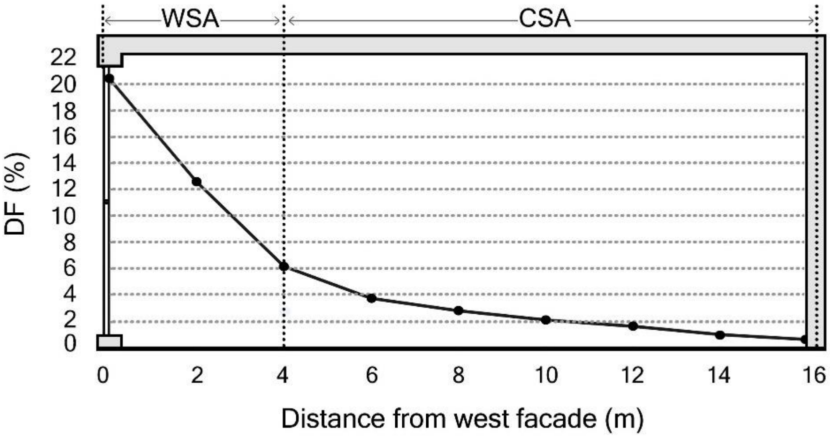


Figure 5.7. Contour map of DF levels overlaid onto the floor plan (upper) and the section through seating area showing variation of DF with distance from west facade (lower). Mean values of DF are shown for each investigated area (WSA: window seating area, CSA: central seating area).

The illuminance availability curves from raw data obtained for summer and autumn observation periods are plotted in Figure 5.8. The data revealed seasonal variations in daylight conditions, i.e. indoor illuminances tend to scatter around rather low values (<500 lux) in autumn and around rather high values (>1000 lux) in summer. It should be noted that these are the horizontal illuminance data at 2-minute intervals in aggregate over a specified period of time. That is, the contour lines are based only on values derived from the raw data representing the observation period. The mean work plane illuminance over the seating area was 3129 lux during summer and 704 lux during autumn, with the standard deviations being 2721 and 552, respectively.

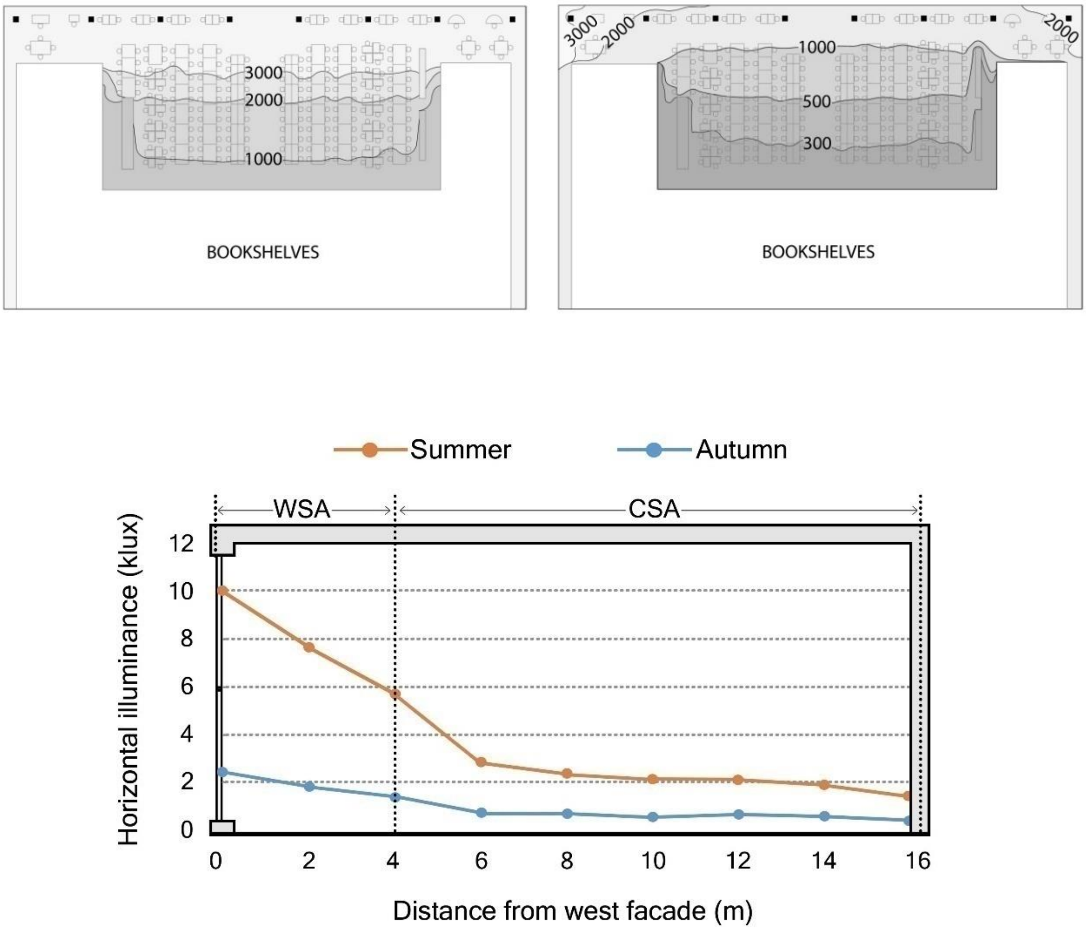


Figure 5.8. Contour maps for the reading room displaying mean horizontal illuminance on the work plane, based on 2-minute interval illuminance data calculated with DAYSIM. Summer observation period (upper left), autumn observation period (upper right), the comparison of the illuminance profiles for the two observation periods (lower) (WSA: window seating area, CSA: central seating area).

Several illuminance threshold values were observed and cumulated over the observation period and subsequently evaluated by daylight autonomy (DA) and useful daylight illuminance (UDI) matrix. This step involves the breakdown of each of the metrics with the corresponding observation period (the DA and UDI both imply a data reduction to one value each). The calculation proceeds in much the same way as the annual metrics, with the only difference that all thresholds were interpreted relative to the timestamp count of observation period (i.e. 2-minute illuminance data for a period of two weeks). This process involves the use of a two-step evaluation algorithm, which takes illuminance values on a sensor point grid as input, with defined threshold limits.

The new equivalents to the annual DA and UDI metrics are denoted as mDA for the modified daylight autonomy, and mUDI for the modified useful daylight illuminance. Assuming that the number of timesteps in a given period represented by N_p and a function defined by D(t), which is 1 for each timestep t in which a given threshold is exceeded, otherwise 0, the mDA at a sensor point can be expressed as:

$$mDA = \frac{\sum_{t=1}^{N} D(t)}{Np} \qquad D(t) = \begin{Bmatrix} 1, & D(t) \geq E \\ 0, & D(t) < E \end{Bmatrix}$$ *Equation 5.3*

where

D(t) = occurrence count of exceeding the DA illuminance threshold at time step t

N_p = timestep count for period p

E = illuminance threshold

Similar to mDA, the mUDI metric also operates with illuminance and threshold values, with the only difference being that the mUDI includes an upper illuminance threshold. The mUDI can then be expressed by a similar mathematical expression:

$$mUDI = \frac{\sum_{t=1}^{N} U(t)}{Np} \qquad U(t) = \begin{Bmatrix} 1, & Emin \leq U(t) \leq Emax \\ 0, & U(t) < Emin \\ 0, & U(t) > Emax \end{Bmatrix}$$ *Equation 5.4*

where

$U(t)$ = occurrence count of values in UDI range at time step t

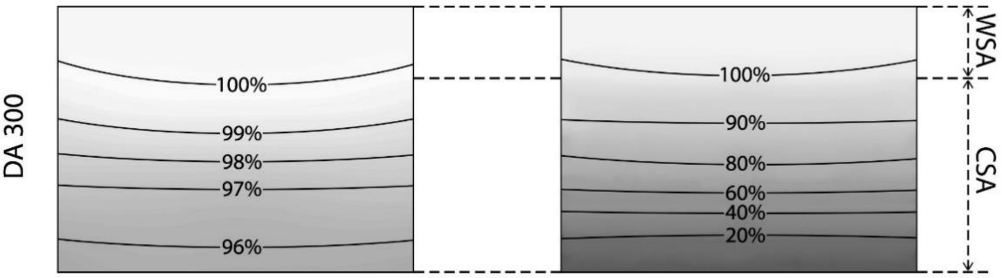
N_p = timestep count for period p

Emin = minimum illuminance threshold

Emax = maximum illuminance threshold

Each metric reveals certain characteristics of the illuminance data set: For DA, it is how often the illuminance at an individual sensor point is above a threshold, whereas for UDI, it is how often the illuminance is between two thresholds. It should be noted that these are abstract quantities that aggregate values from the illuminance time-series across space and over the observation period. For illustrative purposes, the plots in the remaining part of this section cover only those sensor points that fall within the seating area.

The illuminance data were processed to generate plots showing the distribution of DA across the seating area. The resulting distributions were visualized in a condensed format as done in the plots shown in Figure 5.9. The top of the figure shows the seating area with contour lines representing percentage of the total observation period that daylight illuminance at the sensor point exceeded the DA threshold at 2-min intervals. Assuming a work that requires a minimum desktop illuminance of 300 lux on the desk, the occupants seated in the window seating area (WSA) can potentially work by daylight alone throughout the entire observation period. In the central seating area (CSA), there appears to be a decrease in the percentage of time that daylight illuminance exceeded the threshold value of 300 lux. However, this difference between the two seating areas seems to be negligible during summer period.



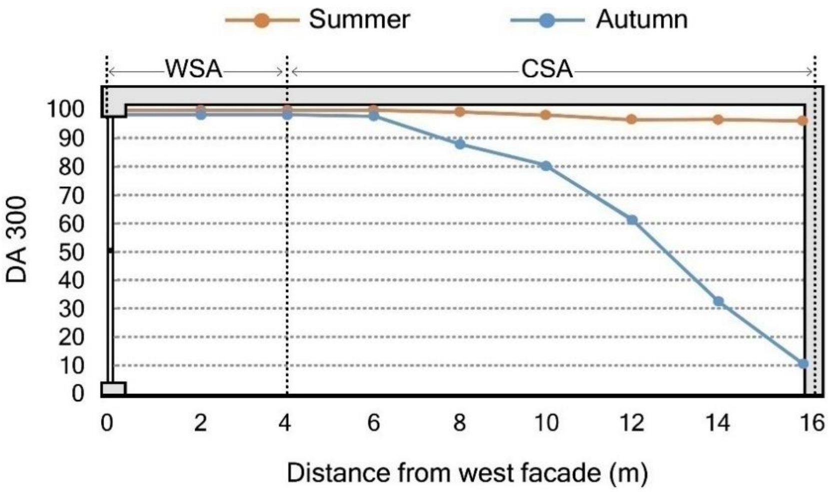


Figure 5.9. Distribution of DA on the work plane during summer observation period (upper left) and autumn observation period (upper right), and the comparison of the DA profiles for the two observation periods (lower). Contour maps show the DA distributions for the seating areas only (WSA: window seating area, CSA: central seating area).

The last plots for this section are those showing the UDI distribution across the work plane. As with the plots of DA distribution, a condensed visualization format is used. Following the approach proposed by Mardaljevic (2015), the UDI scheme was applied by determining at each sensor point the occurrence of daylight levels where the illuminance is:

- less than 100 lux: UDI not achieved (UDI-n)
- greater than 100 lux and less than 300 lux: UDI supplementary (UDI-s)
- greater than 300 lux and less than 3000 lux: UDI autonomous (UDI-a)
- greater than 3000 lux: UDI exceeded (UDIx)

Figure 5.10 shows occurrence of the four UDI metrics averaged across the seating area for the two observation periods, summer and autumn.

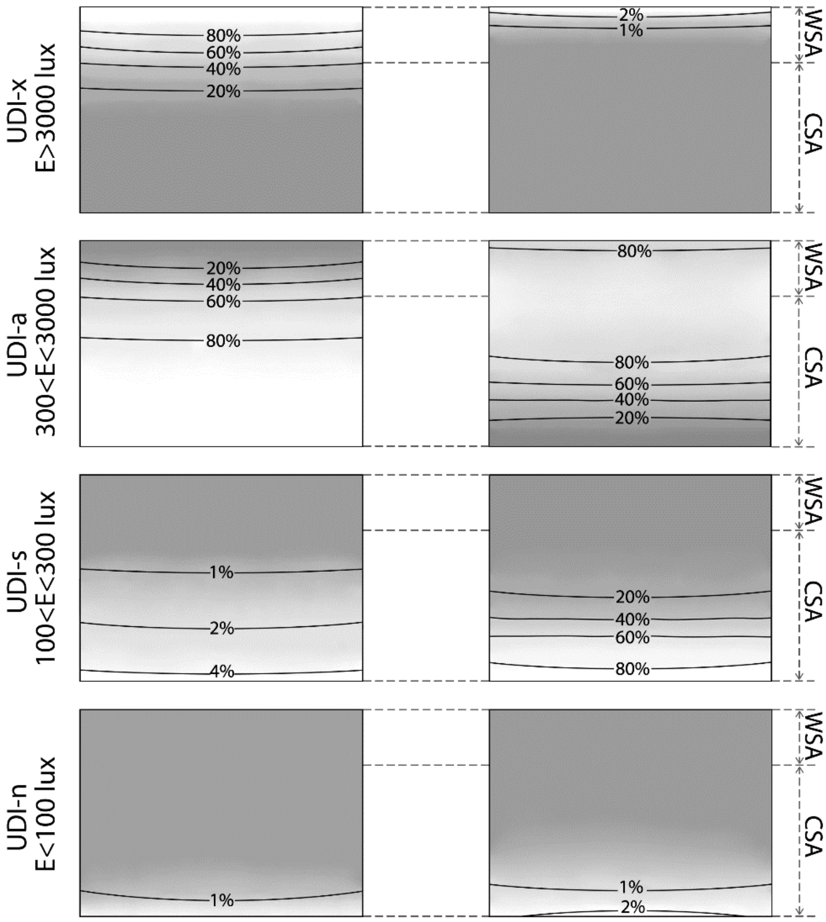


Figure 5.10. Distribution of UDI on the work plane during summer observation period (left) and autumn observation period (right). Note that contour maps show the UDI distributions for the seating areas only (WSA: window seating area, CSA: central seating area). UDI-x: UDI exceeded, UDI-a: UDI autonomous, UDI-s: UDI supplementary, and UDI-n: UDI not achieved.

The results show that the useful range of 300 to 3000 lux (UDI-a) was mostly found in the central seating area during summer period, whereas during autumn period, the distribution of these levels of illuminance was found to be shifted towards the window seating area. This suggests that occupants seated in these areas were most likely able to work comfortably without artificial light. Another range that is considered useful for the occupants is UDI supplementary (UDI-s), which gives the occurrence of daylight illuminances in the range 100 to 300 lux. Reading from the contour plots, the criteria for UDI-s were met in the central seating area during autumn period, whereas illuminances during summer period only occasionally fall within the UDI-s range. These data indicate that supplementary artificial light was likely to be needed by the occupants seated in the central seating area during autumn period. Taken with the results from the UDI-a plots, this suggests that a much greater proportion of the central seating area remains in the useful range of 100 to 3000 lux in summer than in autumn.

An examination of the data outside the useful range did not show any noticeable differences in occurrence of UDI not achieved (UDI-n). The values for both observation periods were very low (close to zero), indicating that the illumination level was never less than 100 lux, where the light would be considered insufficient without electric lighting. Given the upper threshold value of 3000 lux, a high occurrence of UDI exceeded (UDI-x) was found in summer, whereas in autumn the values were close to zero. This is to be expected given the higher illuminance levels in the summer dataset, with significantly more data points exceeding 3000 lux. Note that the DA value for an illuminance of 300 lux is very similar to UDI-a, with the only difference being that the UDI-a includes the occurrence of exceedances of an upper illuminance limit (3000 lux). The data were further processed and reduced in the plot presented in Figure 5.11 by taking the mean value of the four sets of UDI metrics in an attempt to summarize the overall changes in daylight performance during the two observation periods.

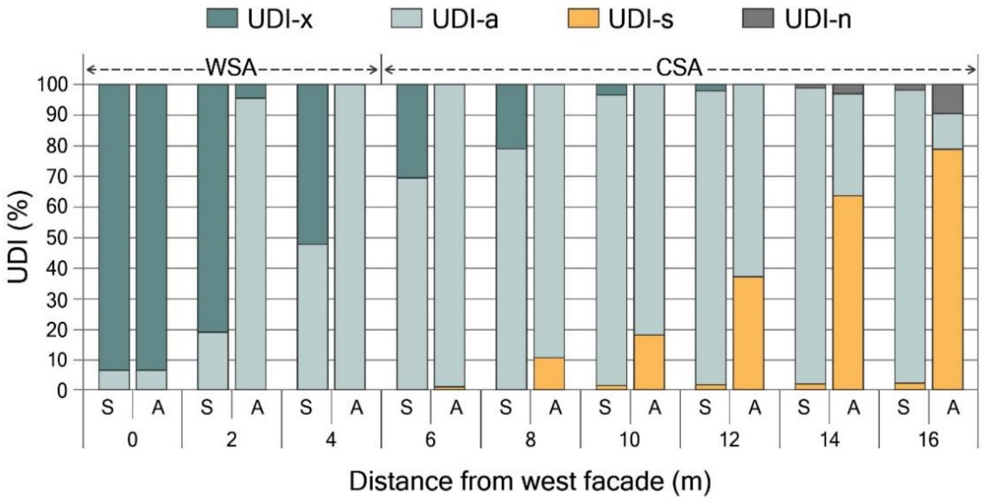


Figure 5.11. Stacked bar plot showing the distribution of UDI, with results averaged over the seating area for the two datasets: Summer (S) and Autumn (A). (WSA: window seating area, CSA: central seating area) (UDI-x: UDI exceeded, UDI-a: UDI autonomous, UDI-s: UDI supplementary, and UDI-n: UDI not achieved). Based on Figure 5.10, UDI contour plots.

While each of the metrics has been discussed separately, it is important to note that they may produce similar distribution patterns. For example, the DF and DA plots share a similar character in the overall form of the distributions, with higher values in the window area and lower values in the central area. However, the form of the distribution of UDI changes seasonally, in response to the availability of daylight. It can be seen in the respective plots (Figure 5.10 and 5.11) that the UDI distribution (100-3000 lux) follows a pattern that is almost the inverse of the DF or DA patterns in summer: lower UDI values in the window area and higher UDI values in the central area.

The UDI exceedance plot for the summer dataset reveals that illuminances greater than 3000 lux are expected for at least 40% of the observation period for window seating area. These levels of illumination are likely to be indicative of visual discomfort through glare. In autumn, however, the UDI range is split between the two seating areas, with increased occurrence of UDI-s in the central area and decreased occurrence of UDI-a in the window area. It can be seen that the increase in UDI-s in central area is due mostly to the reduced occurrence in UDI exceedances (i.e. lower occurrence of illuminances greater than 3000 lux).

On a final note, the contour plots presented in this section produce an estimate of the daylight availability, and thus should not be regarded as definitive. Given the inherent variability of daylight, it is not possible to state precisely how much light falls on a given surface at a given point in time, although, based on data obtained in previous validation studies, the simulation approach seems to produce fairly robust estimates of daylight availability for the given time period. The metrics are relatively straightforward measures to derive from simulated data. It should be noted, however, that different conclusions may have been drawn if a different set of thresholds was used. Thus, investigations at this stage are, necessarily, exploratory in nature.

5.3 Comparative analysis of simulation results and occupancy data

This section presents the results of a comparative analysis between simulation results and the occupancy data. In order to provide a relevant basis of comparison between the simulations and the conditions present when the occupancy observations were carried out, the simulated data were extracted for each core work plane sensor representing the period of observation; and these were subsequently correlated with corresponding occupancy data. Two approaches were used to determine the occupancy (see Chapter 4); it was therefore decided to split the analysis into two parts, dealing first with the snapshot data and then with the walk-through data.

5.3.1 Analysis of snapshot data

This section analyses occupancy rates recorded for each individual seat during snapshot observations. The data were examined to determine whether they appeared to be drawn from a normal distribution by inspecting the Shapiro - Wilk test and the residual distributions (see Appendix J). Three separate tests of normality were performed on the data for each experiment, but also for each seating area, these being the window and central seating areas.

The Shapiro - Wilk test indicated that the data are not drawn from a normally distributed population in most cases ($p < 0.05$), however this is to be expected as the two seating areas are different from each other in terms of daylight and occupancy distribution. The linear models assume that errors, also called residuals or deviations from the fitted model, are normally distributed (Altman, 1991). It is important to examine the normality of the residuals because it describes how the variation, which is not explained as part of the linear predictor, is distributed. An examination of the distribution of residuals revealed normality for some of the datasets, and parametric statistical tests have been applied in such cases. For non-normal data distributions, median values are reported and nonparametric tests have been used as a means of comparison. The occupancy rate calculated for each individual seat was used as a metric. A series of comparisons were then made between occupancy rates and daylight metrics in each experiment. The analysis was confirmed through comparison of correlation coefficients for each pair of variables as in Table 5.4.

Table 5.4. Correlation coefficient and significance level for the relationship each daylight metric has with occupancy rate (OR). DF: Daylight Factor, E_h: Horizontal Illuminance, DA: Daylight Autonomy, UDI: Useful Daylight Illuminance.

Dataset	**Variables**	**EX1**		**EX2**		**EX3a**	
		Correlation coefficient	Sig. level	Correlation coefficient	Sig. level	Correlation coefficient	Sig. level
Whole dataset n=250	DF - OR	0.78	**< 0.001**	0.69	**< 0.001**	0.79	**< 0.001**
	E_h - OR	0.74	**< 0.001**	0.65	**< 0.001**	0.73	**< 0.001**
	DA - OR	0.15	**0.019**	0.39	**< 0.001**	0.20	**0.011**
	UDI - OR	- 0.64	**< 0.001**	0.29	**< 0.001**	- 0.54	**< 0.001**
WSA n=32	DF - OR	0.65	**< 0.001**	0.76	**< 0.001**	0.67	**< 0.001**
	E_h - OR	0.50	**0.003**	0.38	**0.033**	0.54	**0.001**
	DA - OR	-	-	0.06	0.740	-	**-**
	UDI - OR	- 0.34	0.060	- 0.35	0.051	- 0.36	0.077
CSA n=218	DF - OR	0.01	0.917	0.12	0.077	0.07	0.252
	E_h - OR	0.01	0.915	0.13	0.059	0.08	0.215
	DA - OR	0.02	0.822	0.15	**0.022**	0.10	0.130
	UDI - OR	- 0.01	0.879	0.16	**0.020**	- 0.02	0.795

Note: Values in bold are those where $p < 0.05$ (two-tailed).

A graphical representation of the most highly correlated measures (DF – OR in the whole dataset) is shown in Figure 5.12, with each line representing a separate set of data (EX1, EX2, EX3). Visual inspection of this plot reveals the expected pattern of occupancy rate increasing with daylight factor in the three experiments. However, the data points at the higher levels of DF appear to be influential (see the rightmost data points), affecting regression lines. These trends were verified using Pearson's correlation tests as shown in Table 5.4. The correlation between daylight factor and occupancy rate was found to be statistically significant in all three experiments (n=250, $p < 0.05$). However, applying correlation analysis that excludes those data points at the higher levels of DF (>10%) decreases the strength of correlation experienced (DF – OR in the CSA dataset). The correlations are far from significance in this case (n=218, p-values range between 0.077 and 0.917). For this latter case, note that data are not normally distributed in EX1 and EX3 so the Spearman's rank correlation test has been used to confirm the trends.

What these findings show is that the data points at the higher levels of DF, which are found in the window seating area (n=32), greatly influences correlation analysis, including the correlation coefficient (r) and the statistical significance of correlations (p). This explains the finding discussed earlier in Chapter 4, that any influence of daylight on occupancy rate is far less clear in the central seating area, but there is a suggestion that a higher daylight factor near the window may result in a higher occupancy rate.

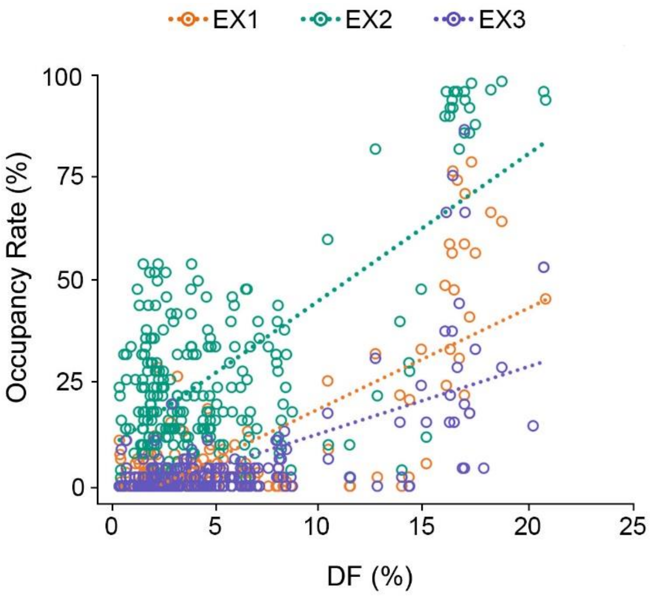


Figure 5.12. Occupancy rate plotted against daylight factor. Data for the entire seating area are shown. (a) EX1, (b) EX2 and (c) EX3.

Figure 5.13 shows a scatterplot of the relationship between the mean horizontal illuminance across each observation period and occupancy rate for that same period. Applying the same procedure to the data demonstrated similar patterns to those displayed for the daylight factor. As might be expected, the occupancy rate tends to increase as the horizontal illuminance increases, and the effect is influenced by the data points found in the window seating area. There also appears to be seasonal patterns in these data: the summer data tend to follow a similar pattern (EX1 and EX3), whereas the autumn data (EX2) deviate from that pattern. These findings were supported by a Pearson’s correlation test between the mean horizontal illuminance and the occupancy rate which showed the correlation to be significant in all three experiments ($n=250$, $p < 0.05$). The correlation coefficients for these data were found to be very nearly the same as those reported for daylight factor data (see Table 5.5). When data for the two seating areas are considered separately, the results again demonstrate that the correlations are not statistically significant in the central seating area dataset.

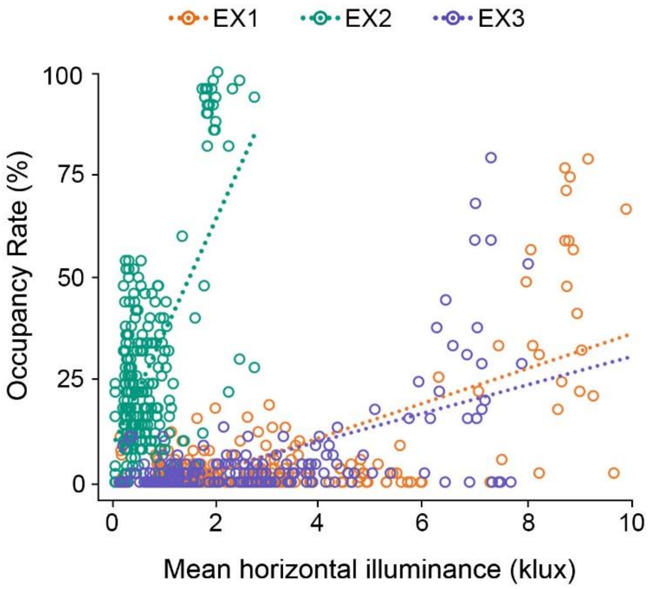


Figure 5.13. Occupancy rate plotted against mean horizontal illuminance. Data for the entire seating area are shown. (a) EX1, (b) EX2 and (c) EX3.

A further comparison was made with dynamic metrics to evaluate the cumulative effects of daylight on occupancy over time. The evaluation founded on the cumulative approach does not appear to have as strong of an association with the occupancy rate as does daylight factor or horizontal illuminance. If the illuminance preferred by occupants was within the useful range of 300–3000 lux, for example, a positive correlation would be found between UDI and occupancy rate in each experiment. The results presented in Table 5.5 suggest that this is not always the case, and that for the summer period (EX1 and EX3), there is a negative correlation between UDI and occupancy rate, which is statistically significant (n=250, $p < 0.05$). This is to be expected because the distribution of useful range of 300–3000 lux across the room is widely scattered in autumn, unlike in summer in which the data tends to be clustered around the central seating area (see Section 5.2.6 for UDI distribution). What is evident in these data is that the distribution of UDI inversely correlates with that of occupancy in the summer experiments. This means that the seating preferences of the majority of occupants do not correspond to the UDI levels and that the illuminance levels in the preferred areas fall outside the useful range (i.e. more than 3000 lux). This supports previous findings that the occupants preferred seats with high daylight despite the risk of glare.

When considering the central seating area dataset, the findings fail to support a statistically significant correlation of UDI with occupancy rate, with the exception of the correlation found in EX2 which is significant (n=218, $p < 0.05$). The lowest correlations were found for daylight autonomy, suggesting that daylight autonomy distributions do not necessarily correspond to the preferred seating areas. With regard to the significance of correlation, daylight autonomy gives similar results to those obtained with UDI. Note that for the WSA dataset the test failed to produce any results for daylight autonomy in EX1 and EX3, because data values were constant in these two experiments. When drawing conclusions from the simulation model, the effect of electric lighting should be noted as the findings relate only to daylight conditions. The simulations did not consider the illuminance data generated from the electric lighting system, which might partially account for the association between daylight autonomy and the occupancy rate. When electric lighting illuminance is added to the daylight data, there is a slight tendency for the strength of daylight autonomy-occupancy rate correlations to decrease in all datasets, with the exception of window seating area. This may have been because the window seating area is predominantly lit by daylight and under such conditions electric lighting is unlikely to have an effect. The fact that electric lighting contributes little to horizontal illuminance in the window area is also informative about the seat choice behaviour as it is indicative that the occupants chose window seats on a basis other than that of electric lighting. The electric lighting system does not allow light levels to fall below the minimum illuminance threshold of 300 lux at certain points in the central seating area. This will be examined further in Section 5.3.2.

Although correlations were significant for most of the comparisons (less than 0.05), the nature and context of the experiments should be taken into account when interpreting these results. If, in the present study, those data points at higher levels of daylight (window seating area) had been excluded from the analysis, there would have been no statistically significant correlations. This suggests that the results should be interpreted alongside other information about seating behaviour. As discussed in Chapter 2, seat choice may also be affected by other factors not examined in this thesis, such as the outside view. Based on the snapshot data, the analysis provided some evidence of the link between daylight availability and where people sit. However, results from this analysis should be interpreted with caution, because as evident by examining the relationship between the variables, variations in occupancy rates cannot be explained by daylight alone. That is, the correlation between daylight metrics and occupancy rate does not imply causation, as there are other dimensions of behaviour that could partly account for the correlation. For example, sitting by the window may often have an association with being able to see nature outside the window, and it may be this connection to the outside that influences the seat choice behaviour rather than the daylight itself.

5.3.2 Analysis of the contribution of electric lighting

The simulation approach might cause loss of accuracy as the impact of electric lighting is ignored. The results from daylight analysis suggest that there is a nonlinear gradient of daylight across the workplane and that the amount of daylight drops sharply as the occupants move away from window area through the central area. The results revealed seasonal variations of daylight, with higher values of illuminance in summer and lower in autumn. Notable findings included lower levels of daylight illuminance in the parts of the room distant from the window in autumn. While the illuminance profiles varied between the two seasons, the occupancy patterns were similar. One explanation could be that electric lighting provides additional task light during autumn when daylight is insufficient, and therefore allow occupants to carry out tasks or sit in locations they perhaps would not otherwise have done. It may be that the illuminance from daylight and electric lighting together achieved the recommended light levels. To create a better understanding of how electric lighting and daylight are distributed in the space further analysis was carried out on the horizontal illuminance values.

A simple calculation was performed to estimate the potential contribution of electric lighting system to total illuminance. The total illuminance level of a sensor point is equal to the sum of the illuminance levels created by daylight and all contributing electric light sources at this point. The total illuminance at a sensor point (P) can then be expressed as:

$$E_T(P) = E_D(P) + E_E(P) \qquad \textit{Equation 5.5}$$

where

$E_T(P)$ = total illuminance

$E_D(P)$ = daylight contribution to total illuminance

$E_E(P)$ = illuminance when the electric lights are switched on and there is no daylight

The lighting system in the room consisted of ceiling-recessed luminaires controlled by an automatic lighting control system. The illuminance from electric lighting was determined for each sensor point after dark (see Section 5.2.4 for the location of sensor points at which illuminance measurements were taken). The mean work plane illuminance from electric light was 170 lux with a standard deviation of 61 lux. Figure 5.14 shows the relative contributions of daylight and electric lighting to total illuminance.

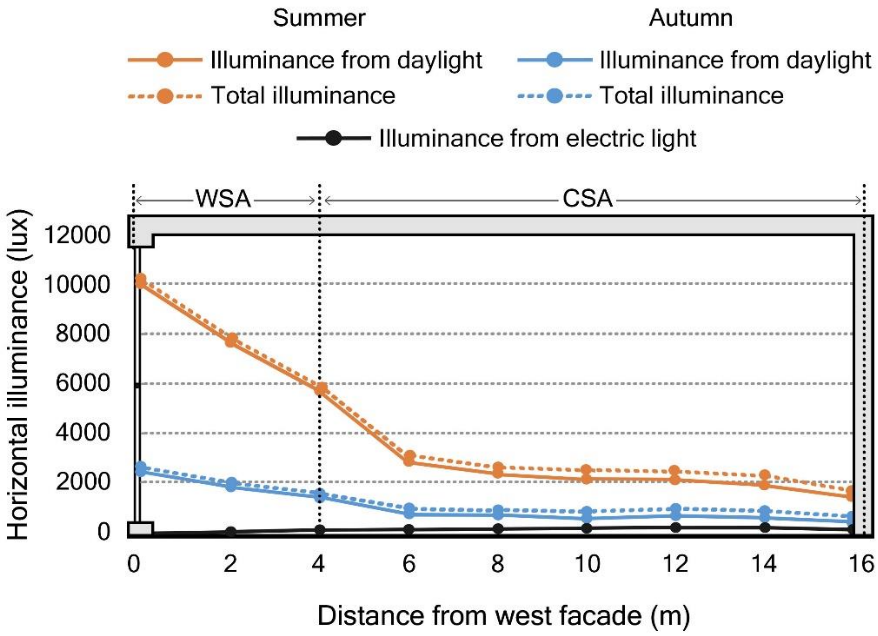


Figure 5.14. Contribution of electric light to the total illuminance on the work plane. Mean values are displayed. (WSA: window seating area, CSA: central seating area).

As shown in Figure 5.14 the presence of electric light during daytime had very little effect on illuminance levels in the room. The mean illuminance on the work plane from electric light sources ranged between 11 and 264 lux. There seems to be little difference in the electric lighting levels between window area and central area. As daylight illumination decreases, electric lighting appears to contribute more to the total illumination. For example, in parts of window area where the mean desktop illuminance from daylight was 1800 lux in autumn, the mean electric light contribution was 60 lux. In the central area, where mean desktop illuminance from daylight was 350 lux, the mean electric light contribution was 190 lux. This suggest that electric lighting had the largest effect on total illumination during autumn when daylight illumination levels were low in the central area.

Electric lighting increases light levels but does not change the shape of the distribution, meaning that the effect on total illuminance is due to the variations in daylight availability. The luminaires are arranged in such a way that the daylight character of the room is retained. The results from this investigation suggest that the illuminance from daylight was enough to provide the required illuminance for the task during the observation period and that the electric lighting provided additional illuminance in autumn where daylight illuminance was low in the parts of the room distant from the windows.

5.3.3 Classification of snapshot data based on sky conditions

As described in Section 5.5, DAYSIM uses Perez all-weather sky model for the generation of sky luminance distributions based on measured irradiance data. Dynamic metrics are calculated based on customized luminance distributions predicted by the Perez all-weather sky model, while the daylight factor is calculated with the standard overcast sky. The daylight factor approach is therefore only applicable in overcast sky conditions and takes no account of variations in the sky luminance distribution.

The daylight factor data derived from the simulations is valid only in cases where the actual weather conditions during the observation period match those of the overcast sky conditions. What needs to be considered is how well the overcast sky represents the actual weather conditions. This may ultimately provide justification for the use of daylight factor metric, but it may also suggest that alternative metrics should be used. One method for identifying overcast sky conditions is to compare the clearness index based on the solar radiation data recorded at the weather station. The clearness index is defined as the ratio between the global horizontal irradiance and its extraterrestrial value (Li and Lam, 2001; Liu and Jordan, 1960). The extraterrestrial radiation is the solar radiation incident at the top of the atmosphere, and it can be determined based on solar geometry and a knowledge of the solar constant (1367 W/m²) (Muneer, 2004). Given that the earth has an elliptical orbit around the sun, the extraterrestrial radiation varies by ±3.3% around the mean, reaching maximum values in January and minimum values in July. The extraterrestrial normal radiation is defined as follows:

$$G_{on} = I_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \qquad \textit{Equation 5.6}$$

where

G_{on} = the extraterrestrial normal radiation

I_{sc} = the solar constant of 1367 W/m^2

n = the day of the year (a number between 1 and 365)

The extraterrestrial horizontal radiation can be described using Equation 5.7.

$$G_o = G_{on} \cos(\text{SZA}) \qquad \textit{Equation 5.7}$$

where

G_o = the extraterrestrial horizontal radiation

G_{on} = the extraterrestrial normal radiation

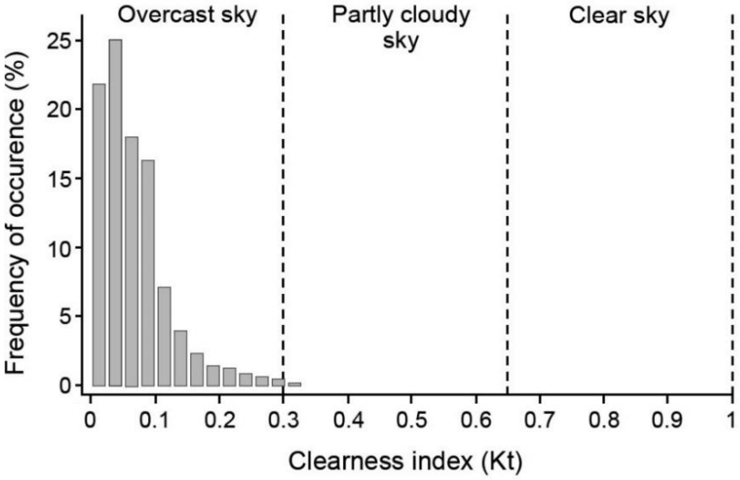
SZA = the solar zenith angle calculated at a given time

The time series of measured global horizontal irradiance in combination with information on extraterrestrial horizontal radiation at each time step were used as the basis for prediction of the clearness indices. The clearness index is essentially a measure of the relative clearness of the atmosphere, and is scaled to range from 0 to 1 with lower values indicating overcast skies. Following the work of Alves et al (2013) and Gueymard (2011), solar radiation data for the observation period were analyzed separately for three different Kt ranges: clear (0.65 < Kt ≤ 1), partly cloudy (0.3 < Kt ≤ 0.65) and overcast sky conditions (0 < Kt ≤ 0.3). The results are reported in Table 5.5.

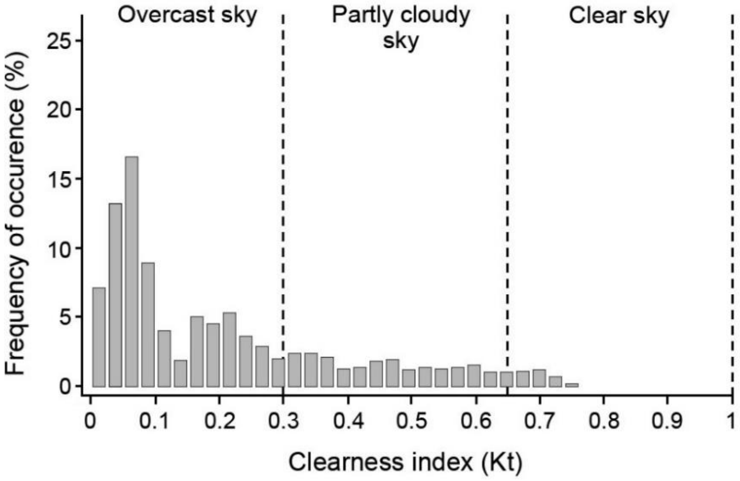
Table 5.5. Definition of the three sky ranges as defined by clearness index (Kt) (EX 1= Experiment 1, EX 2= Experiment 2, EX 3= Experiment 3).

Sky clearness range	**Description**	**Number of records**		
		EX1	**EX2**	**EX3**
0.65 < Kt ≤ 1	Clear sky	52 (3%)	0 (0%)	37 (3%)
0.3 < Kt ≤ 0.65	Partly cloudy sky	783 (43%)	63 (3%)	426 (35%)
0 < Kt ≤ 0.3	Overcast sky	975 (54%)	1747 (97%)	742 (62%)

A histogram of the clearness index recorded during the observation period is given in Figure 5.15. The plots provide a graphical representation of the frequency distribution of clearness index for the two observation periods, autumn and summer, and led to the identification of periods with overcast sky conditions. While autumn period is characterized by the lowest clearness indices, the summer period shows in general the highest values. The long tail of the distribution observed in the autumn dataset suggests that the majority of clearness index values fall within the range of 0 to 0.3, which is representative of overcast sky conditions. In the autumn period there were only a few instances when the sky was partly cloudy, and there was no record found for clear sky conditions.



(a)



(b)

Figure 5.15. Histogram of the clearness index for the two observation period. (a) Autumn; (b) Summer.

The results suggest that a seasonal variation in the frequency distribution of clearness index exists: the percentage of overcast skies range from 58% in summer to 97% in autumn, reflecting clearer sky conditions in summer. The percentage of partly cloudy skies range from 3% in winter to 39% in summer. Clear sky was only observed in summer which is about 3%. In the summer period, it seems to be less cloudy than that in the autumn period when the overcast sky conditions tend to predominate for much more of the time.

As far as the daylight factor method is concerned, these findings suggest that the simulation model tended to underestimate daylight illumination levels in the test room, particularly in summer when sky conditions were characterized as predominantly clear. As a result, the daylight factor method is likely to produce accurate results for the periods of overcast skies but underestimates interior illumination under clear and partly overcast conditions.

5.3.4 Analysis of walk-through data

The data produced by the snapshot observation approach and daylight analysis confirmed that the occupants preferred seats with high levels of daylight in spite of increased risk of glare, particularly during summer period when illuminances exceeded the upper limit of 3000 lux. The finding that occupants were likely to tolerate potential glare when they were seated near windows is consistent with what previous studies have found (Christoffersen et al, 2000; Parpairi et al, 2000; Kim and Wineman, 2005; Dubois et al, 2009; Othman and Mazli, 2012; Wang and Boubekri, 2009). It should also be noted that other research has produced results that question the relatively high tolerance to glare, particularly when the window offers an interesting view. For example, Tuaycharoen and Tregenza (2005; 2007) investigated the effects of window views on perceived discomfort glare, and found that a window with an interesting view is associated with less glare than a window with a view of less interest. These results were interpreted as demonstrating how the visual content of the view through the window extended subjects’ tolerance level of discomfort glare.

Given the potential role of outside view as a mediating or an enhancing factor, the glare tolerance found in the current study could be attributed to the view of a natural setting seen through the windows. That is, the view of Weston Park may have increased the tolerance to high illuminances near windows. An interesting issue to be examined would be whether the choices made and their evaluations would differ depending on how they were experienced with a different view (i.e. man-made rather than natural setting). It remains, therefore, an open question whether seat choice depends on the visual content of the view through the window. This is likely to be an important area for future research on daylight and seat choice.

Since the choice of seating is inherently a dynamic process, it could be argued that the preference of an individual is influenced by the conditions of sequential choice. As people enter the room they are seated sequentially; and each individual can choose only from among the available seats. In this section, further analysis of occupancy data was carried out to compare results from the walk-through approach to determining the impact of this dynamic process on individuals' choices. The question examined is whether there was any available seat in the area with high levels of daylight (the window seating area) when people chose their seats.

Comparison of datasets using statistical tests was not possible for the occupancy rates as these values were already a summary statistic based on the occupancy data over a time period. Therefore, an alternative approach to analysing occupancy was adopted that would allow statistical analysis to be carried out. In this approach an availability ratio was calculated for each occupant, based on the percentage of seats occupied in the window seating area, and this was used as a metric. For example, if an occupant chose a seat in the central seating area, and there were 25 seats available seats (out of 32) in the window area at the time of decision making, then the availability ratio would be 78% for that occupant. In this example, the occupant had the option of choosing a seat with better daylight if that was a critical factor in seat choice, but chose not to do so. If the sequential process had an effect on seat choice, it was expected that the availability ratio would be low (the window seats were full therefore people were forced to sit in the central area).

The analysis has been extended where each day was divided into sub-periods to distinguish between the effects of time of day. In doing this, the daily dataset was split into three, covering the periods 09:00-12:00 (morning), 12:00-14:00 (midday), and 14:00-17:00 (afternoon). For the full set of data in both seating areas, Table 5.6 displays the mean and standard deviation for the availability ratios calculated for each occupant. Data for the three time periods are considered separately and for each the values given represent the means of the entire observation period.

Table 5.6. Mean and standard deviation for the availability ratios calculated for CSA (n=102) and WSA (n=101).

Time of day	CSA		WSA	
	Mean	Standard deviation	Mean	Standard deviation
Morning	82.08	9.39	98.61	1.23
Midday	58.27	13.84	96.51	1.19
Afternoon	44.03	11.38	93.57	3.14
Total	57.59	20.08	96.64	3.01

A distribution of availability ratios calculated for each occupant seated in the central seating area is presented in Figure 5.16, with each line representing the data for each day of the observation period. The figure highlights three different times of the day and what may be observed at these times during the observation period. The number of occupants can be determined by the number of data points in the graph. When there were many available seats in the window seating area (i.e. higher availability ratios), for example, in the morning, fewer occupants were seated in the central seating area (19%). When the window seating area had a limited amount of seating available (i.e. lower availability ratios), for example, in the afternoon, the number of occupants seated in the central area was much higher (64%).

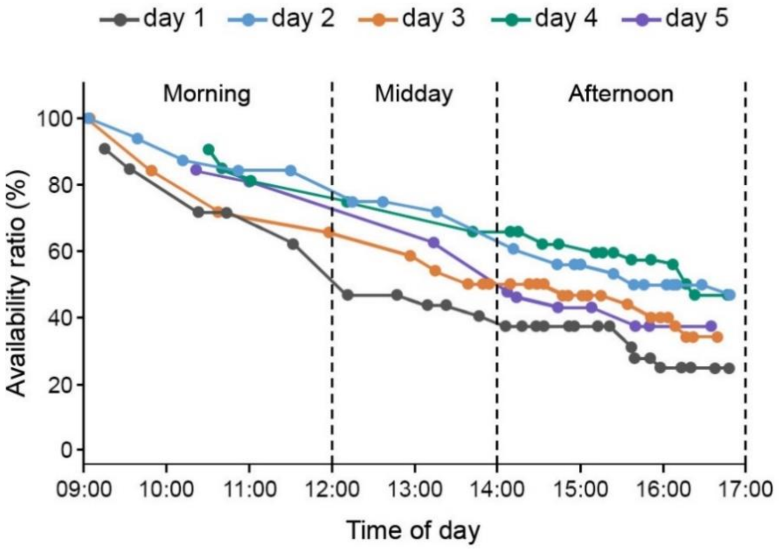


Figure 5.16. Availability ratios as a function of time of day. Each data point represents one participant's availability ratio (n=102). Data for window seating area (WSA) are shown.

These data show that during the morning period, there were a few seating locations in the central seating area identified as preferred even though the availability ratios were high during this period (there were seats available in the window seating area). However, differences were found in the number of occupants in each time period, with a notably higher number of people in the afternoon than in the morning. These results suggested that the availability may have distorted seating preferences of occupants: lower availability ratios late in the afternoon may deter occupants from using the window seats that they otherwise would prefer.

The next stage of analysis was to compare the data obtained from window seating area to determine whether availability ratios were different than those found in the central seating area. In doing this, availability ratios were calculated for each occupant seated in the window area based on proportions of available seats in the central area at the time of seating. The resulting values are plotted against time of day as in Figure 5.17. Each data point represents one occupant for which an availability ratio was calculated.

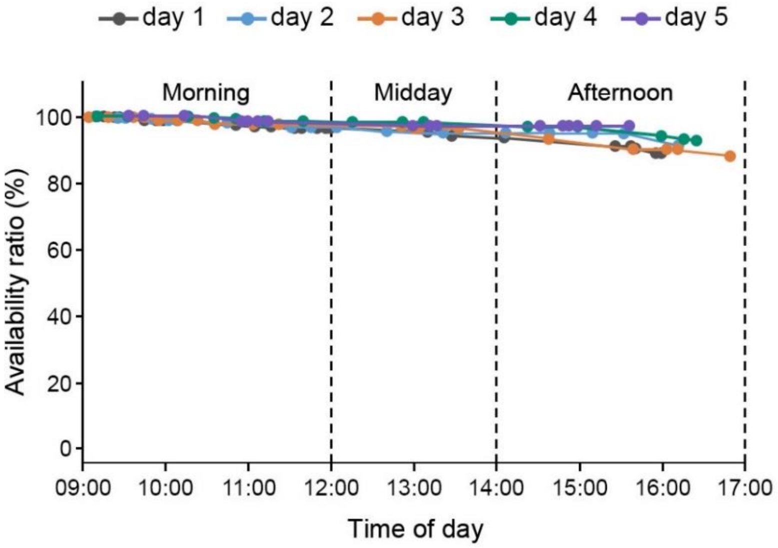


Figure 5.17. Availability ratios as a function of time of day. Each data point represents one participant's availability ratio (n=101). Data for central seating area (CSA) are shown.

There does not appear to be any noticeable difference between the three time periods in terms of seat availability in central seating area. In contrast to the case in the first analysis, availability ratios generally seem higher. This is as would be expected given that occupants tend to sit in the window seating area regardless of the amount of seating available in the central seating area at any given time. As far as the window area is concerned, seat availability in the central area appears to have had a negligible effect on the seat choice.

The results produced by the analysis of walk-through data demonstrated that availability of window seats is likely to have an influence on seating decision. Preferences for each seating areas and availability ratios were determined to test if seat use was associated with availability (i.e. if seats were used or avoided at a level commensurate with their availability). To check whether any such effects occurred during the observation period the calculations were repeated for the two seating areas (CSA and WSA). This allowed direct comparison of the availability ratios between the two seating areas. The experiment found an effect of availability but only in the central seating area, with a lower availability ratio in the afternoon (i.e. low amount of seating available in the window area) resulting in increased number of people seated in the central area.

5.4 Summary

The goal of the work described in this chapter was the accurate simulation of the quantity and distribution of daylight in the test space. The methods of modelling and simulation were described along with their limitations and restrictions. RADIANCE-based DAYSIM simulation method was used to predict sub-hourly time series of daylight illuminance based on direct and diffuse irradiances taken from the weather file. To determine daylight levels for the observation period, a modified version of climate-based daylight simulation approach was adopted. The approach included a breakdown of each established daylight metrics with the corresponding time period and the illuminance threshold. This enabled the evaluation of indoor daylight availability over a specific period of time, including the occurrence of excessive or insufficient illuminances.

In the second part of the chapter occupancy data were analysed to explore the relationship between seat choice and daylight performance metrics. A range of metrics were analysed to find out if any daylighting characteristics mattered more than others to seat choice. Daylight levels considered 'useful' were mostly found in the central seating area. Nevertheless, occupants tended to prefer window seating area where they were exposed to greater amounts of daylight and potential glare, particularly in summer. Consistent with the findings of the previous studies, this work revealed that individuals who sit near windows tend to be tolerant towards discomfort glare, and this is assumed to be related to the interesting content of the window view in which the natural environment is dominant.

One limitation of previous research is it is unable to confirm whether seat availability is of significance or relevance to the seat choice. This limitation makes it difficult to interpret results from previous research on seating behaviour in terms of the effects of seat availability. In the current study, this was investigated using walk through data which enabled the availability ratio to be calculated for each individual occupant. Results from the two seating areas were compared. It was found that the availability of seats in the window seating area decreased rapidly over time, resulting in an increase in the number of occupants seated in the central seating area in the afternoon. This suggests that seat choice behaviour is driven by prior states of the room such as the number of occupants in the window seating area. The next chapter discusses the implications of the findings from these experiments and future areas of research required.

CHAPTER 6. DISCUSSION

6.1 Introduction

The research reported in this thesis has investigated the relationship between daylight and seat choice in an open-plan library reading room. An examination of the literature revealed an overall tendency for people to sit near windows where they were exposed to high levels of daylight. A series of experiments was designed to provide further evidence about the relationship of daylight and seat choice; and two approaches were taken to provide such evidence. The first, the stated preference approach, was to ask individuals how daylight conditions affect their seat choices. The data were collected by means of questionnaires, the aim was to understand the relative importance of daylight to seat choice alongside other factors. The second, the revealed preference approach, was to record actual seating behaviour over a period of time. The frequency of seat use was then quantified as an indicator of preference by occupants. Predictions of illuminance distributions within the room were made using a RADIANCE-based DAYSIM simulation tool, and a set of performance metrics were explored with respect to their potential in predicting occupancy patterns found in the test room. This chapter provides a discussion of the main findings from the experiments and their implications in relation to previous research.

6.2 Stated preference surveys

Stated preference method provided respondents with a set of response options in a randomised order and asked them to express their preferences by selecting among the given options. The door-room survey explored differences in the perceived importance of daylight across two groups, with participants in one group being those who were about to enter the room while participants in the other group being those seated in the room. When asked to select three most important factors out of the listed ten factors that potentially influence their decision on where to sit, the majority of respondents in the door survey stated that the availability of power socket was the most important factor, followed by noise and daylight. Those who were seated in the room tended to state that daylight was the most important factor for their seat choice, followed by noise and distance from others.

Statistical tests suggested that room survey responses differed significantly from the door survey for the two items, the one being availability of power sockets and the other being distance from others. The availability of power sockets was significantly less important to the participants in the room survey than those in the door survey, whereas distance from others showed opposite patterns of change between two groups of participants. One possible explanation for this discrepancy is that although the availability of power sockets was considered to be an important factor before entering the room, when seated at a desk without a power socket it was not stated to be important. What this suggests is that the item concerning power sockets is less likely to be chosen in the room survey simply because power sockets are often not accessible, regardless of how important the participant perceives it to be. This gives an indication that the perceptions actually experienced as a result of the outcome of a seat choice may not concur with earlier expectations, leading people to look for justifications for their choice. Likewise, being distant from others was perceived to be more important by respondents of room survey than those of door survey, possibly reflecting the individuals' tendency to sit away from each other upon entering the room.

As a means of validating the method of questioning, the room survey asked respondents to define each of the ten items as important or not important. By having responses from both multiple-option and importance questions, it was possible to compare the responses to each item. Multiple-option data was in good agreement with that obtained from importance analysis, as indicated by a Pearson correlation value of 0.76 for the two datasets. These data indicate that participants think daylight has an effect on their seat choice without the questioning method having led them in this direction. The close agreement of the two sets of results thus contributes to validating the findings. The importance questions consisted of two parts, asking participants to give more details about their response. The objective of the second part was for participants to give reasons to support their answers. The room survey also sought to explore whether, and if so why, participants changed their seat locations. The reason most frequently mentioned was the availability of power sockets. This is as would be expected given that some participants were able to access to power sockets, whereas others were not, and this may have played a part in changing seat locations. Participants were also asked to make comments at the end of the survey. This provided parallel support for the investigations that may have biased respondents to indicate the importance of daylight; for example, by choosing from the rather limited set of options.

To summarize, the stated preference study provided evidence on the perceptions of the participants regarding the conditions that influenced their choice of seating location. The experiment aimed to explore the perceived influence of daylight using different types of response scales. The findings suggest that daylight is perceived to be important as it was mentioned with high frequency as a reason for seat choice. This is indicated by the fact that, in door and room surveys, daylight was the third and the most frequently chosen category of response respectively. The room survey used two different methods of questioning, one which required participants to choose three items out of ten, and another which required to define each item as important or not. The experiment found that participants think daylight matters to their seat choice in the test room using all methods tested.

6.2.1 Comparison with previous research

A review of literature revealed that research on seating preference is limited, and few studies have been carried out in library settings. Of the few studies that have been carried out with the specific goal of investigating seating preferences, none has analysed the differences in the perceived importance of daylight before and after the seating decision is made. A door-room survey method was suggested to be a useful way of identifying the perceived importance of daylight before and after making a decision about where to sit. Participants were presented with a list of statements and asked to select three that they think are the most important. This type of measurement was used in previous research for evaluating occupant preferences and satisfaction with the visual environment (Hygge and Loffberg, 1999; Christoffersen et al, 2000; Parpairi et al., 2000) and for examining seating preferences (Dubois et al., 2009; Othman and Mazli, 2012). The current study aimed to further extend previous research by examining alternative methods of measuring the perceived importance of daylight in seat choice decisions.

The results of surveys demonstrated that daylight has a consistent role to play in influencing perceived seating behaviour: although the frequency by which daylight was considered to be important differed between the two surveys, this difference was not statistically significant. However, significant differences were observed for the relative importance of some factors (availability of power sockets and the distance from others), suggesting that the context in which surveys take place matters. Daylight was found to be the one of the most important factors perceived by respondents, a result similar to that produced in previous stated preference studies.

6.2.2 Limitations

A number of limitations exist with the stated preference method that limit what it can tell us about which perceived influences are the most important when choosing a seat location. First, participants were presented with a set of predefined items and asked to evaluate them by expressing their preferences on the measurement scale being used. This method can lead to misleading conclusions for a variety of reasons. For example, the survey format may force participants to evaluate an item they otherwise would not have considered relevant. Likewise, the response options provided by the researcher do not necessarily represent those of the participants either. These issues need to be considered when constructing a measurement scale, including the number of categories and the procedure being used to account for response order effects.

One step towards addressing the limitations with the current survey format is to give the respondents an opportunity to express their personal opinion, thus reducing the constraints on responding. Other survey methods such as interviews could allow for that flexibility by giving respondents the opportunity to state the reasons applied to their seat choice without being restricted to the given set of options. In this case, however, the analysis and interpretation of data can be challenging and less straightforward than for instance that obtained by the door-room survey method.

A further limitation is that the opportunity sampling can produce a biased sample as only certain types of people were selected from a limited area, in this case a library reading room. The sample taken may not be representative of the entire population. The findings are therefore not generalizable beyond the sample surveyed, but researchers may identify survey elements that are transferable to other similar settings (i.e. other library reading areas).

Finally, stated preference surveys provided only indirect reports of seating behaviour and therefore may not be a reliable source of evidence about actual seating behaviour. Evidence from the surveys has the potential to be misleading if the data is interpreted as representing seating behaviours that are actually occurring inside the reading room.

6.3 Revealed preference surveys

Further evidence for the association of daylight with seating preference has been provided from direct observations on actual behaviour of individuals in the test room. Three experiments were designed to provide a series of snapshots of seat use at specific times (snapshot approach), and one of these included an additional investigation in which the seating behaviour of an individual was recorded from the time of entering until the time of leaving the room (walkthrough approach). A summary of the results from the experiments is given in Table 6.1, and are discussed below in terms of the variables that were being examined.

Table 6.1. Summary of findings from revealed seating preference surveys.

Snapshot observation	**Main findings:** • Occupancy rates decreased sharply from window seating area to central seating area, then stayed fairly evenly distributed throughout the central seating area. • Comparison between daytime and night-time frequencies revealed some similarities of seating pattern, suggesting the effect of daylight may be small (R^2= 0.57, p<0.001). However, length of stay appears to have confounded the analysis.
	Experimental variations: • Observation data is not affected by the interval for which observations were recorded (R^2= 0.99, p<0.001).
Walk-through observation	**Main findings:** • Possible effect of physical proximity: Occupants were usually seated individually rather than in groups, and preferred seats with low local occupancy density. • Possible effect of length of stay: The mean length of stay differed significantly between seating areas, with higher proportion in window area than that in central area. • There was no clear evidence of an association between availability of power sockets and seat choice. • Occupants who arrived later in the afternoon preferred to sit in the central seating area when the availability ratio in window seating area was low.
	Experimental variations: • Analyses of the inter-observer reliability for the recording of seating behaviour with the two approaches (snapshot and walk-through) indicate that the observations were reliable (R^2= 0.99, p<0.001).

Whilst the three experiments were carried out at different times, during summer and autumn, the overall occupancy patterns were similar: the occupancy rates were relatively high for window seating area compared to central seating area, but there was no apparent pattern in the distribution of occupancy rates across central seating area. The analysis did not reveal any significant difference between the observation intervals, meaning that occupancy rates are not dependent upon the time interval over which they are measured. This should perhaps be expected as people are more likely to stay for longer periods of time in library workspaces compared to other physical settings such as restaurants or cafes.

Another question being addressed by this study was whether there were any differences between the daytime and after-dark occupancy rates. The occupancy rates observed during daylight hours were compared with those observed during hours of darkness. The pattern of results obtained in the two datasets was somewhat similar, suggesting that the effect of daylight may be small. However, these data should be interpreted with caution given the differences in length of stay observed in two periods: people arriving during daylight hours may have remained at their seats during hours of darkness, leading to overestimation of occupancy after-dark.

The third experiment used walk-through approach in an attempt to improve the accuracy and validity of snapshot data by establishing inter-observer reliability. In order to obtain inter-observer reliability, another experimenter recorded the seating behaviours of individuals as they choose a seat. This was done in parallel to the snapshot experiment, thereby enabling direct comparison between the two datasets. An analysis of the occupancy was then performed to identify relevant contextual factors in the physical setting and to control, at least to some extent, potential differences that might arise from different physical characteristics of seating areas. The following information was recorded: (a) group settings, (b) time seated, (c) time departed, (d) the type of activity, and (e) the availability of power socket at desk. Group settings were identified as instances when individuals interact with each other for a common purpose (i.e. a group of individuals working together).

Results from the walk-through observation data indicated that the room was predominantly used by individuals rather than groups. This is as would be expected considering the room is a silent study area where social interactions are less likely to occur. The data collected on group settings suggested that those working in groups tended to sit in the central seating area, possibly because of its high seat capacity (i.e. presence of large tables that groups could use). A further examination of the effects of local occupancy density on seating behaviour suggested that occupants preferred to sit in areas where the local density was low. This latter analysis is based on the concept of modified Moore neighbourhood, which takes into account the immediate surrounding seats within the occupant’s field of vision. Local occupancy density was then calculated as the ratio of occupied seats within the neighbourhood.

To examine potential differences that might arise from different periods of seat occupation, length of stay was determined for each individual from their arrival and departure records. This was assumed to be a reasonable estimate of how long individuals remained in their seat during the observation period. The results revealed differences in mean lengths of stay among seating areas, with window seating area having the highest values compared with the other areas. What this means is that the high occupancy rates found in window seating area during snapshot experiments may be due to the longer lengths of stay rather than high number of occupants seated in that area. On the one hand, this suggests that snapshot experiments may have produced misleading results because of inherent bias in the estimates of occupancy. On the other hand, if a longer length of stay indicates a predominantly strong preference for one particular seat, then the results might indicate that those who prefer window seating area tend to stay longer in their seats. Longer length of stay may thus be interpreted as being an indicator of preference for a particular seating location.

As far as computer and paper-based tasks are concerned results indicated only slight differences in seating preferences of these two task groups. In the window seating area where the power sockets are located, the proportion of occupants who carry out computer-based tasks was slightly higher than those who carry out paper-based tasks, whereas the opposite pattern was found in the central seating area. However, the availability of power sockets itself may not be the most important factor for those who carry out computer-based tasks: more than a third preferred to sit in the central seating area with no power socket available, the opposite to what might be expected considering the need for a power supply. This means that seating preferences may be related to the tasks being undertaken in the reading room (i.e. higher proportion of computer-based task group seated in the window seating area), but not necessarily to the availability of power sockets.

The daylight availability predictions provided a quantitative basis for explaining seat choice behaviour in relation to daylight. An approach based on simulation modelling was proposed to estimate the daylight illuminance levels at the work plane with an acceptable level of accuracy and precision. For each sensor point, a representative illuminance value was determined for each time interval over the observation period. The resulting time series of illuminances were then analysed using a set of metrics, which served as indicators of actual daylight illumination throughout the room. This procedure allowed evaluating the way that seasonal changes affect the availability of daylight within the room and is derived from data representing the observation period. The illuminance level produced at the sensor points that fall within the window seating area reached 2000 lux in the autumn and as high as around 10000 lux in the summer. These results suggested that occupants seated in the window seating area were exposed to considerably higher levels of illuminance in summer than in winter. This outcome is notable, as it indicates that the high levels of daylight in window seating area may have led to increased level of discomfort glare in summer as opposed to in the winter when discomfort glare appears to be less of an issue. During both periods, the illuminance decreased rapidly from window to central seating area, but did not fall below the minimum illuminance threshold of 100 lux, meaning that daylight by itself did provide sufficient illuminance to carry out visual tasks.

The occupancy rate calculated for each individual seat was correlated with the corresponding daylight metric to test whether there was a relationship. For the entire seating area, horizontal illuminance and daylight factor produced similar results, both having positive correlations with the occupancy rate. Useful daylight illuminance showed negative correlations in summer experiments, indicating that people preferred areas with illuminances outside the useful range, even to the extent they produce discomfort glare. The results suggest daylight autonomy does not have a relationship with the occupancy rate, unlike the other metrics examined. This confirmed that daylight autonomy distributions are of limited use for the purpose of this study. Examination of each seating area separately revealed that the relationships between daylight metrics and the occupancy rate are strongly influenced by the data points obtained from window seating area. Excluding these data points from the analysis resulted in negligible correlation values, or more often, no correlation at all.

A final approach to the analysis of revealed preference data was to consider sequential choices made by occupants over time. If the seating behaviour depends upon the previous decisions, then it may be useful to consider the factors that might account for such dependence. One factor that is likely to be important is the seat availability at the time of making a seat choice. This was investigated using data from walk-through observation, and an availability ratio was calculated for each individual based on the ratio of available seats in the window seating area. As might be expected, individuals who arrived early in the morning tended to sit in the window seating area when the availability ratio was high, whereas those who arrived later in the afternoon preferred to sit in the central seating area when the availability ratio was low. What these results suggest is that occupants seated in window seating area might feel more responsible for their choices given the potential opportunity of finding the very best seating option, but those arrived later may have limited options and as a result tended to defer decision and search for alternative locations in the central seating area.

6.3.1 Comparisons with previous research

The literature review presented in Chapter 2 provided an overview of previous revealed preference studies that sought to determine the effect of daylight on seating preference (Kim and Wineman, 2005; Dubois et al., 2009; Wang and Boubekri, 2009; Othman and Mazli, 2012). Although some common findings emerged, such as the tendency of people to choose seats near windows where the high level of daylight is likely to cause glare, there are major limitations with previous research. First, previous studies do not provide insights into how procedural aspects such as the observation interval, the time of day or season influence the occupancy patterns observed and the conclusions drawn. Second, although evidence is provided that people preferred to sit in areas with high levels of daylight, much of this evidence comes from measurement of illuminance for some representative points in the test room rather than for each seating location. There has been no further attempt to explore any correlation that might exist between the measured light levels and the observed seat choices. Third, observations were carried out in dynamic environments where seat availability could change with time and previous seat choice decisions, yet none of the reported studies included data on such dynamic aspects of seating behaviour and had no method of measuring seat availability.

The revealed preference experiments reported in this thesis built on previous research by testing the effects of data collection methods. Occupancy observations were recorded at different time intervals in different times of the year, and using a second approach which provided additional insights into seating behaviour, such as how occupants positioned themselves in relation to others or whether the presence of power sockets affected their seat choice. Further analysis of the occupancy was carried out to compare results from the daytime and night-time datasets. It was noted that factors associated with extended length of stay might have influenced the results. A simulation-based framework was proposed which allowed dynamic assessment of daylight in the test space. The occupancy rates and the estimates of daylight illuminance levels generated by simulations have enabled comparisons to be made between the datasets. Finally, to account for the differences in the availability of seats during the observation period, availability ratios were calculated by the percentage of seats that were unoccupied at a given moment, with variations with time of day being examined.

6.3.2 Limitations

The advantage of revealed preference method is the reliance on actual choices, avoiding the potential problems associated with responses in stated preference surveys, such as the tendency to give answers that the respondent considers to be socially acceptable or a failure to properly consider physical constraints imposed by the layout of the workplace. On the contrary, the snapshot approach provided information about seating behaviours but did not generate insight into associated meanings necessary to understand dynamic interactions between seating behaviour and the physical environment. Walk-through approach was proposed as an alternative and complementary approach, providing contextual information relating to seating behaviours and interactions, including the type of activity undertaken and physical proximity between the groups or individuals. By relying on such observations, however, analysis was restricted to include only those aspects of the behaviour that could be directly observed and measured.

Another concern is that occupants may have different levels of ability to behave in accordance to their preferences, depending on the context in which the seating decision is made. For example, occupants may be forced to choose a seat they may otherwise have not chosen. This effect has been noted from the availability analysis. An analysis of walk-through data suggested that the evaluation and selection of a particular location may be affected by the number of seating options available at the time of seating decision is being made. It is thus evident that when occupants choose a seat their behavioural response is biased and constrained by the range of available seats and therefore the outcome should not be interpreted as evidence of a preferred seat. Occupancy observations provided information regarding common patterns of seating behaviour but not absolute preferences. Since the actual seat choices reflect the joint influences of preference and availability, estimates derived from revealed preference approach require careful interpretation.

The lighting characteristic that was of interest was the illuminance on the horizontal work plane, predicted through the use of computer simulations with validated software (see Chapter 5). This perhaps has to be accepted as a limitation, for at least two reasons. First, the analysis was entirely carried out through simulation and should thus be appreciated as a function of the limitations of the simulation tool and of the simulation framework proposed. Second, the analysis relied on daylight metrics on the photometric quantity of illuminance, rather than luminance. Given that the human visual system is frequently oriented vertically, seating preferences may be better predicted by patterns of luminance in the vertical visual field than by absolute illuminances on horizontal work plane. It should be noted however that the luminance method requires knowledge of the relative positions of the observer and the light source as well as the reflection properties of the surface material. This type of evaluation method is thus limited to being applicable only in situations where such assumptions about the observation point and the view direction can be made. As the test room in the current study was a large open-plan room where multiple directions of view are likely, horizontal illuminance is assumed to be sufficiently reliable to compare daylighting conditions in different seating areas. The assumption was that the measurement of luminance would involve an effort inappropriate for the exploratory nature of this investigation.

Finally, it is worth noting that, while revealed preference surveys provided insights into real-world, naturally occurring behaviour; they did illustrate some common problems in field studies. For instance, a finding of high occupancy rate in areas in close proximity to windows might be due to the daylight coming in through the window or the view of a natural setting seen out of it. It is possible that some people who prefer to sit near windows may actually be as much concerned about the visual access to the natural environment as they are about daylight. This could have a confounding effect and may compromise conclusions drawn from revealed preference surveys.

6.4 Summary

The research presented in this thesis has described the different, yet complementary, nature of the two approaches used to investigate the behavioural effects of daylight in a library working environment. The evaluation was based on the data obtained by direct observation of behaviour (revealed preference) and that obtained in surveys asking individuals about their seating behaviour (stated preference). In this chapter research findings from these two approaches have been summarised and compared with those reported in previous studies. From the stated preference survey results it is evident that daylight is perceived as one of the important factors when choosing a seat. Among other factors likely to be important are noise, availability of power sockets, distance from other people, and the outside view.

The revealed preference surveys confirmed the preference for seats in close proximity to windows observed in previous research and provided further evidence that seat choice reflects the joint influences of preferences and other contextual factors such as seat availability. It is also important to appreciate that the results discussed in this chapter are a small sample of those that could be obtained through observations. Future research might attempt to replicate these findings using a large sample. The next chapter discusses implications of research findings and potential areas for future research.

CHAPTER 7. CONCLUSION

7.1 Introduction

The previous chapter presented a discussion of the results and a review of the potential limitations of the study. This final chapter describes conclusions drawn from the research and discusses their implications for daylight research and practice. The chapter begins with a summary of the research carried out and then outlines the conclusions and implications of findings. Finally, the chapter highlights potential areas for future research that would further improve the fields of occupant seating behaviour and daylighting.

7.2 Summary of thesis

The research presented in this thesis has sought to identify how seating preferences would be affected by daylight in an open-plan library workspace. An examination of the literature revealed that research on the relationship of daylight and the seat choice behaviour of individuals is limited. The stated preference studies reviewed in Chapter 2 provide evidence on the perceptions of occupants regarding the importance of daylight in their seat choice decisions. Specifically, the surveys explored which perceived influences were the most important when choosing where to sit. The data collected with the survey questions were the frequencies of the responses to each pre-defined factor. However, these surveys tend to provide only limited information about the perceived influence of daylight as the respondents were sought only from those already sat within the test room. Perception of the importance of daylight may be influenced by expectations and experiences of choosing a seat location. If this is the case, then the information obtained from outside the test room would be different from the information in the room. The stated preference study described in Chapter 3 therefore aimed to explore differences in the perceived importance of daylight across two groups of participants, those about to enter the test room (door survey) and those seated in the room (room survey). This allowed direct comparison of responses from the two surveys, to test the differences in responses before and after making the seat choice decision. Respondents were given a series of statements about their seat choice and asked to choose three of these statements that they think are the most important. The results were consistent with those of previous research that identified daylight as perceived to be one of the most important factors when choosing a seat location. For the room survey group, it was the most important out of the options presented and for the door survey group it was the third most important after the availability of power sockets and quietness. The limitation of the stated preference surveys is that they rely on data from survey questions asking people about their seating preferences and are therefore should not be regarded as a source of direct evidence about actual behaviour. The expression of preferences is an action, in this case making a seat choice, which presumably is guided by these very same preferences.

An objective way to identify seating preferences is through observation of actual behaviour. The second chapter reviewed previous revealed preference studies and what they tell us about where people sit in relation to daylight. Findings from these studies suggest that people prefer to sit in areas near windows where daylight levels are high. However, one limitation of previous research is the tendency to record seat occupancy at some predefined intervals. An alternative method is to use walk-through approach that could withstand potential loss of data between two successive intervals. However, few if any studies of seat choice have used walk-through approach to record seat choice behaviour. Another important consideration is the time period in which the experiments are carried out, particularly because these experiments take place in dynamic conditions, where occupancy and daylight could vary significantly at different times of day and season. Such variation may limit the conclusions that can be drawn from a particular study. The revealed preference experiments reported in Chapter 4 attempted to address these limitations by examining the effects of different methods of recording occupancy data. Walk-through method was suggested as an alternative method to be used in parallel to snapshot approach. The results from these two methods applied to the same set of occupancy data converge toward similar conclusions, so it was possible to place more confidence in those conclusions.

The revealed preference experiments were extended to include summer as well as autumn conditions so that the effect of the seasonal variations in lighting conditions and occupancy could be investigated. A relatively high proportion of occupants seated in the window seating area has suggested a possible link between daylight and seat choice. It should be noted that these results did indicate sitting near windows but did not tell what might be behind the behaviours observed in the test room.

Previous seat choice studies employed physical measurement techniques to determine the distribution of daylight in the test space. The approaches taken in these studies ranged from illuminance measurements at representative points on the work plane to the predictions of the luminance distributions in the vertical visual field. Given the methodological differences across the studies, the question arises whether a prediction of illuminance or luminance for a particular location in the test space is sufficiently representative to allow comparison with occupancy data. This study applied a dynamic simulation modelling method to perform prediction of daylight illuminance for each individual seat in the test room, and Chapter 5 presented simulation method. The illuminance data set were experimentally acquired from respective illuminance sensors specified on the work plane, corresponding to each seat location. A set of metrics were then analysed to determine whether they correlate with the occupancy data derived from revealed preference observations. On the basis of simulation results, it is possible to conclude with a reasonable degree of certainty that the level of daylight received into the window area was higher in the central area, even to the extent of causing discomfort glare in summer. It should be noted that the study does not involve any physical measurement of daylight and should thus be appreciated as a function of this limitation. Although these findings are tentative, based upon a rather limited computer simulation analysis, they do provide reasonable estimates of daylight availability in the test room over the observation period. This concluding chapter draws together the conclusions from the research and suggests potential research areas for further investigation.

7.3 Conclusions

7.3.1 Comparison of methods

Previous studies have provided limited evidence of an association between daylight and seat choice behaviour, in part because each study employed different methods to measure and quantify daylight and seating preferences of individuals. What is lacking is an evaluation of the reliability of the data; for example, by a critical review of the observation procedures and the metrics used for measuring daylight. In evaluating the question of the reliability of the data reported in previous seat choice studies, some methodological limitations are evident. Table 7.1 presents a summary of procedures used in previous studies. Note that these are the studies specifically focused on seat choice behaviour.

Table 7.1. Summary of procedures and results from past studies of daylight and seat choice.

Study	Stated Preference		Revealed Preference						
	Method	Key Findings	Method						Key Findings
			Snapshot/ Walk through	Daytime/ Night time	Interval	Duration	Season	Daylight metrics	
Kim and Wineman (2005)	n/a	n/a	Snapshot	Daytime	10 min 30 min	6 days 8 days	Spring Autumn	Horizontal illuminance	Higher occupancy in areas near windows with outdoor views
Dubois et al (2009)	Room survey	Daylight was reported to be the most influential factor on seat choice	Snapshot	Daytime	15 min	2 weeks	Autumn	Luminance based metrics	Higher occupancy in window zones in spite of high variability in daylight conditions
Wang and Boubekri (2009)	n/a	n/a	Snapshot	Daytime	30 min	3 days	Spring	Horizontal illuminance	Higher occupancy in sunny areas and a general preference for open areas when sitting away from sunny areas
Othman and Mazli (2012)	Room survey	The majority of respondents agreed that daylight affects their seat choice	Walk through	Daytime	n.a	Not reported	Not reported	Horizontal illuminance	Variations in occupancy during the day: lower occupancy near windows due to excessive contrast in light levels in the morning
Gou et al (2018)	Room survey	Daylight was the fourth highest rated reason of seat choice after quietness, furniture and privacy	Snapshot	Daytime	30 min	2 days	Spring	Horizontal illuminance	Variations in occupancy in different weather conditions: higher occupancy rate in south-facing workstations on a sunny day than on a cloudy day; and a preference for the sky view over the view of high-density trees
Current study	Door survey Room survey	Daylight was the third and the most frequently chosen category of response in door and room surveys respectively	Snapshot Walk through	Daytime Night time	15 min 30 min 60 min	10 days 5 days 10 days	Autumn Summer	Horizontal illuminance Daylight factor Dynamic metrics	Substantial differences in occupancy and daylight levels between window and central area: occupancy rates decreased dramatically from window to central area, possibly reflecting the impact of two different environments on seat occupancy

The relationship between daylight and seat choice found in the experiments presented in this thesis is consistent with a number of other seat choice studies. Most of the studies presented in Table 7.1 demonstrated the tendency of occupants to sit near windows despite exposure to high levels of daylight and potential glare, with the exception of Othman and Mazli (2012) who reported that the occupants avoided daylight when it caused excessive contrast in the morning. The results from the current study confirmed the high levels of occupancy near windows and the presence of excessive amount of daylight in these areas, thus supporting the conclusions drawn from previous studies (Kim and Wineman, 2005; Dubois et al., 2009; Wang and Boubekri, 2009; Gou et al., 2018). High occupancy rates were only found in those areas located in close proximity to windows, and occupancy rates decreased drastically from window to central area. In the central area however, occupancy rates did not follow the same pattern, but rather formed a pattern that appears random. Previous studies reported higher occupancy in areas near windows, but did not provide information regarding occupancy patterns in the remaining seating areas (i.e. areas away from windows).

The stated preference experiment used the door-room survey approach to determine the perceived importance of daylight in seat choice decisions. Asking participants to choose from a predefined list of response options was used as a means of identifying which perceived influences are the most important for seat choice. The analysis of the data suggested that daylight is an important consideration for occupants when choosing a seat, supporting previous research that has found similar results (Dubois et al., 2009; Othman and Mazli, 2012; Gou et al., 2018). The quietness of the seating area was also an important factor, a result that is supported by the two studies of Dubois et al (2009) and Gou et al (2018). Alongside daylight and quietness, a third consideration for seat choice that was stated as being important is the availability of power sockets. The effect of presence of power sockets on seat choice was not examined in previous studies. As regards the data from door and room surveys, there is an indication that daylight appear to have had some behavioural influence, mostly on those already seated in the test room rather than on participants outside the room. One limitation of previous studies was that they did not identify differences in perceived importance of daylight before and after the seat choice is made, hence the effect of this is unknown.

From a methodological perspective, previous studies relied on physical measurements to analyse daylight performance of the test space. Although there have been similarities in the way in which daylight is measured, for example, using horizontal illuminance as the metric of choice, relatively little attention has been given to the methodological issues, nor to understanding the relationship between daylight metrics and occupancy rates. While it is not common in previous studies to question the procedures used to derive the daylight metrics, the current study demonstrated a need for further investigation to determine the validity of the chosen metric in predicting seat choice behaviour. Unlike previous studies in which the illuminance level was measured at some arbitrary points across the work plane (Kim and Wineman, 2005; Wang and Boubekri, 2009; Othman and Mazli, 2012), this study used a range of metrics to determine daylight availability in each seat location, and attempted to establish a correlation between the metrics and the occupancy rates.

The research reported in this thesis extends previous work in two ways. First, neither of the previous seat choice studies focused on exploring differences in the perceived influences of daylight inside and outside the test room. The comparison of survey responses between the two locations is important, as the perceptions of the participants regarding the conditions that influence their seat choice at least partly depends on the context in which they receive information and make decisions. This was examined in the stated preference study, in which participants completed two questionnaires, one before and one after entering the test room.

Second, this study investigated the impact that using different daylight metrics and different methods of recording seat choice behaviour has on the results. Seat occupancy was recorded at different time intervals in different time periods, and using a second procedure which expanded the study to include individual tracking of occupants in the test room. One aspect missing from previous studies is that whilst they have reported a tendency to sit near windows, they did not correlate seating preference with daylight metrics or other quantitative measure. This study investigated the association between daylight and seat choice behaviour, with occupancy rates used as a quantitative measure for seat choice behaviour, and subsequently which daylight metric best predicted this behaviour.

7.3.2 Daylight and seat choice: Evidence from field experiments

As with the findings of the previous studies, the experiments reported in this thesis have found some evidence of an association between daylight and seat choice. The first conclusion to be drawn from the stated preference experiments presented in Chapter 3 is that daylight was only one, and apparently a major factor among many that affected seating preferences of people. The door-room survey, which asked respondents what mattered to them when choosing a seat found that they think daylight matters. Daylight was suggested to be the most important factor amongst those respondents already seated in the room, but was less important among those people who responded at the entrance. The availability of power sockets, noise and the distance from others were also found to be important factors.

The revealed preference experiments reported in Chapter 4 provided data on actual seating behaviour and allowed the occupancy of different seating areas to be compared. It was found that higher illuminances led to increased occupancy rates, though this was only in close proximity to windows. In particular, the results showed high levels of illuminance near the windows with a rapid reduction in illuminance as the occupants move away from the windows through the central seating area. In the central seating area, the illuminance decreased to a lower level, below which a further decrease in illuminance had negligible influence upon seat choices, rather than leading toward a decline in occupancy rates across the central seating area. The analysis revealed a similar pattern of occupancy in summer and autumn periods, although the illuminance levels differed. Simulation results indicated considerably higher work plane illuminances in the window seating area in summer compared to autumn, with illuminance values being well above the upper limit for preferred daylight illuminance (3000 lux) in summer. This may have resulted in higher daylight levels experienced by the occupants seated in that area, increasing their disability and discomfort glare. Yet, occupants seemed to have tolerance to discomfort glare as evidenced by their preference for window seating area over central seating area.

The snapshot experiments employing the day-dark approach tend to draw the somewhat controversial conclusion that the effect of daylight may be small. A significant bias noted in the comparison of snapshot data captured during daytime and night-time is suggested to be associated with the length of stay of occupants. This is because the data does not include information about the possibility that one might be able to choose a sit in the daytime and remain in the same seat through the night. This means that the results are likely to be biased towards the conclusion that the occupancy rates are similar between the two observation periods. The snapshot data are supported by the results of the availability analysis which also found that the occupants preferred to sit in the window seating area when room density was sufficiently low to allow this choice. This was investigated by the walk-through experiment using alternative procedures. One conclusion that could be drawn from this experiment is that occupants avoided sitting in close proximity to one another and those who preferred to sit in the window seating area tended to remain in their seats for longer periods of time. These factors provided alternative explanations of actual seating behaviour, although it is important to note that the analysis was restricted to include the observable and measurable aspects of behaviour and that the results should be interpreted along with the other dimensions of behaviour.

Given the empirical evidence from stated and revealed preference surveys, daylight appears to have had some influences on seating behaviour. While no actual recommendations can - or should - yet be made because of our limited understanding of the effects of daylight on human behaviour, especially when choosing a seat location, the relevance of some critical factors in perceived and actual seating behaviour is certainly a topic worth further investigation. The next section discusses the implications of the findings from the research, in particular what they may mean for seating behaviour research and daylighting design guidelines.

7.4 Implications

The insights gained in this research have potentially important implications for daylighting design of library buildings as well as for understanding the relationship between daylight and human behaviour. This research focused on one particular type of behaviour, seat choice behaviour, and used a library reading room as the physical setting to investigate the potential role of daylight in choosing a seat location. Daylight availability is likely to be an important reason for choosing a particular seat location and it is therefore important to know how daylight influences seat choice behaviour. Given that the desire to sit in close proximity to windows has been established by previous studies and that the results of this field study appear to indicate that this may be influenced by the amount of daylight available in the space, improvements could be made in current design standards. Daylighting codes and standards were developed based primarily on considerations of visual task requirements but only on a limited scientific understanding of the important role daylight plays in seat choice behaviour. This thesis presented an experimental investigation of seat choice behaviour, and the evidence from this research can be used to develop daylighting design guidelines that are better based on seating preference data. With regard to design process, understanding seat choice behaviour can potentially contribute to an awareness of human dimensions, spatial organization and the management of space.

The study also offers some implications in the field of daylight-seating behaviour research with regard to the methodological approach taken. Probably the most significant implication can be found in data collection methods used in this study. The method of previous work exploring perceived importance of daylight by the use of questionnaire surveys was extended to include the effect of the survey location which has not previously been done. This allowed to explore users' expectations and experiences of choosing a seat location. Another contribution that this study has made to the methods of previous research is the way that revealed-preference surveys were conducted. Seat choice behaviours were observed at different time intervals for different time periods. These data collection methods worked well for this research by identifying potential sources of variation in the data captured during direct observations, while also providing a basis for the replicability of the experiments. Most of the literature showed effects of daylight on seating preferences, but no attempt has been made to examine these experimental variations. Following individuals as they choose a seat, rather than relying on snapshot recordings was also suggested to be useful as an alternative method for recording seat occupancy. This allowed data from these two methods to be compared and more robust conclusions to be made about the actual seating behaviour.

This study was essentially exploratory in nature, given that the purpose of the experiments was to examine the effects of daylight on occupant behaviour, with a particular focus on seating preferences. Yet clearly the methods used in this research provide only a partial understanding of the role that the daylight plays in seat choice behaviour. Further research is needed to validate the findings and to overcome some of the limitations which are inherent in the experiments. These are discussed in the next section.

7.5 Recommendations for future research

The literature review presented in Chapter 2 has highlighted a number of areas where further research is needed to better understand whether and how daylight influences seat choice behaviour. Whilst some of these were addressed by the research in this thesis, others remain. First, preferences for window seats are to some degree dependant on the presence of outside view. The stated preference surveys revealed the importance that library users place on the outside view, however, no data within the revealed preference experiments exists to confirm this. A potentially important work that might shed some more light on this issue is the examination of the link between seat choice and the view content using alternative methods. An alternative explanation for the study findings would be that the occupants seated in the window area were seeking additional stimulation, something that was provided by the view of the natural setting seen through their windows, and their seat choice had nothing to do with daylight. One way to test this possibility would be to repeat the experiments in a space lit solely by skylights, in which case the differences in seating behaviour due to the presence of outside view would be expected to disappear. This approach would remove outside view as a variable factor.

Second, future studies could use different methods for recording seating behavior of individuals, such as photography or video recording. These methods could be used to enhance the data collected during observations while also providing permanent visual records. This would enable to record seating behavior over longer periods, and would enhance what we know about how people choose their seating positions.

Third, the study has relied upon illuminance-based metrics to assess the daylight conditions in the test room. It would also be useful to explore through evaluation of luminance-based metrics other aspects of visual environment not covered by the present study, such as those related to visual discomfort. It is important to appreciate that illuminance-based metrics such as UDI do not deal with discomfort glare apart from limiting the illuminances received to less than 3000 lux. Alternative evaluation metrics could provide more comprehensive measures of discomfort glare from windows, and these could be used to support findings from the current study. Particularly useful in this regard are high dynamic range (HDR) imaging techniques that allow a larger luminance range to be captured. While luminance provides a better measure of what people see, it is a function of surface reflectance, often unknown at design stage, and is valid for only one direction of view. Visual scenes can be very complex, comprising a range of surface types (size, location and reflectance) that can vary with factors such as time and viewing direction. While illuminance has limitations, it is insensitive to these variations, and thus may provide a better metric.

Finally, it is worth noting that the study is inevitably limited in that the results are applicable to the specific context in which they were obtained, and cannot be generalized to other contexts. Research on seat choice behaviour is generally based on single case studies and has lacked empirical evidence on a large number of observations. As with all such field studies, the current findings are a snapshot particular to time and place. What deserves attention in the future is the extent to which the proposed methods can be used for different contexts, that is, for different types of buildings and different groups of people. It is only by accumulating the results of many such evaluations made using the same methods that any general understanding about daylight and seat choice behaviour can be developed.

APPENDIX A. CASE STUDY RESULTS

This appendix presents the results from a study carried out parallel to the work presented in this thesis (Keskin et al, 2015). The observations were made in another university library, Information Commons (IC), and the results were compared with those obtained in Western Bank Library (WB). The reading area in WB were divided into subareas, defined as observation zones, which can be used for ease of interpretation. As for IC, it was decided to calculate occupancy for each individual seat due to the irregularity of desk configuration.

Figure A.1 shows the comparison of occupancy rates between daytime (10:00-14:00) and night time (18:00-21:00) for both WB and IC. This suggests a strong relationship, a tendency for a seating to be used with equal frequency at daytime and after dark, and thus the influence of daylight is small.

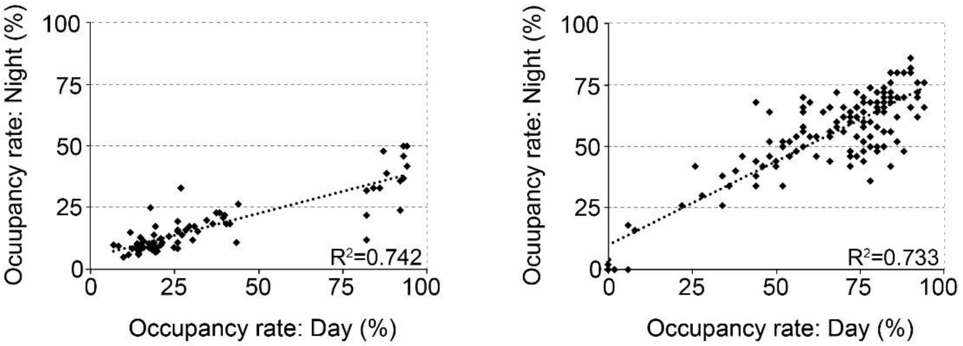


Figure A.1. Comparison of occupancy rates between daytime and night time - Western Bank Library (left) and Information Commons (right).

Figure A.2 shows occupancy rate plotted against the three daylight metrics for daytime seating behaviour. While the IC data suggest negligible correlation between daylight and seat choice, the WB data exhibit a much stronger association. For both buildings, DF gives a higher degree of correlation with space use than does UDI or DA.One difference between the two spaces is the regularity of the seating: in WB the seats are arranged largely in uniform rows whereas in IC they are arranged in an irregular pattern. There are a group of seats in IC that are more regular in layout. For this group of seats the correlation between DF and seat choices increases (Figure A.3). This suggests seating regularity may be an important factor.

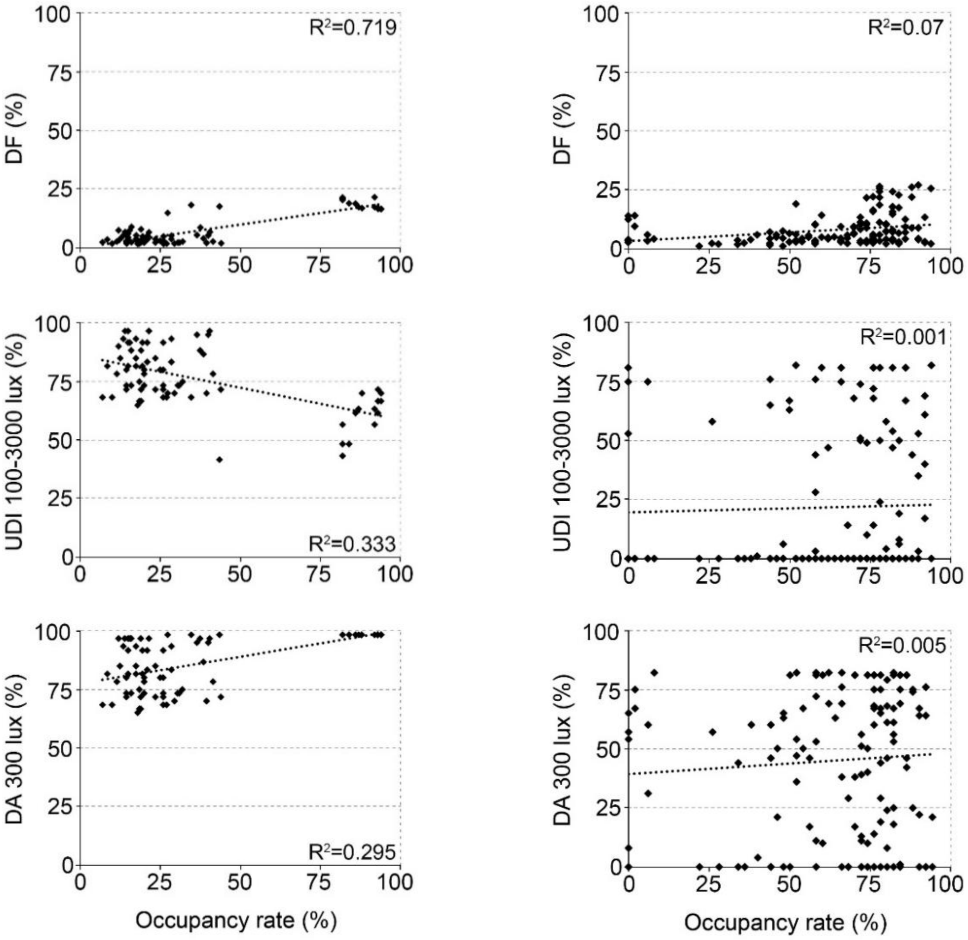


Figure A.2. Comparison of daylight performance metrics and seat choice - Western Bank Library (left) and Information Commons (right).

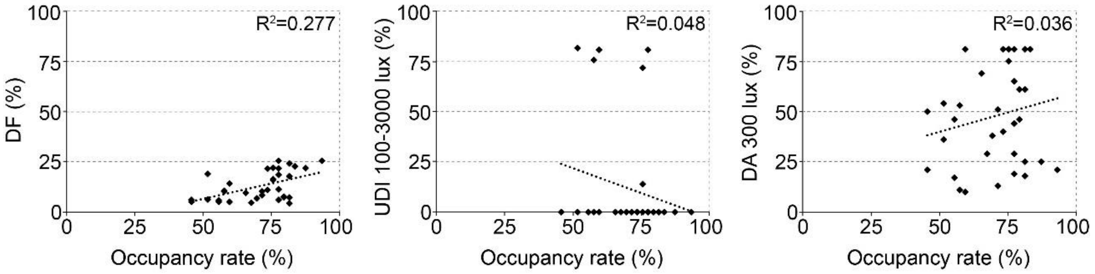


Figure A.3. Comparison of daylight performance measures and seat choice for regular seats.

APPENDIX B. DOOR-ROOM SURVEY

This appendix presents the variations in which the ten seat choice factors were presented in door and room surveys. Five variations were created as a way to minimize question order bias (Table B.1 and Table B.2).

Table B.1. Door Survey: The five variations in which the ten seat choice factors were presented.

Order	Version 1	Version 2	Version 3	Version 4	Version 5
1	A place near power sockets	The closest available seat	A place where there is good electric lighting	It is near to the book shelves	It is distant from other people
2	A place where there is good daylight	A place which is quieter	It is distant from other people	A place near power sockets	A place which is quieter
3	A place where there is good electric lighting	A place where there is good electric lighting	The closest available seat	The closest available seat	The closest available seat
4	A place close to other people	It is close to other people	It is close to other people	A place where there are only a few people passing by	A place where there is a nice view
5	A place distant from other people	There is good daylight	A place which is quieter	There is good daylight	There is good daylight
6	A place where there is a nice view	A place where there are only a few people passing by	A place near power sockets	A place where there is a nice view	A place where there are only a few people passing by
7	A place where there are only a few people passing by	A place near power sockets	A place where there are only a few people passing by	It is distant from other people	It is near to the book shelves
8	A place which is quieter	A place where there is a nice view	There is good daylight	A place where there is good electric lighting	It is close to other people
9	The closest available seat	It is distant from other people	It is near to the book shelves	It is close to other people	A place where there is good electric lighting
10	A place near to the book shelves	It is near to the book shelves	A place where there is a nice view	A place which is quieter	A place near power sockets

Table B.2. Room Survey: The five variations in which the ten seat choice factors were presented.

Order	**Version 1**	**Version 2**	**Version 3**	**Version 4**	**Version 5**
1	It is near power sockets	It was the closest available seat	There is good electric lighting	It is near to the book shelves	It is distant from other people
2	There is good daylight	The noise level is lower	It is distant from other people	It is near power sockets	The noise level is lower
3	There is good electric lighting	There is good electric lighting	It was the closest available seat	It was the closest available seat	It was the closest available seat
4	It is close to other people	It is close to other people	It is close to other people	There are only a few people passing by	There is a nice view
5	It is distant from other people	There is good daylight	The noise level is lower	There is good daylight	There is good daylight
6	There is a nice view	There are only a few people passing by	It is near power sockets	There is a nice view	There are only a few people passing by
7	There are only a few people passing by	It is near power sockets	There are only a few people passing by	It is distant from other people	It is near to the book shelves
8	The noise level is lower	There is a nice view	There is good daylight	There is good electric lighting	It is close to other people
9	It was the closest available seat	It is distant from other people	It is near to the book shelves	It is close to other people	There is good electric lighting
10	It is near to the book shelves	It is near to the book shelves	There is a nice view	The noise level is lower	It is near power sockets

APPENDIX C. RESEARCH ETHICS APPROVAL

Table C.1. University Research Ethics Application.

Section A: Applicant details	
First name	Zeynep
Last name	Keskin
Email	zkeskin1@sheffield.ac.uk
Programme name	Architecture
Module name	PhD Research Project
Department	School of Architecture
Applying as	Postgraduate research
Research project title	Daylight and Seating Preference in Open-Plan Spaces
Section B: Basic Information	
Supervisor	
Name	Steve Fotios
Email	steve.fotios@sheffield.ac.uk
Proposed project duration	
Start date (of data collection)	Mon 10 August 2015
Anticipated end date (of project)	Thu 31 December 2015
Suitability	
Takes place outside UK?	No
Involves NHS?	No
Human-interventional study?	No
ESRC funded?	No
Likely to lead to a publication in a peer-reviewed journal?	No
Led by another UK institution?	No
Involves human tissue?	No
Clinical trial?	No
Social care research?	No
Involves adults who lack the capacity to consent?	No
Vulnerability	
Involves potentially vulnerable participants?	No
Involves potentially highly sensitive topics?	No
Section C: Summary of research	
1. Aims & Objectives	
Does daylight affect where you choose to sit? This project investigates the extent to which the influence of daylight on behaviour can be predicted, and for this the behaviour investigated is seating preferences of occupants in an open plan, hot-desking space in a university library.	

2. Methodology

There are two parts to this experiment: observation of behaviour and a questionnaire.

The observation study will be conducted in the reading room in Western Bank Library. The investigators will note where people choose to sit, but will not otherwise interact with them. This procedure does not require personal data to be recorded. In one approach, seat occupancy across the whole space will be recorded every 15 minutes: A seat map will be used for taking notes. In a second approach, individual people will be observed from their entrance to the room to their chosen seat. This will be carried out continuously. Both observations will be carried out visually, and cameras or other recording devices will not be used. The observations will be recorded for one week (5 days) from 10:00 to 18:00. Subsequently these data will be correlated with daylight metrics.

The questionnaire will investigate perceived influences on seat choice. In one approach, visitors to the library will be targeted as they approach the building: in the second approach, occupants of the reading room will be targeted. These questionnaires seek to identify the most important factors for seat choice. The aim is to seek responses from 200 people, half for each approach. These will be chosen randomly from those people entering the library room and will a mixture of age and gender. They will be asked to give their age and gender but will not be asked for their names or other identification. They will be shown the possible options on a sheet of paper and the experimenter will record their response.

3. Personal Safety

Raises personal safety issues?	No

Section D: About the participants

1. Potential Participants

In the observations we do not record any details about people.
In the questionnaire we record gender and age: this is to ensure a representative sample, as we do not expect these factors to influence the response.

2. Recruiting Potential Participants

Questionnaire respondents will be approached as they enter the library (approach 1) or when they are sat in the reading room (approach 2).

2.1. Advertising methods

Will the study be advertised using the volunteer lists for staff or students maintained by CICS?	No

3. Consent

Will informed consent be obtained from the participants? (i.e. the proposed process) No

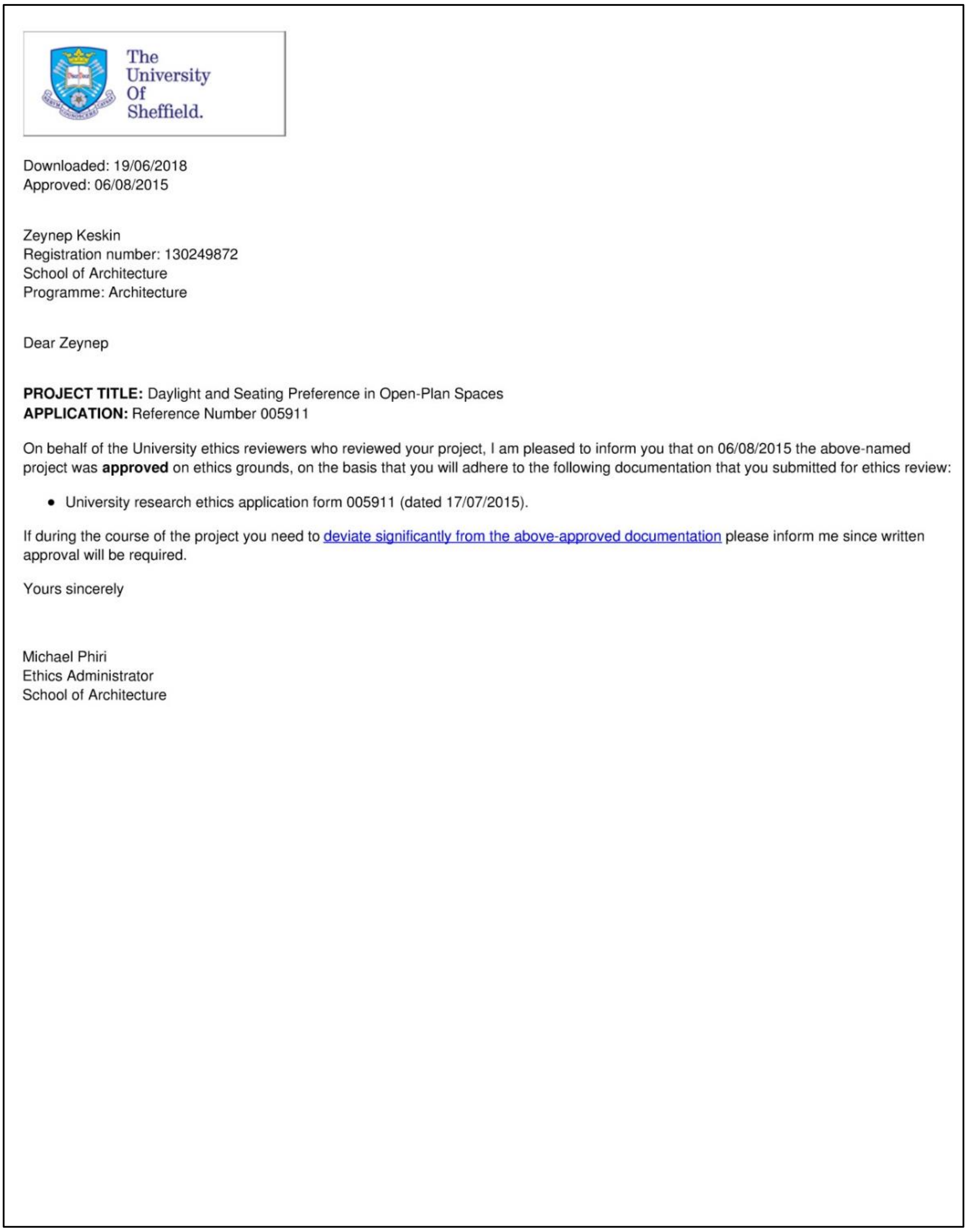
The observation data are gathered anonymously: no personal data are captured and the observation does not expose people to risks that are greater than, or additional to, those they encounter in their normal lifestyles. Therefore, consent is not appropriate.

The questionnaire data requires active participation, and the age/gender (but not identity) of respondents will be recorded (to ensure a representative sample). Agreement to provide a response to the brief questionnaire will be assumed if they provide a response. The experimenter will inform potential participants that their participation is voluntary, brief, and that they are able to withdraw from, or refuse to take part in the engagement at any time.

4. Payment

Will financial/in kind payments be offered to participants?	No

5. Potential Harm to Participants	
What is the potential for physical and/or psychological harm/distress to the participants? There is no potential for harm. The data gathering is not invasive and does not raise significant personal issues. The questionnaire is purposefully brief to minimise disruption. They will not be exposed to risks that are greater than, or additional to, those they encounter in their normal lifestyles. How will this be managed to ensure appropriate protection and well-being of the participants? n/a	
Section E: About the data	
1. Data Confidentiality Measures	
n/a	
2. Data Storage	
The observation study does not capture any personal data. The questionnaire study captures participants' age, gender and seating preferences and there is no means of connecting a response to an individual person. These data will be summarised in the students' theses and the data sheets will be stored by the supervisor after use.	
Section F: Supporting documentation	
Information & Consent	
Participant information sheets relevant to project?	No
Consent forms relevant to project?	No
Additional Documentation	
n/a	
External Documentation	
n/a	
Section G: Declaration	
Signed by: Steve Fotios	
Date signed: Fri 17 July 2015	
Signed by: Zeynep Keskin	
Date signed: Fri 17 July 2015	
Official notes	
n/a	



The
University
Of
Sheffield.

Downloaded: 19/06/2018
Approved: 06/08/2015

Zeynep Keskin
Registration number: 130249872
School of Architecture
Programme: Architecture

Dear Zeynep

PROJECT TITLE: Daylight and Seating Preference in Open-Plan Spaces
APPLICATION: Reference Number 005911

On behalf of the University ethics reviewers who reviewed your project, I am pleased to inform you that on 06/08/2015 the above-named project was **approved** on ethics grounds, on the basis that you will adhere to the following documentation that you submitted for ethics review:

- University research ethics application form 005911 (dated 17/07/2015).

If during the course of the project you need to deviate significantly from the above-approved documentation please inform me since written approval will be required.

Yours sincerely

Michael Phiri
Ethics Administrator
School of Architecture

Figure C.1. Ethics Committee Approval Letter

APPENDIX D. MULTIPLE-OPTION DATA: EFFECTS OF GENDER AND AGE

This Appendix reports analyses designed to determine whether there were any gender and age differences in the preferences for the ten factors. Table D.1 lists characteristics of all the participants. Figure D.1 shows the differences between males and females in their preferences for the ten factors.

Table D.1. Participants completing the door and the room surveys.

Test	n	Gender		Age distribution	
Door Survey	200	Male (109)	52%	18 to 24 (166)	83.0 %
		Female (91)	48%	25 to 40 (32)	16.0 %
				40 to 65 (1)	0.5 %
				65 and over (1)	0.5 %
Room Survey	200	Male (101)	50.5%	18 to 24 (167)	83.5 %
		Female (99)	49.5%	25 to 40 (29)	14.5 %
				40 to 65 (4)	2.0 %
				65 and over (0)	0 %

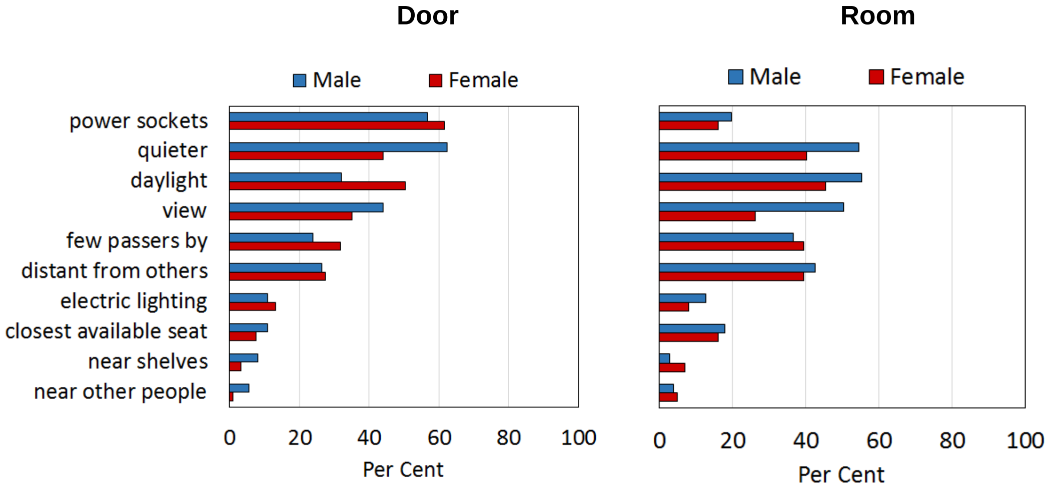


Figure D.1. Differences between males and females in their preferences for the ten factors.

A chi-square test showed that the frequencies by which each factor was picked as being an important factor for seat choice were not significantly different for males and females in door survey (Table D.2) and in room survey (Table D.3) (df = 1, p< 0.05) (Coolican, 1994, p.453). The data revealed no significant difference between male and female responses, thus eliminating the effects of gender differences.

Table D.2. Door Survey: Statistical analysis of difference in responses of males and females.

Factor		Observed Frequency (O)		Expected Frequency (E)		X^2 $\sum(O-E)^2/E$	df	Level of Sig.
		Male	Female	Male	Female			
Power sockets	Ticked	62	56	64.31	53.69	0.20	1	n.s
	Did not tick	47	35	44.69	37.31			
Quieter	Ticked	68	40	58.86	49.14	3.09	1	n.s
	Did not tick	41	51	50.14	41.86			
Daylight	Ticked	35	46	44.15	36.86	3.18	1	n.s
	Did not tick	74	45	64.86	54.15			
View	Ticked	48	32	43.60	36.40	0.74	1	n.s
	Did not tick	61	59	65.40	54.60			
Few passers by	Ticked	26	29	29.98	25.03	0.73	1	n.s
	Did not tick	83	62	79.03	65.98			
Distance from others	Ticked	29	25	29.43	24.57	0.01	1	n.s
	Did not tick	80	66	79.57	66.43			
Electric lighting	Ticked	12	12	13.08	10.92	0.10	1	n.s
	Did not tick	97	79	95.92	80.08			
Closest available seat	Ticked	12	7	10.36	8.65	0.29	1	n.s
	Did not tick	97	84	98.65	82.36			
Near shelves	Ticked	9	3	6.54	5.46	0.98	1	n.s
	Did not tick	100	88	102.4	85.54			
Near other people	Ticked	6	1	3.82	3.19	1.30	1	n.s
	Did not tick	103	90	105.1	87.82			

Table D.3. Room Survey: Statistical analysis of difference in responses of males and females.

Factor		Observed Frequency (O)		Expected Frequency (E)		X^2 $\sum(O-E)^2/E$	df	Level of Sig.
		Male	Female	Male	Female			
Power sockets	Ticked	20	16	19.62	16.38	0.01	1	n.s
	Did not tick	89	75	89.38	74.62			
Quieter	Ticked	55	40	51.78	43.23	0.38	1	n.s
	Did not tick	54	51	57.23	47.78			
Daylight	Ticked	56	45	55.05	45.96	0.03	1	n.s
	Did not tick	53	46	53.96	45.05			
View	Ticked	51	26	41.97	35.04	3.16	1	n.s
	Did not tick	58	65	67.04	55.97			
Few passers by	Ticked	37	39	41.42	34.58	0.76	1	n.s
	Did not tick	72	52	67.58	56.42			
Distance from others	Ticked	43	39	44.69	37.31	0.11	1	n.s
	Did not tick	66	52	64.31	53.69			
Electric lighting	Ticked	13	8	11.45	9.56	0.24	1	n.s
	Did not tick	96	83	97.56	81.45			
Closest available seat	Ticked	18	16	18.53	15.47	0.02	1	n.s
	Did not tick	91	75	90.47	75.53			
Near shelves	Ticked	3	7	5.45	4.55	1.16	1	n.s
	Did not tick	106	84	103.5	86.45			
Near other people	Ticked	4	5	4.91	4.10	0.17	1	n.s
	Did not tick	105	86	104.1	86.91			

For analysis of the age variable, participants were grouped into four age categories: 18-24, 25-40, 40-65, and 65+. There were only four people aged "40-65" in room survey and only 1 person aged "40-65" in door survey. As for older age groups, there were only 1 person aged "65 and over" that participated in room survey, and nobody in door survey was aged "65 and over". Thus, age was analysed for the first two groups only ("18-24" and "25-40") to satisfy the assumptions of the chi-square test. Figure D.2 shows the differences between the younger (aged 18-24) and the older (aged 25-40) respondents in their preferences for the ten factors.

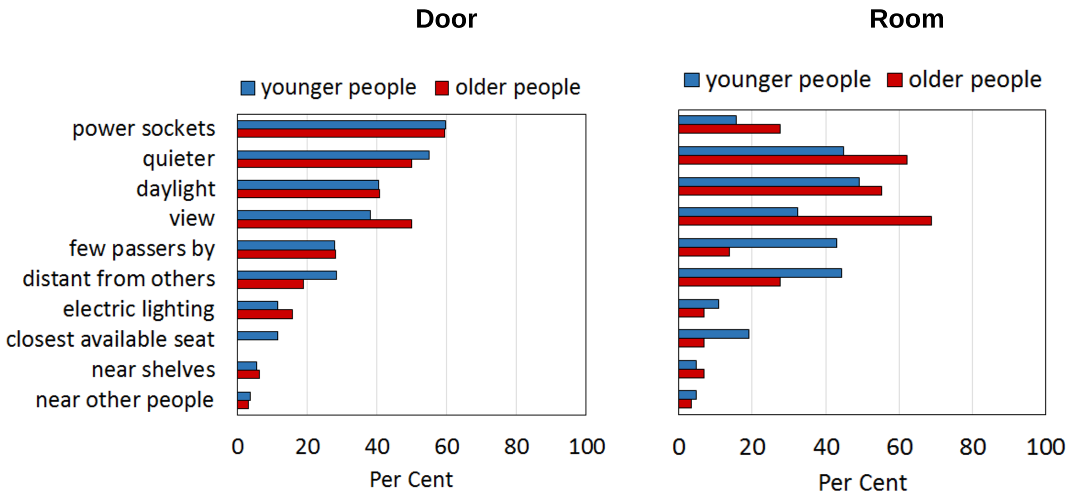


Figure D.2. Differences between younger people (aged 18-24) and older people (aged 25-40) in their preferences for the ten factors.

A chi-square test showed that the frequencies by which each factor was picked as being an important factor for seat choice were not significantly different for younger and older respondents in door survey (Table D.4) and in room survey (Table D.5) (df = 1, $p < 0.05$) (Coolican, 1994, p.453). The data do not suggest that there is an effect of age on factors perceived to affect seat choice.

Table D.4. Door Survey: Statistical analysis of difference in responses of younger (aged 18-24) and older (aged 25-40) participants.

Factor		**Observed Frequency (O)**		**Expected Frequency (E)**		**X^2 $\sum(O-E)^2/E$**	**df**	**Level of Sig.**
		Young	Old	Young	Old			
Power sockets	Ticked	99	19	98.93	19.07	0.00	1	n.s
	Did not tick	67	13	67.07	12.93			
Quieter	Ticked	91	16	89.71	17.29	0.04	1	n.s
	Did not tick	75	16	76.29	14.71			
Daylight	Ticked	67	13	67.07	12.93	0.00	1	n.s
	Did not tick	99	19	98.93	19.07			
View	Ticked	63	16	66.23	12.77	0.26	1	n.s
	Did not tick	103	16	99.77	19.23			
Few passers by	Ticked	46	9	46.11	8.89	0.00	1	n.s
	Did not tick	120	23	119.89	23.11			
Distance from others	Ticked	47	6	44.43	8.57	0.20	1	n.s
	Did not tick	119	26	121.57	23.43			
Electric lighting	Ticked	19	5	20.12	3.88	0.07	1	n.s
	Did not tick	147	27	145.88	28.12			
Closest available seat	Ticked	19	0	15.93	3.07	0.65	1	n.s
	Did not tick	147	32	150.07	28.93			
Near shelves	Ticked	9	2	9.22	1.78	0.01	1	n.s
	Did not tick	157	30	156.78	30.22			
Near other people	Ticked	6	1	5.87	1.13	0.00	1	n.s
	Did not tick	160	31	160.13	30.87			

Table D.5. Room Survey: Statistical analysis of difference in responses of younger (aged 18-24) and older (aged 25-40) participants.

Factor		**Observed Frequency (O)**		**Expected Frequency (E)**		**X^2 $\sum(O-E)^2/E$**	**df**	**Level of Sig.**
		Young	Old	Young	Old			
Power sockets	Ticked	26	8	28.97	5.03	0.37	1	n.s
	Did not tick	141	21	138.03	23.97			
Quieter	Ticked	75	18	79.24	13.76	0.43	1	n.s
	Did not tick	92	11	87.76	15.24			
Daylight	Ticked	82	16	83.50	14.50	0.05	1	n.s
	Did not tick	85	13	83.50	14.50			
View	Ticked	54	20	63.05	10.95	2.09	1	n.s
	Did not tick	113	9	103.95	18.05			
Few passers by	Ticked	72	4	64.76	11.24	1.32	1	n.s
	Did not tick	95	25	102.24	17.76			
Distance from others	Ticked	74	8	69.87	12.13	0.42	1	n.s
	Did not tick	93	21	97.13	16.87			
Electric lighting	Ticked	18	2	17.04	2.96	0.06	1	n.s
	Did not tick	149	27	149.96	26.04			
Closest available seat	Ticked	32	2	28.97	5.03	0.38	1	n.s
	Did not tick	135	27	138.03	23.97			
Near shelves	Ticked	8	2	8.52	1.48	0.03	1	n.s
	Did not tick	159	27	158.48	27.52			
Near other people	Ticked	8	1	7.67	1.33	0.02	1	n.s
	Did not tick	159	28	159.33	27.67			

APPENDIX E. SNAPSHOT OBSERVATION RAW DATA

Table E.1. Occupancy rate (%) calculated for each individual seat.

Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3
1	45.5	94.0	43.3	**45**	3.3	26.0	0.0	**89**	0.0	12.0	0.0
2	66.7	98.0	50.0	**46**	2.2	2.0	0.0	**90**	1.1	18.0	0.0
3	22.2	30.0	12.0	**47**	10.0	34.0	6.4	**91**	6.7	32.0	4.4
4	22.2	22.0	11.2	**48**	0.0	20.0	2.2	**92**	3.3	8.0	4.4
5	32.2	82.0	31.1	**49**	0.0	36.0	0.0	**93**	0.0	2.0	0.0
6	21.1	28.0	21.0	**50**	0.0	14.0	0.0	**94**	2.2	16.0	2.2
7	78.9	98.0	66.0	**51**	7.8	14.0	4.4	**95**	0.0	18.0	0.0
8	17.8	86.0	14.0	**52**	0.0	2.0	2.2	**96**	2.2	14.0	0.0
9	56.7	94.0	47.8	**53**	0.0	14.0	0.0	**97**	4.4	16.0	4.4
10	41.1	92.0	37.0	**54**	3.3	4.0	2.2	**98**	0.0	12.0	0.0
11	74.4	96.0	58.0	**55**	2.2	12.0	2.2	**99**	0.0	12.0	4.4
12	33.3	92.0	22.2	**56**	2.2	10.0	0.0	**100**	1.1	36.0	0.0
13	58.9	90.0	45.6	**57**	4.4	20.0	2.2	**101**	0.0	18.0	0.0
14	47.8	96.0	35.6	**58**	2.2	4.0	2.2	**102**	0.0	8.0	0.0
15	58.9	96.0	66.7	**59**	0.0	32.0	0.0	**103**	3.3	12.0	1.1
16	48.9	90.0	47.8	**60**	4.4	24.0	4.4	**104**	1.1	18.0	1.1
17	24.4	96.0	26.7	**61**	0.0	18.0	2.2	**105**	0.0	32.0	0.0
18	76.7	92.0	75.6	**62**	0.0	10.0	0.0	**106**	0.0	24.0	0.0
19	71.1	94.0	66.7	**63**	0.0	40.0	1.1	**107**	0.0	12.0	2.2
20	31.1	82.0	44.4	**64**	4.4	44.0	2.2	**108**	3.3	34.0	2.2
21	22.2	86.0	20.0	**65**	2.2	44.0	2.2	**109**	0.0	24.0	2.2
22	56.7	88.0	43.3	**66**	10.0	34.0	8.7	**110**	0.0	46.0	0.0
23	64.4	100.0	48.9	**67**	1.1	34.0	1.1	**111**	8.9	18.0	6.2
24	53.3	96.0	53.3	**68**	0.0	22.0	1.1	**112**	1.1	16.0	0.0
25	5.6	12.0	15.6	**69**	3.3	34.0	0.0	**113**	2.2	8.0	0.0
26	33.3	48.0	24.4	**70**	1.1	54.0	1.1	**114**	0.0	22.0	2.2
27	22.2	40.0	15.6	**71**	1.1	42.0	2.2	**115**	0.0	34.0	2.2
28	0.0	4.0	2.2	**72**	0.0	22.0	0.0	**116**	0.0	42.0	0.0
29	0.0	2.0	2.2	**73**	1.1	52.0	0.0	**117**	1.1	14.0	0.0
30	0.0	10.0	2.2	**74**	4.4	46.0	4.4	**118**	0.0	12.0	0.0
31	25.6	60.0	17.8	**75**	0.0	26.0	2.2	**119**	3.3	22.0	0.0
32	8.9	10.0	6.7	**76**	1.1	28.0	0.0	**120**	0.0	38.0	0.0
33	0.0	4.0	0.0	**77**	3.3	50.0	2.2	**121**	1.1	24.0	0.0
34	0.0	20.0	0.0	**78**	0.0	54.0	0.0	**122**	0.0	28.0	2.2
35	0.0	28.0	0.0	**79**	5.6	2.0	4.4	**123**	10.0	10.0	6.7
36	3.3	10.0	0.0	**80**	3.3	2.0	4.4	**124**	0.0	30.0	0.0
37	3.3	16.0	2.2	**81**	3.3	2.0	0.0	**125**	3.3	38.0	0.0
38	3.3	0.0	0.0	**82**	3.3	0.0	0.0	**126**	0.0	34.0	0.0
39	2.2	8.0	4.4	**83**	1.1	8.0	0.0	**127**	1.1	0.0	0.0
40	0.0	14.0	0.0	**84**	7.8	0.0	4.4	**128**	2.2	0.0	0.0
41	5.6	32.0	4.2	**85**	2.2	8.0	2.2	**129**	4.4	48.0	4.4
42	0.0	24.0	0.0	**86**	0.0	34.0	2.2	**130**	5.6	48.0	4.4
43	2.2	16.0	4.7	**87**	3.3	24.0	0.0	**131**	2.2	30.0	2.2
44	2.2	12.0	4.4	**88**	0.0	18.0	2.2	**132**	2.2	40.0	0.0

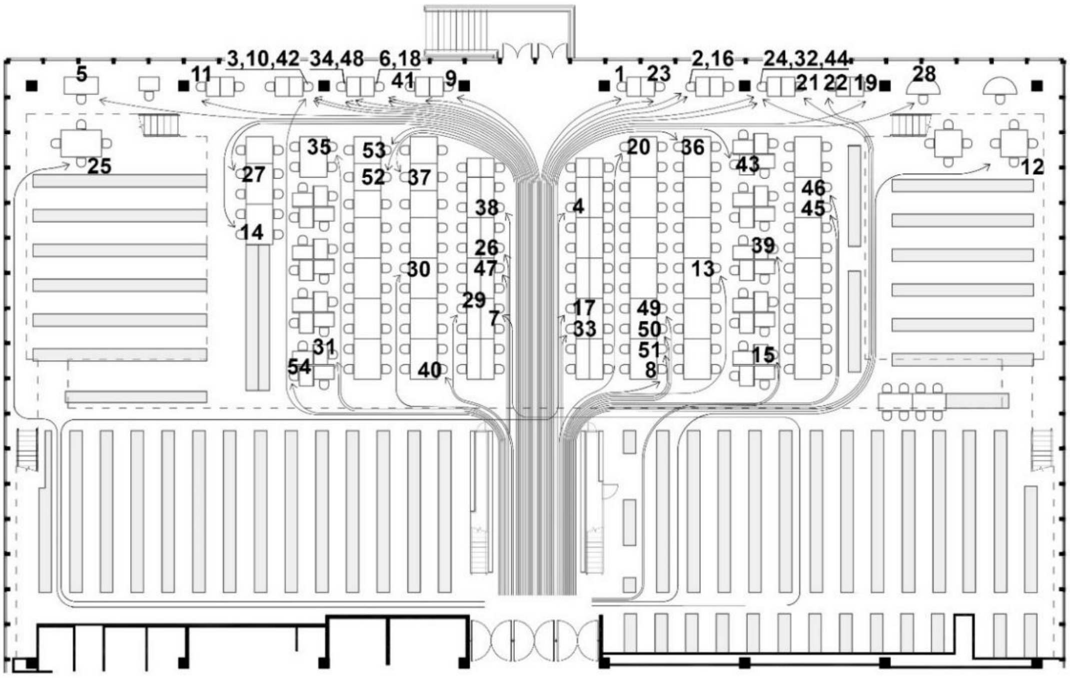
Table E.1. Occupancy rate (%) calculated for each individual seat (continued).

Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3
133	0.0	14.0	0.0	**173**	2.2	36.0	0.0	**213**	1.1	30.0	0.0
134	0.0	12.0	0.0	**174**	0.0	18.0	0.0	**214**	7.8	36.0	0.0
135	0.0	50.0	0.0	**175**	2.2	10.0	2.9	**215**	0.0	26.0	0.0
136	0.0	14.0	0.0	**176**	0.0	30.0	2.2	**216**	2.2	54.0	2.2
137	0.0	18.0	2.2	**177**	0.0	6.0	4.4	**217**	5.6	44.0	2.0
138	0.0	32.0	0.0	**178**	0.0	16.0	0.0	**218**	6.7	48.0	0.0
139	0.0	40.0	0.0	**179**	6.7	18.0	4.4	**219**	0.0	18.0	0.0
140	2.2	14.0	0.0	**180**	8.9	10.0	4.4	**220**	0.0	24.0	0.0
141	0.0	28.0	2.2	**181**	6.7	16.0	4.4	**221**	0.0	14.0	0.0
142	2.2	26.0	0.0	**182**	3.3	22.0	3.3	**222**	2.2	8.0	4.4
143	1.1	44.0	1.1	**183**	0.0	22.0	6.7	**223**	0.0	34.0	0.0
144	0.0	28.0	0.0	**184**	10.2	12.0	8.4	**224**	5.6	24.0	2.2
145	2.2	18.0	0.0	**185**	0.0	6.0	0.0	**225**	5.6	10.0	6.7
146	0.0	22.0	0.0	**186**	10.6	22.0	14.4	**226**	13.3	18.0	11.1
147	1.1	52.0	1.1	**187**	0.0	6.0	0.0	**227**	0.0	4.0	0.0
148	0.0	28.0	0.0	**188**	1.1	14.0	2.2	**228**	1.1	14.0	0.0
149	1.1	0.0	1.1	**189**	0.0	12.0	4.4	**229**	1.1	18.0	0.0
150	0.0	0.0	0.0	**190**	7.8	30.0	6.4	**230**	7.8	44.0	6.7
151	0.0	32.0	6.1	**191**	2.2	10.0	2.2	**231**	0.0	14.0	0.0
152	0.0	28.0	2.2	**192**	2.2	24.0	2.2	**232**	1.1	10.0	1.1
153	13.3	16.0	10.3	**193**	0.0	20.0	2.2	**233**	1.1	10.0	1.1
154	2.2	18.0	0.0	**194**	0.0	22.0	0.0	**234**	5.6	26.0	4.4
155	0.0	8.0	0.0	**195**	3.3	8.0	0.0	**235**	2.2	8.0	2.2
156	2.2	10.0	4.4	**196**	2.2	16.0	0.0	**236**	0.0	34.0	0.0
157	0.0	46.0	4.4	**197**	0.0	14.0	0.0	**237**	0.0	14.0	0.0
158	0.0	12.0	2.2	**198**	0.0	24.0	0.0	**238**	3.3	26.0	4.4
159	2.2	10.0	0.0	**199**	0.0	38.0	4.4	**239**	0.0	14.0	2.2
160	0.0	12.0	0.0	**200**	1.1	32.0	1.9	**240**	4.4	32.0	4.4
161	4.4	18.0	0.0	**201**	3.3	40.0	4.4	**241**	0.0	14.0	0.0
162	2.2	14.0	2.2	**202**	0.0	36.0	0.0	**242**	0.0	32.0	0.0
163	2.2	10.0	0.0	**203**	0.0	14.0	0.0	**243**	1.1	16.0	1.9
164	0.0	20.0	2.2	**204**	18.8	38.0	12.2	**244**	6.7	4.0	6.2
165	0.0	24.0	0.0	**205**	0.0	32.0	0.0	**245**	7.8	22.0	8.2
166	0.0	24.0	2.2	**206**	1.1	48.0	6.7	**246**	11.1	24.0	14.4
167	10.9	22.0	8.2	**207**	0.0	26.0	0.0	**247**	0.0	0.0	0.00
168	0.0	18.0	2.2	**208**	15.6	42.0	12.2	**248**	0.0	0.0	0.00
169	0.0	30.0	2.2	**209**	1.1	24.0	0.0	**249**	0.0	2.0	0.00
170	0.0	16.0	2.2	**210**	4.4	14.0	0.0	**250**	0.0	0.0	0.00
171	0.0	10.0	0.0	**211**	4.4	36.0	0.0				
172	1.1	16.0	0.0	**212**	12.2	52.0	1.1				

APPENDIX F. WALK-THROUGH OBSERVATION RAW DATA

Table F.1. Raw data for walk-through experiment (**day 1**). S=Single, G=Group, P=Paper-based, C=Computer-based.

DATE: 10.08.2015



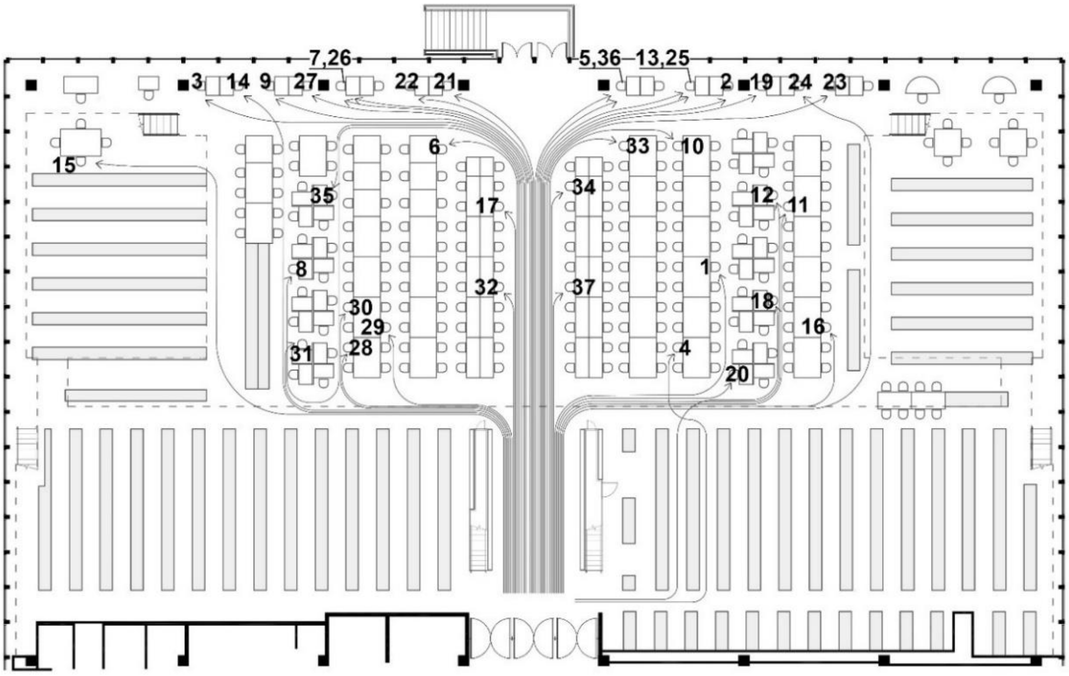
Occupant ID Number	Intended Use (S/G)	Time Seated	Time Departed	Activity (P/C)	Power Socket at Desk	
					Availability (Yes/No)	Usage (Yes/No)
1	S	09:08	17:05	P	Y	N
2	S	09:11	10:00	P	N	N
3	S	09:14	09:52	P	Y	N
4	S	09:15	12:04	C	N	N
5	S	09:21	16:00	C	Y	Y
6	S	09:22	10:25	P	N	N
7	S	09:27	10:44	P	N	N
8	S	09:34	10:13	C	N	N
9	S	09:43	11:07	C	Y	Y
10	S	09:52	15:17	C	Y	Y
11	S	09:54	16:34	C	Y	Y
12	S	10:07	16:12	C	Y	Y
13	S	10:22	16:14	P	N	N
14	S	10:23	12:22	P	N	N
15	S	10:42	10:44	P	N	N
16	S	10:49	18:00	P	Y	N
17	S	11:01	11:04	P	N	N
18	S	11:03	14:46	C	N	N
19	S	11:14	18:00	C	Y	Y
20	S	11:31	16:26	P	N	N

Table F.1. Continued.

Occupant ID Number	**Intended Use (S/G)**	**Time Seated**	**Time Departed**	**Activity (P/C)**	**Power Socket at Desk**	
					Availability (Yes/No)	**Usage (Yes/No)**
21	G (22)	11:33	14:56	C	N	N
22	G (21)	11:33	14:56	P	N	N
23	S	11:35	14:23	C	N	N
24	S	11:48	12:05	P	Y	N
25	S	11:57	18:00	P	Y	N
26	S	12:10	12:28	P	N	N
27	S	12:46	15:27	C	N	N
28	S	13:08	14:21	C	Y	Y
29	S	13:09	17:00	P	N	N
30	S	13:18	16:14	P	N	N
31	S	13:21	14:28	P	N	N
32	S	13:25	13:42	P	Y	N
33	S	13:46	13:52	C	N	N
34	S	14:03	15:00	P	Y	N
35	S	14:05	14:15	C	N	N
36	S	14:17	15:13	P	N	N
37	S	14:27	18:00	P	N	N
38	S	14:55	15:01	C	N	N
39	S	15:12	17:15	P	N	N
40	S	15:20	16:15	P	N	N
41	S	15:24	17:45	C	N	N
42	S	15:35	18:00	P	Y	N
43	S	15:37	16:22	C	N	N
44	S	15:37	17:07	P	Y	N
45	G (46)	15:38	17:00	P	N	N
46	G (45)	15:38	17:00	P	N	N
47	S	15:49	17:15	C	N	N
48	S	15:55	18:00	P	Y	N
49	G (50,51)	15:57	17:45	P	N	N
50	G (49,51)	15:57	17:45	P	N	N
51	G (49,51)	15:57	17:45	P	N	N
52	G (53)	15:58	17:10	P	N	N
53	G (52)	15:58	17:10	P	N	N
54	S	16:48	17:45	C	N	N

Table F.2. Raw data for walk-through experiment (**day 2**). S=Single, G=Group, P=Paper-based, C=Computer-based.

DATE: 11.08.2015



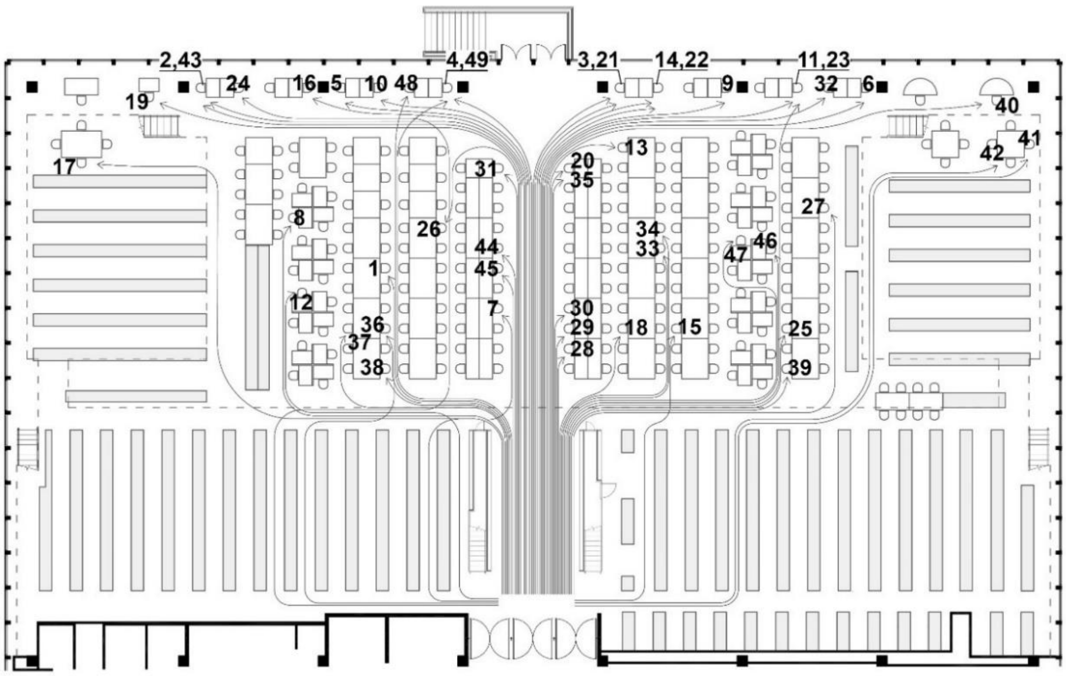
Occupant ID Number	Intended Use (S/G)	Time Seated	Time Departed	Activity (P/C)	Power Socket at Desk	
					Availability (Yes/No)	Usage (Yes/No)
1	S	09:00	11:05	P	N	N
2	S	09:24	18:00	C	Y	Y
3	S	09:28	12:37	C	Y	Y
4	S	09:37	12:58	P	N	N
5	S	09:48	16:07	P	Y	N
6	S	09:59	15:23	P	N	N
7	S	10:01	15:12	C	Y	Y
8	S	10:09	10:41	P	N	N
9	S	10:43	18:00	P	N	N
10	S	10:50	12:15	C	N	N
11	S	11:15	15:27	P	N	N
12	S	11:28	16:45	C	N	N
13	S	11:30	15:02	C	N	N
14	S	11:43	15:45	P	N	N
15	S	12:02	18:00	C	Y	Y
16	S	12:14	16:01	C	N	N
17	S	12:22	12:24	P	N	N
18	S	12:36	15:22	P	N	N
19	S	12:38	18:00	C	Y	Y
20	S	13:15	13:30	P	N	N
21	G (21,22)	13:20	18:00	C	Y	Y
22	G (21,22)	13:20	18:00	C	N	N

Table F.2. Continued.

Occupant ID Number	**Intended Use (S/G)**	**Time Seated**	**Time Departed**	**Activity (P/C)**	**Power Socket at Desk**	
					Availability (Yes/No)	**Usage (Yes/No)**
23	S	14:05	18:00	C	N	N
24	S	14:36	18:00	C	N	N
25	S	15:07	16:00	P	N	N
26	G (26,27)	15:31	18:00	C	Y	Y
27	G (26,27)	15:31	18:00	C	Y	Y
28	G (28-30)	15:38	18:00	C	N	N
29	G (28-30)	15:38	18:00	C	N	N
30	G (28-30)	15:38	18:00	C	N	N
31	S	15:38	16:30	P	N	N
32	S	15:45	15:52	P	N	N
33	S	16:02	17:00	C	N	N
34	S	16:07	18:00	P	N	N
35	S	16:08	18:00	C	N	N
36	S	16:10	18:00	C	Y	Y
37	S	16:48	17:30	C	N	N

Table F.3. Raw data for walk-through experiment (**day 3**). S=Single, G=Group, P=Paper-based, C=Computer-based.

DATE: 12.08.2015



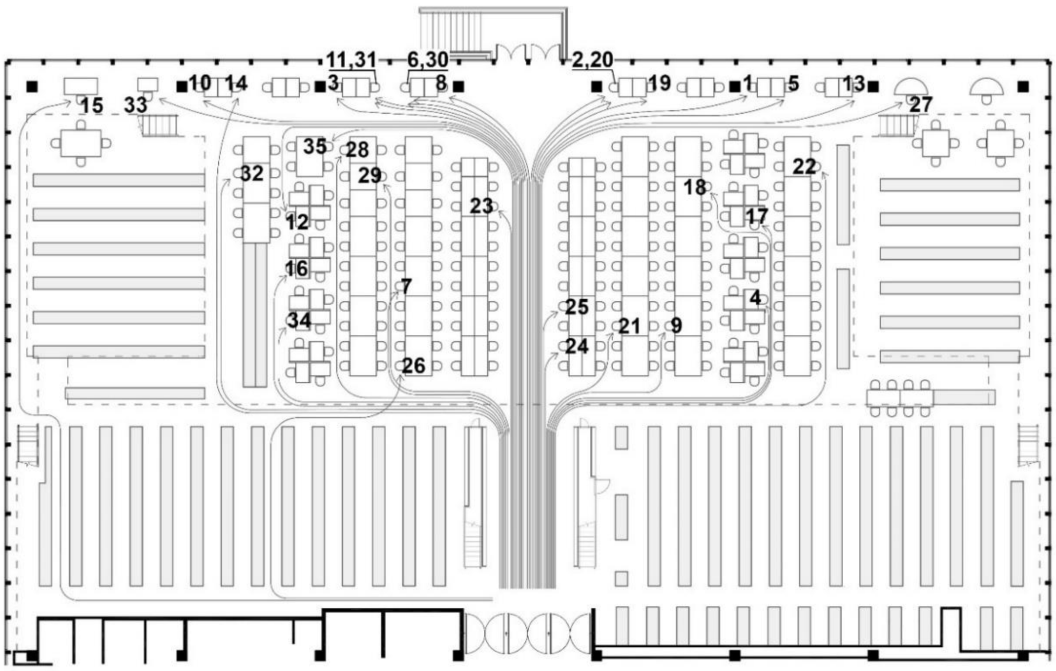
Occupant ID Number	Intended Use (S/G)	Time Seated	Time Departed	Activity (P/C)	Power Socket at Desk	
					Availability (Yes/No)	Usage (Yes/No)
1	S	09:00	18:00	P	Y	N
2	S	09:03	14:06	P	N	N
3	S	09:16	12:17	P	Y	N
4	S	09:36	15:00	C	N	N
5	S	09:41	17:00	C	Y	Y
6	S	09:43	14:10	P	N	N
7	S	09:46	10:59	P	N	N
8	S	09:47	13:10	C	N	N
9	S	09:52	13:56	C	Y	Y
10	S	10:06	16:40	C	Y	Y
11	S	10:21	11:15	C	Y	Y
12	S	10:22	13:00	C	Y	Y
13	S	10:26	12:26	P	N	N
14	S	10:33	12:43	P	N	N
15	S	10:35	13:15	P	N	N
16	S	11:02	16:44	P	Y	N
17	S	11:21	13:10	P	N	N
18	S	11:57	13:26	C	N	N
19	S	12:50	18:00	C	Y	Y
20	S	12:56	13:00	P	N	N
21	G (22)	12:58	16:00	C	N	N
22	G (21)	12:58	14:06	P	N	N
23	S	09:00	17:00	P	N	N

Table F.3. Continued.

Occupant ID Number	Intended Use (S/G)	Time Seated	Time Departed	Activity (P/C)	Power Socket at Desk	
					Availability (Yes/No)	Usage (Yes/No)
24	S	13:00	13:24	P	N	N
25	S	13:30	13:58	P	N	N
26	S	13:38	14:00	P	N	N
27	S	13:49	14:42	P	N	N
28	G (29,30)	13:52	17:45	P	N	N
29	G (28,30)	14:23	14:15	P	N	N
30	G (28,29)	14:23	14:51	P	N	N
31	S	14:23	15:15	P	N	N
32	S	14:30	15:30	C	N	N
33	G (34)	14:36	14:30	C	N	N
34	G (33)	14:47	14:30	P	N	N
35	S	14:47	14:30	P	N	N
36	G (37,38)	14:48	14:46	C	N	N
37	G (36,38)	15:02	17:15	P	N	N
38	G (36,37)	15:02	16:41	P	N	N
39	S	15:02	16:41	C	N	N
40	S	15:13	15:00	P	Y	N
41	G (42)	15:37	18:00	C	Y	Y
42	G (41)	16:03	18:00	P	N	N
43	S	16:03	18:00	P	Y	N
44	G (45)	16:08	17:30	C	N	N
45	G (44)	16:17	17:15	P	N	N
46	G (47)	16:17	18:00	C	N	N
47	G (46)	16:39	16:10	P	N	N
48	G (49)	16:39	18:00	P	N	N
49	G (48)	16:47	17:15	P	Y	N

Table F.4. Raw data for walk-through experiment (**day 4**). S=Single, G=Group, P=Paper-based, C=Computer-based.

DATE: 13.08.2015



Occupant ID Number	Intended Use (S/G)	Time Seated	Time Departed	Activity (P/C)	Power Socket at Desk	
					Availability (Yes/No)	**Usage (Yes/No)**
1	S	09:09	17:05	P	Y	N
2	S	09:30	14:56	C	Y	Y
3	S	10:15	17:13	C	Y	Y
4	S	10:29	15:58	C	N	N
5	S	10:34	14:26	C	N	N
6	S	10:34	13:31	P	N	N
7	S	10:38	16:31	P	N	N
8	S	10:49	12:26	C	Y	Y
9	S	11:00	12:30	P	N	N
10	S	11:10	12:34	C	Y	Y
11	S	11:37	14:23	P	N	N
12	S	12:11	13:22	P	N	N
13	S	12:14	18:00	C	Y	Y
14	S	12:49	15:45	P	N	N
15	S	13:05	15:30	C	Y	Y
16	S	13:41	15:23	C	N	N
17	G (18)	14:08	18:00	P	N	N
18	G (17)	14:08	18:00	P	N	N
19	S	14:20	15:45	P	N	N
20	S	14:56	18:00	P	Y	N
21	S	15:10	15:37	P	N	N
22	S	15:14	18:00	C	N	N

Table F.4. Continued.

Occupant ID Number	Intended Use (S/G)	Time Seated	Time Departed	Activity (P/C)	Power Socket at Desk	
					Availability (Yes/No)	Usage (Yes/No)
23	S	15:23	15:46	C	N	N
24	G (25)	15:35	15:46	P	N	N
25	G (24)	15:35	15:46	P	N	N
26	S	15:35	15:41	P	N	N
27	S	15:58	18:00	P	Y	N
28	G (29)	16:07	18:00	C	N	N
29	G (28)	16:07	18:00	P	N	N
30	G (31)	16:15	18:00	P	N	N
31	G (30)	16:15	18:00	P	N	N
32	S	16:15	18:00	P	N	N
33	S	16:22	18:00	P	Y	N
34	S	16:23	18:00	P	N	N
35	S	16:47	18:00	P	N	N

Table F.5. Raw data for walk-through experiment (**day 5**). S=Single, G=Group, P=Paper-based, C=Computer-based.

DATE: 14.08.2015

Occupant ID Number	Intended Use (S/G)	Time Seated	Time Departed	Activity (P/C)	Power Socket at Desk	
					Availability (Yes/No)	**Usage (Yes/No)**
1	S	09:32	14:57	C	Y	Y
2	S	09:42	14:42	C	Y	Y
3	G (4)	10:12	14:20	C	Y	Y
4	G (3)	10:12	14:20	C	N	N
5	S	10:21	15:52	C	N	N
6	S	10:23	10:35	P	N	N
7	S	10:27	13:03	P	N	N
8	S	10:54	16:43	C	Y	Y
9	S	10:56	14:24	P	N	N
10	S	10:58	11:04	P	N	N
11	S	11:05	14:38	P	N	N
12	S	11:13	12:36	C	Y	Y
13	S	11:55	14:28	P	N	N
14	S	12:04	12:57	P	N	N
15	S	12:58	14:14	P	Y	N
16	G (17)	13:10	13:32	C	Y	Y
17	G (16)	13:10	13:32	C	N	N
18	S	13:13	17:15	P	Y	N
19	S	14:30	17:53	P	Y	N
20	S	14:47	18:00	C	Y	Y
21	S	14:47	17:55	C	Y	Y
22	S	14:50	18:00	P	Y	N
23	S	14:55	17:13	C	Y	Y

Table F.5. Continued.

Occupant ID Number	**Intended Use (S/G)**	**Time Seated**	**Time Departed**	**Activity (P/C)**	**Power Socket at Desk**	
					Availability (Yes/No)	**Usage (Yes/No)**
24	S	14:57	18:00	C	Y	Y
25	S	15:11	17:29	P	N	N
26	S	15:34	18:00	P	N	N
27	S	15:39	17:47	C	N	N
28	S	16:33	17:35	P	N	N

APPENDIX G. AVAILABILITY OF POWER SOCKETS

Table G.1. Availability of power socket for each individual seat. AV= Availability, Y=Yes, N=No.

Seat	AV	Seat	AV	Seat	AV	Seat	AV	Seat	AV	Seat	AV
1	Y	**46**	N	**91**	N	**136**	N	**181**	N	**226**	N
2	Y	**47**	N	**92**	N	**137**	N	**182**	N	**227**	N
3	Y	**48**	N	**93**	N	**138**	N	**183**	N	**228**	N
4	Y	**49**	N	**94**	N	**139**	N	**184**	N	**229**	N
5	Y	**50**	N	**95**	N	**140**	N	**185**	N	**230**	N
6	Y	**51**	N	**96**	N	**141**	N	**186**	N	**231**	N
7	Y	**52**	N	**97**	N	**142**	N	**187**	N	**232**	N
8	N	**53**	N	**98**	N	**143**	N	**188**	N	**233**	N
9	N	**54**	N	**99**	N	**144**	N	**189**	N	**234**	N
10	Y	**55**	N	**100**	N	**145**	N	**190**	N	**235**	N
11	Y	**56**	N	**101**	N	**146**	N	**191**	N	**236**	N
12	N	**57**	N	**102**	N	**147**	N	**192**	N	**237**	N
13	N	**58**	N	**103**	N	**148**	N	**193**	N	**238**	N
14	Y	**59**	N	**104**	N	**149**	N	**194**	N	**239**	N
15	Y	**60**	N	**105**	N	**150**	N	**195**	N	**240**	N
16	N	**61**	N	**106**	N	**151**	N	**196**	N	**241**	N
17	N	**62**	N	**107**	N	**152**	N	**197**	N	**242**	N
18	Y	**63**	N	**108**	N	**153**	N	**198**	N	**243**	N
19	Y	**64**	N	**109**	N	**154**	N	**199**	N	**244**	N
20	N	**65**	N	**110**	N	**155**	N	**200**	N	**245**	N
21	N	**66**	N	**111**	N	**156**	N	**201**	N	**246**	N
22	Y	**67**	N	**112**	N	**157**	N	**202**	N	**247**	N
23	Y	**68**	N	**113**	N	**158**	N	**203**	N	**248**	N
24	Y	**69**	N	**114**	N	**159**	N	**204**	N	**249**	N
25	Y	**70**	N	**115**	N	**160**	N	**205**	N	**250**	N
26	Y	**71**	N	**116**	N	**161**	N	**206**	N		
27	Y	**72**	N	**117**	N	**162**	N	**207**	N		
28	Y	**73**	N	**118**	N	**163**	N	**208**	N		
29	N	**74**	N	**119**	N	**164**	N	**209**	N		
30	N	**75**	N	**120**	N	**165**	N	**210**	N		
31	N	**76**	N	**121**	N	**166**	N	**211**	N		
32	N	**77**	N	**122**	N	**167**	N	**212**	N		
33	N	**78**	N	**123**	N	**168**	N	**213**	N		
34	N	**79**	N	**124**	N	**169**	N	**214**	N		
35	N	**80**	N	**125**	N	**170**	N	**215**	N		
36	N	**81**	N	**126**	N	**171**	N	**216**	N		
37	N	**82**	N	**127**	N	**172**	N	**217**	N		
38	N	**83**	N	**128**	N	**173**	N	**218**	N		
39	N	**84**	N	**129**	N	**174**	N	**219**	N		
40	N	**85**	N	**130**	N	**175**	N	**220**	N		
41	N	**86**	N	**131**	N	**176**	N	**221**	N		
42	N	**87**	N	**132**	N	**177**	N	**222**	N		
43	N	**88**	N	**133**	N	**178**	N	**223**	N		
44	N	**89**	N	**134**	N	**179**	N	**224**	N		
45	N	**90**	N	**135**	N	**180**	N	**225**	N		

APPENDIX H. THE LOCAL OCCUPANCY DENSITY

Table H.1. Local occupancy density calculated for each occupant. ON=Occupant number, LOD=Local occupancy density.

Day 1		Day 2		Day 3		Day 4		Day 5	
ON	**LOD**	**ON**	**LOD**	**ON**	**LOD**	**ON**	**LOD**	**ON**	**LOD**
1	0	**1**	0	**1**	0	**1**	0	**1**	0
2	0	**2**	0	**2**	0	**2**	0	**2**	0
3	0	**3**	0	**3**	0	**3**	0	**3**	0
4	0	**4**	0	**4**	0	**4**	0	**4**	0
5	0	**5**	0	**5**	0	**5**	0	**5**	0
6	0	**6**	0	**6**	0	**6**	0	**6**	0
7	0	**7**	0	**7**	0	**7**	0	**7**	0
8	0	**8**	0	**8**	0	**8**	0	**8**	0
9	0	**9**	0	**9**	0	**9**	0	**9**	0
10	0	**10**	0	**10**	0	**10**	0	**10**	0
11	0	**11**	0	**11**	0	**11**	0	**11**	0
12	0	**12**	0	**12**	0	**12**	0	**12**	0
13	0	**13**	0	**13**	0	**13**	0	**13**	0
14	0	**14**	0	**14**	0	**14**	0	**14**	0
15	0	**15**	0	**15**	0	**15**	0	**15**	0
16	0	**16**	0	**16**	0	**16**	0	**16**	0
17	0	**17**	0	**17**	0	**17**	0	**17**	0
18	0	**18**	0	**18**	0	**18**	0	**18**	0
19	0	**19**	0	**19**	0	**19**	0	**19**	0
20	0	**20**	0	**20**	0	**20**	0	**20**	0
21	0	**21**	0	**21**	0	**21**	0	**21**	0
22	0	**22**	0	**22**	0	**22**	0	**22**	0
23	0	**23**	0	**23**	0	**23**	0	**23**	0
24	0	**24**	0	**24**	0	**24**	0	**24**	0
25	0	**25**	0	**25**	0	**25**	0	**25**	0
26	0	**26**	0	**26**	0	**26**	0	**26**	0
27	0	**27**	0	**27**	0	**27**	0	**27**	0
28	0	**28**	0.2	**28**	0.2	**28**	0.3	**28**	0
29	0	**29**	0.4	**29**	0.4	**29**	0.2		
30	0	**30**	0.2	**30**	0.4	**30**	0		
31	0	**31**	0	**31**	0	**31**	1		
32	0	**32**	0	**32**	0	**32**	0		
33	0	**33**	0	**33**	0.2	**33**	0		
34	0	**34**	0	**34**	0.2	**34**	0		
35	0	**35**	0	**35**	0	**35**	0		
36	0	**36**	0	**36**	0.2				
37	0	**37**	0	**37**	0.2				
38	0			**38**	0				
39	0			**39**	0				
40	0			**40**	0				
41	0			**41**	0.3				
42	0			**42**	0.3				
43	0			**43**	0				
44	0			**44**	0.2				
45	0.2			**45**	0.2				
46	0.2			**46**	0				
47	0			**47**	0				
48	0			**48**	1				
49	0.2			**49**	1				
50	0.4								
51	0.2								
52	0.2								
53	0.2								
54	0								

APPENDIX I. SIMULATION RESULTS

Table I.1. Mean horizontal illuminance (lux) for each individual seat.

Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3
1	14334	2723	10487	**45**	4732	945	3717	**89**	3247	649	2754
2	9828	2441	7623	**46**	4787	922	3827	**90**	3252	661	2754
3	9602	2432	7431	**47**	2446	678	2052	**91**	2282	573	2024
4	8173	2229	6367	**48**	3320	712	2763	**92**	2859	573	2537
5	8984	2229	6792	**49**	2161	574	1845	**93**	1991	466	1667
6	9207	2717	7265	**50**	3128	556	2653	**94**	2000	483	1675
7	9102	1926	7389	**51**	1855	412	1542	**95**	1785	357	1512
8	8533	1949	6840	**52**	1905	433	1538	**96**	1796	360	1516
9	8820	1975	6991	**53**	1488	373	1215	**97**	1323	354	1192
10	8900	1927	7075	**54**	1692	388	1492	**98**	1561	355	1441
11	8759	1788	7078	**55**	1383	289	1190	**99**	1151	296	917
12	8045	1818	6256	**56**	1381	307	1198	**100**	1389	297	1170
13	8662	1833	6976	**57**	1245	235	1064	**101**	1094	281	925
14	8697	1902	6807	**58**	1305	275	1134	**102**	1336	284	1176
15	8742	1725	7191	**59**	848	213	660	**103**	913	262	832
16	7923	1803	6213	**60**	891	249	722	**104**	952	266	762
17	8606	1822	6882	**61**	744	202	599	**105**	882	234	726
18	8669	1861	6902	**62**	854	217	665	**106**	943	235	754
19	8683	1768	7198	**63**	4380	986	3967	**107**	4566	827	3445
20	8171	1824	6382	**64**	5088	1025	4052	**108**	4362	836	3480
21	8951	1971	7131	**65**	3054	822	2623	**109**	2679	768	2358
22	8005	1983	6522	**66**	3581	769	3143	**110**	3496	757	3126
23	10125	2022	7838	**67**	2609	658	2224	**111**	2939	634	2520
24	10323	2302	7958	**68**	2370	663	1992	**112**	3171	637	2775
25	7454	1730	6085	**69**	2804	547	2506	**113**	2569	550	2285
26	7392	1753	5868	**70**	2002	549	1750	**114**	2230	564	2026
27	7014	1582	5673	**71**	1964	449	1586	**115**	1734	483	1408
28	7237	1587	5973	**72**	1733	452	1345	**116**	1969	485	1657
29	5926	1373	4974	**73**	1688	411	1396	**117**	1865	389	1391
30	5903	1378	5326	**74**	1701	413	1403	**118**	1869	390	1395
31	6249	1342	5022	**75**	1510	359	1252	**119**	1615	364	1341
32	5508	1361	4798	**76**	1521	361	1258	**120**	1386	365	1100
33	5712	1166	4628	**77**	1392	311	1217	**121**	1498	339	1220
34	5533	1095	4509	**78**	1401	313	1226	**122**	1268	339	978
35	3779	879	3340	**79**	1198	277	1121	**123**	1343	286	1120
36	3756	825	3367	**80**	1207	280	1132	**124**	1109	288	873
37	3299	680	2876	**81**	912	247	717	**125**	981	258	789
38	3101	675	2771	**82**	915	264	780	**126**	990	265	777
39	2933	521	2512	**83**	844	235	687	**127**	945	256	766
40	2644	580	2460	**84**	904	228	725	**128**	907	230	747
41	3027	535	2683	**85**	4522	1009	4098	**129**	4567	885	3750
42	3091	556	2687	**86**	5254	958	4302	**130**	4750	864	3830
43	5371	1087	4223	**87**	3455	786	3035	**131**	3210	722	2853
44	4818	1089	3805	**88**	3712	841	3206	**132**	3372	718	2984

Table I.1. Continued.

Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3
133	2290	625	2033	**173**	958	262	772	**213**	1320	307	1059
134	3053	630	2658	**174**	906	251	722	**214**	1073	285	897
135	2869	506	2598	**175**	5443	1009	4154	**215**	959	240	712
136	2826	509	2467	**176**	4892	967	3783	**216**	880	253	723
137	2004	460	1605	**177**	4865	846	3894	**217**	869	238	649
138	2009	476	1605	**178**	4861	842	3814	**218**	822	221	608
139	1708	434	1550	**179**	3554	742	3013	**219**	4704	1125	4264
140	1706	448	1551	**180**	3514	743	2879	**220**	5652	1171	4586
141	1627	366	1363	**181**	2306	589	1957	**221**	4148	906	4093
142	1631	382	1365	**182**	3056	587	2574	**222**	3488	936	3630
143	1415	331	1212	**183**	2615	518	2183	**223**	3395	742	2860
144	1418	316	1213	**184**	2791	517	2279	**224**	3427	701	2945
145	1386	285	1178	**185**	1791	443	1361	**225**	3097	632	2350
146	1156	271	932	**186**	2016	445	1608	**226**	3061	612	2351
147	1003	262	859	**187**	1694	366	1452	**227**	2183	494	2015
148	947	254	817	**188**	1690	381	1451	**228**	2705	560	1845
149	962	259	770	**189**	1550	350	1242	**229**	1776	447	1112
150	886	243	730	**190**	1552	350	1238	**230**	1752	425	1090
151	4571	1002	3274	**191**	1399	326	1186	**231**	1325	381	974
152	4155	1030	3709	**192**	1395	325	1176	**232**	1615	353	986
153	3307	857	2925	**193**	1257	295	1115	**233**	1247	331	670
154	3743	872	3388	**194**	1252	295	1107	**234**	1465	335	825
155	2896	731	2256	**195**	946	258	752	**235**	1049	302	526
156	2721	730	2157	**196**	928	245	738	**236**	1383	330	723
157	3204	623	2747	**197**	874	234	700	**237**	1177	245	433
158	2635	626	2246	**198**	903	248	697	**238**	1267	303	616
159	2856	534	2450	**199**	5243	1040	4309	**239**	911	237	348
160	2267	519	1942	**200**	4751	1075	3891	**240**	861	257	373
161	1933	455	1662	**201**	4374	922	3633	**241**	836	228	340
162	1941	455	1658	**202**	4418	906	3420	**242**	826	232	306
163	1746	396	1551	**203**	3227	678	2669	**243**	189	62	209
164	1749	397	1551	**204**	3000	687	2597	**244**	175	56	181
165	1655	399	1371	**205**	2995	587	2441	**245**	173	58	154
166	1651	399	1368	**206**	2938	552	2554	**246**	154	52	136
167	1398	315	1249	**207**	1886	463	1505	**247**	203	65	214
168	1390	314	1245	**208**	1626	477	1274	**248**	172	54	164
169	1297	275	1140	**209**	1705	386	1357	**249**	175	61	157
170	1291	275	1133	**210**	1547	414	1184	**250**	157	56	136
171	974	250	805	**211**	1435	312	1145				
172	973	268	803	**212**	1129	312	965				

Table I.2. Daylight factor (DF, %) for each individual seat.

Seat	DF	Seat	DF	Seat	DF	Seat	DF	Seat	DF	Seat	DF
1	20.83	**46**	6.50	**91**	3.98	**136**	4.22	**181**	4.47	**226**	3.50
2	18.21	**47**	4.83	**92**	3.99	**137**	3.22	**182**	4.45	**227**	2.64
3	14.30	**48**	5.11	**93**	3.38	**138**	3.22	**183**	3.66	**228**	2.43
4	12.79	**49**	4.81	**94**	3.40	**139**	3.05	**184**	3.62	**229**	1.95
5	12.68	**50**	4.43	**95**	2.97	**140**	3.06	**185**	3.24	**230**	1.84
6	14.34	**51**	3.11	**96**	2.98	**141**	2.55	**186**	3.24	**231**	1.59
7	17.29	**52**	3.07	**97**	2.79	**142**	2.56	**187**	2.82	**232**	1.58
8	17.18	**53**	2.90	**98**	2.79	**143**	2.18	**188**	2.81	**233**	1.47
9	16.35	**54**	2.95	**99**	2.09	**144**	2.19	**189**	2.26	**234**	1.23
10	17.20	**55**	2.24	**100**	2.11	**145**	2.10	**190**	2.25	**235**	1.15
11	16.60	**56**	2.23	**101**	2.10	**146**	2.10	**191**	2.12	**236**	1.02
12	16.28	**57**	1.92	**102**	2.12	**147**	1.91	**192**	2.10	**237**	0.95
13	16.24	**58**	2.08	**103**	1.86	**148**	1.82	**193**	1.95	**238**	0.78
14	16.44	**59**	1.52	**104**	1.69	**149**	1.73	**194**	1.93	**239**	0.77
15	16.95	**60**	1.65	**105**	1.64	**150**	1.60	**195**	1.68	**240**	0.80
16	16.01	**61**	1.37	**106**	1.67	**151**	7.93	**196**	1.62	**241**	0.76
17	16.08	**62**	1.53	**107**	6.64	**152**	8.04	**197**	1.56	**242**	0.68
18	16.40	**63**	8.01	**108**	6.72	**153**	6.59	**198**	1.53	**243**	0.53
19	16.99	**64**	8.03	**109**	5.82	**154**	6.70	**199**	8.33	**244**	0.51
20	16.71	**65**	5.94	**110**	5.85	**155**	5.23	**200**	8.45	**245**	0.49
21	16.95	**66**	5.97	**111**	4.77	**156**	5.27	**201**	7.07	**246**	0.44
22	17.47	**67**	4.72	**112**	4.80	**157**	4.61	**202**	7.15	**247**	0.55
23	18.74	**68**	4.77	**113**	4.02	**158**	4.64	**203**	4.74	**248**	0.48
24	20.74	**69**	3.91	**114**	4.04	**159**	3.73	**204**	4.68	**249**	0.50
25	15.12	**70**	3.92	**115**	3.87	**160**	3.74	**205**	3.68	**250**	0.45
26	14.87	**71**	3.20	**116**	3.88	**161**	3.36	**206**	3.88		
27	13.87	**72**	3.22	**117**	2.66	**162**	3.35	**207**	2.88		
28	13.94	**73**	2.68	**118**	2.67	**163**	3.04	**208**	2.92		
29	11.48	**74**	2.71	**119**	2.52	**164**	3.04	**209**	2.49		
30	11.46	**75**	2.33	**120**	2.54	**165**	2.57	**210**	2.67		
31	10.40	**76**	2.35	**121**	2.23	**166**	2.56	**211**	2.00		
32	10.44	**77**	2.28	**122**	2.24	**167**	2.26	**212**	2.14		
33	8.64	**78**	2.30	**123**	1.98	**168**	2.25	**213**	1.80		
34	8.27	**79**	2.00	**124**	1.97	**169**	2.01	**214**	1.96		
35	6.34	**80**	2.03	**125**	1.74	**170**	2.00	**215**	1.56		
36	6.43	**81**	1.61	**126**	1.71	**171**	1.80	**216**	1.58		
37	5.05	**82**	1.78	**127**	1.73	**172**	1.80	**217**	1.41		
38	5.46	**83**	1.54	**128**	1.64	**173**	1.72	**218**	1.31		
39	3.95	**84**	1.63	**129**	6.57	**174**	1.60	**219**	8.72		
40	4.52	**85**	8.10	**130**	6.48	**175**	8.18	**220**	8.42		
41	4.13	**86**	7.58	**131**	5.73	**176**	7.98	**221**	7.01		
42	4.11	**87**	6.26	**132**	5.79	**177**	6.25	**222**	6.92		
43	8.20	**88**	5.86	**133**	4.79	**178**	6.31	**223**	5.05		
44	8.08	**89**	4.65	**134**	4.80	**179**	5.41	**224**	5.15		
45	6.56	**90**	4.65	**135**	4.20	**180**	5.41	**225**	3.53		

Table I.3. Daylight autonomy (DA300, %) for each individual seat.

Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3
1	100	100	100	**46**	100	88	100	**91**	100	72	100
2	100	98	100	**47**	100	84	100	**92**	100	72	100
3	100	98	100	**48**	100	86	100	**93**	100	68	100
4	100	98	100	**49**	100	74	100	**94**	100	68	100
5	100	98	100	**50**	100	72	100	**95**	100	60	100
6	100	100	100	**51**	100	60	100	**96**	100	60	100
7	100	98	100	**52**	100	64	100	**97**	100	54	100
8	100	98	100	**53**	100	60	100	**98**	100	54	100
9	100	98	100	**54**	100	60	100	**99**	100	44	100
10	100	98	100	**55**	100	42	100	**100**	100	44	100
11	100	94	100	**56**	100	44	100	**101**	100	42	100
12	100	94	100	**57**	100	26	100	**102**	100	42	100
13	100	94	100	**58**	100	36	100	**103**	99	32	99
14	100	94	100	**59**	99	22	100	**104**	99	32	99
15	100	94	100	**60**	99	28	100	**105**	99	24	99
16	100	94	100	**61**	99	20	100	**106**	99	24	99
17	100	94	100	**62**	99	22	100	**107**	100	88	98
18	100	94	100	**63**	100	92	100	**108**	100	90	100
19	100	94	100	**64**	100	92	100	**109**	100	86	100
20	100	94	100	**65**	100	86	100	**110**	100	86	100
21	100	96	100	**66**	100	86	100	**111**	100	78	100
22	100	96	100	**67**	100	78	100	**112**	100	78	100
23	100	98	100	**68**	100	78	100	**113**	100	72	100
24	100	98	100	**69**	100	72	100	**114**	100	72	100
25	100	96	100	**70**	100	72	100	**115**	100	68	100
26	100	98	100	**71**	100	66	100	**116**	100	68	100
27	100	96	100	**72**	100	66	100	**117**	100	60	100
28	100	96	100	**73**	100	60	100	**118**	100	60	100
29	100	94	100	**74**	100	60	100	**119**	100	60	100
30	100	94	100	**75**	100	58	100	**120**	100	60	100
31	100	94	100	**76**	100	58	100	**121**	100	52	100
32	100	94	100	**77**	100	44	100	**122**	100	52	100
33	100	92	100	**78**	100	44	100	**123**	100	42	100
34	100	92	100	**79**	100	38	100	**124**	100	42	100
35	100	90	100	**80**	100	40	100	**125**	100	32	100
36	100	88	100	**81**	99	28	99	**126**	100	32	100
37	100	86	100	**82**	99	34	99	**127**	99	28	99
38	100	86	100	**83**	99	26	99	**128**	99	24	99
39	100	72	100	**84**	99	22	99	**129**	100	90	98
40	100	74	100	**85**	100	92	100	**130**	100	90	98
41	100	72	100	**86**	100	92	100	**131**	100	86	98
42	100	74	100	**87**	100	86	100	**132**	100	86	98
43	100	92	100	**88**	100	86	100	**133**	100	78	98
44	100	92	100	**89**	100	80	100	**134**	100	78	98
45	100	88	100	**90**	100	80	100	**135**	100	72	98

Table I.3. Continued.

Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3
136	100	72	98	**175**	100	92	100	**214**	100	40	100
137	100	66	98	**176**	100	92	100	**215**	99	24	99
138	100	66	98	**177**	100	90	100	**216**	99	26	99
139	100	60	96	**178**	100	88	100	**217**	99	24	99
140	100	62	96	**179**	100	86	100	**218**	99	22	99
141	100	58	96	**180**	100	86	100	**219**	100	92	100
142	100	60	96	**181**	100	74	100	**220**	100	92	100
143	100	46	96	**182**	100	74	100	**221**	100	90	100
144	100	44	96	**183**	100	70	100	**222**	100	90	100
145	100	32	96	**184**	100	70	100	**223**	100	86	100
146	100	32	96	**185**	100	64	100	**224**	100	86	100
147	100	32	96	**186**	100	64	100	**225**	100	74	100
148	99	28	96	**187**	100	60	100	**226**	100	74	100
149	100	28	96	**188**	100	60	100	**227**	100	68	100
150	99	26	96	**189**	100	52	100	**228**	100	70	100
151	100	92	100	**190**	100	52	100	**229**	100	60	100
152	100	92	100	**191**	100	46	100	**230**	100	60	100
153	100	88	100	**192**	100	46	100	**231**	100	58	100
154	100	88	100	**193**	100	38	100	**232**	100	50	100
155	100	86	100	**194**	100	38	100	**233**	100	46	100
156	100	86	100	**195**	99	26	99	**234**	100	46	100
157	100	78	100	**196**	99	24	99	**235**	100	40	100
158	100	78	100	**197**	99	24	99	**236**	100	46	100
159	100	70	100	**198**	99	26	99	**237**	99	24	99
160	100	70	100	**199**	100	92	100	**238**	100	34	98
161	100	66	100	**200**	100	92	100	**239**	99	24	98
162	100	66	100	**201**	100	90	100	**240**	99	26	98
163	100	60	100	**202**	100	90	100	**241**	99	22	98
164	100	60	100	**203**	100	84	100	**242**	99	22	98
165	100	60	100	**204**	100	86	100	**243**	6	0	18
166	100	60	100	**205**	100	74	100	**244**	2	0	9
167	100	46	100	**206**	100	74	100	**245**	0	0	4
168	100	46	100	**207**	100	62	100	**246**	0	0	4
169	100	32	100	**208**	100	66	100	**247**	11	0	20
170	100	32	100	**209**	100	60	100	**248**	2	0	4
171	100	26	100	**210**	100	60	100	**249**	0	0	4
172	100	32	100	**211**	100	44	100	**250**	0	0	4
173	99	28	99	**212**	100	44	100				
174	99	26	99	**213**	100	40	100				

Table I.4. Useful daylight illuminance (UDI300-3000, %) for each individual seat.

Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3
1	0	64	24	**46**	63	86	69	**91**	80	72	82
2	1	70	29	**47**	76	84	73	**92**	78	72	82
3	3	68	29	**48**	72	86	71	**93**	84	68	80
4	3	76	36	**49**	81	74	82	**94**	84	68	80
5	3	72	33	**50**	74	72	80	**95**	89	60	80
6	3	70	29	**51**	89	60	82	**96**	89	60	82
7	4	82	31	**52**	87	64	82	**97**	96	54	82
8	6	82	33	**53**	92	60	82	**98**	91	54	80
9	7	80	36	**54**	90	60	80	**99**	97	44	73
10	7	82	36	**55**	93	42	76	**100**	93	44	71
11	12	86	36	**56**	93	44	76	**101**	98	42	73
12	12	82	36	**57**	93	26	73	**102**	93	42	71
13	12	82	36	**58**	93	36	71	**103**	99	32	73
14	12	82	36	**59**	99	22	76	**104**	99	32	73
15	11	88	36	**60**	99	28	76	**105**	99	24	76
16	13	84	38	**61**	99	20	71	**106**	99	24	76
17	12	82	38	**62**	99	22	76	**107**	63	88	71
18	12	84	36	**63**	53	90	64	**108**	63	90	71
19	13	86	36	**64**	52	90	64	**109**	69	86	73
20	7	84	36	**65**	66	86	73	**110**	69	86	73
21	6	82	36	**66**	67	86	73	**111**	74	78	73
22	6	82	36	**67**	76	78	80	**112**	74	78	73
23	3	84	33	**68**	77	78	78	**113**	78	72	82
24	0	74	31	**69**	78	72	82	**114**	80	72	82
25	7	88	36	**70**	82	72	82	**115**	84	68	82
26	8	86	36	**71**	86	66	82	**116**	84	68	80
27	9	90	42	**72**	86	66	84	**117**	88	60	80
28	9	90	42	**73**	90	60	80	**118**	87	60	80
29	22	88	47	**74**	90	60	80	**119**	91	60	80
30	27	88	47	**75**	92	58	78	**120**	92	60	80
31	29	88	51	**76**	92	58	78	**121**	92	52	73
32	29	88	51	**77**	93	44	78	**122**	97	52	78
33	41	84	64	**78**	93	44	78	**123**	93	42	71
34	46	90	64	**79**	93	38	71	**124**	99	42	73
35	63	90	71	**80**	93	38	71	**125**	100	32	73
36	66	88	71	**81**	99	28	76	**126**	100	32	73
37	74	86	73	**82**	99	34	73	**127**	99	28	76
38	74	86	73	**83**	99	26	76	**128**	99	24	76
39	78	72	82	**84**	99	22	76	**129**	66	88	69
40	78	74	80	**85**	50	90	64	**130**	64	90	71
41	78	72	82	**86**	52	92	67	**131**	69	86	73
42	78	74	82	**87**	66	86	71	**132**	69	86	73
43	47	86	64	**88**	66	86	73	**133**	77	78	73
44	47	86	64	**89**	74	80	76	**134**	74	78	73
45	63	84	69	**90**	74	80	76	**135**	78	70	80

Table I.4. Continued.

Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3	Seat	EX1	EX2	EX3
136	78	72	80	**175**	47	90	64	**214**	100	40	73
137	83	66	82	**176**	47	92	64	**215**	99	24	76
138	83	66	82	**177**	64	88	71	**216**	99	26	76
139	89	60	82	**178**	64	86	71	**217**	99	24	73
140	89	62	82	**179**	67	86	71	**218**	99	22	71
141	90	58	80	**180**	67	86	71	**219**	48	86	64
142	90	58	80	**181**	77	74	80	**220**	46	86	64
143	93	46	73	**182**	74	74	80	**221**	63	88	73
144	92	44	73	**183**	78	70	82	**222**	64	88	73
145	93	32	71	**184**	78	70	82	**223**	71	86	73
146	98	32	73	**185**	83	62	82	**224**	72	86	73
147	100	32	73	**186**	83	64	82	**225**	74	74	80
148	99	26	73	**187**	90	60	78	**226**	77	74	80
149	100	28	76	**188**	90	60	78	**227**	80	68	76
150	99	26	76	**189**	91	52	78	**228**	78	70	73
151	53	90	67	**190**	91	52	76	**229**	89	60	71
152	53	90	67	**191**	93	46	71	**230**	89	60	71
153	66	88	71	**192**	93	46	71	**231**	96	58	71
154	66	86	71	**193**	93	34	71	**232**	90	50	71
155	68	86	71	**194**	93	34	71	**233**	97	46	73
156	68	86	71	**195**	99	26	76	**234**	92	46	62
157	74	78	73	**196**	99	24	76	**235**	100	40	67
158	74	78	73	**197**	99	24	47	**236**	93	46	58
159	78	70	82	**198**	99	26	47	**237**	92	24	53
160	80	70	82	**199**	49	90	64	**238**	93	34	36
161	86	66	80	**200**	50	88	64	**239**	99	24	40
162	86	66	80	**201**	63	90	67	**240**	99	26	40
163	89	60	82	**202**	57	88	67	**241**	99	22	25
164	89	60	82	**203**	74	84	73	**242**	99	22	21
165	90	60	78	**204**	74	86	71	**243**	6	0	18
166	90	60	78	**205**	77	74	82	**244**	2	0	9
167	92	46	78	**206**	77	72	80	**245**	0	0	4
168	93	46	78	**207**	87	62	80	**246**	0	0	4
169	93	32	71	**208**	87	66	82	**247**	11	0	20
170	93	32	71	**209**	90	58	78	**248**	2	0	4
171	100	26	73	**210**	89	60	78	**249**	0	0	4
172	100	32	71	**211**	92	44	71	**250**	0	0	4
173	99	28	46	**212**	98	42	73				
174	99	26	47	**213**	93	40	71				

APPENDIX J. NORMALITY TEST FOR SNAPSHOT DATA

The purpose of this appendix is to statistically test the snapshot data to determine whether they can be reasonably assumed to come from a normal distribution. The null hypothesis for this test is that the data are normally distributed, and the confidence interval selected in the test is 95%. Table J.1 presents the results from the Shapiro-Wilk test of normality.

Table J.1 Results of Shapiro-Wilk tests for normality of variables (df: degrees of freedom, WSA: window seating area, CSA: central seating area).

Dataset	Variables	EX1		EX2		EX3	
		Statistic	Sig.	Statistic	Sig.	Statistic	Sig.
Whole dataset df=250	Daylight Factor	0.77	0.00	0.77	0.00	0.77	0.00
	Horizontal Illuminance	0.82	0.00	0.79	0.00	0.85	0.00
	Daylight Autonomy (300)	0.18	0.00	0.93	0.00	0.19	0.00
	UDI (300-3000)	0.80	0.00	0.91	0.00	0.75	0.00
	Occupancy rate	0.50	0.00	0.82	0.00	0.49	0.00
WSA df=32	Daylight Factor	0.95	**0.117**	0.95	**0.117**	0.95	**0.117**
	Horizontal Illuminance	0.87	0.002	0.94	**0.058**	0.90	0.008
	Daylight Autonomy (300)	-	-	0.80	0.00	-	-
	UDI (300-3000)	0.85	0.00	0.87	0.001	0.88	0.002
	Occupancy rate	0.95	**0.169**	0.76	0.00	0.95	**0.165**
CSA df=218	Daylight Factor	0.92	0.00	0.92	0.00	0.92	0.00
	Horizontal Illuminance	0.92	0.00	0.93	0.00	0.93	0.00
	Daylight Autonomy (300)	0.19	0.00	0.94	0.00	0.22	0.00
	UDI (300-3000)	0.80	0.00	0.93	0.00	0.61	0.00
	Occupancy rate	0.72	0.00	0.96	0.00	0.72	0.00

From Table J.1, it can be seen that the data failed the Shapiro-Wilk test on the whole dataset which means significant evidence against normality (significance levels less than 0.05). The tests performed on the data broken down by two seating areas (WSA and CSA) revealed that the samples are normally distributed in some cases (significance levels greater than 0.05), these are presented in bold in Table J.1. Note that for WSA dataset the test failed to produce any evidence about normality of Daylight Autonomy in EX1 and EX3, as the data values were found to be constant across these two datasets.

Next, residuals from all datasets were examined to determine normality. The residuals are defined as the difference between observed and expected values; and standardized residuals are generally preferred to raw residuals (Andrews and Pregibon, 1978; Cook and Weisberg, 1982). By converting residuals into standard units (i.e. values distributed around a mean of 0 with a standard deviation of 1), it was possible to compare residuals from different models. The normality assumption was checked through visual inspection of histograms and P-P plots of standardized residuals, as presented in Table J.2-Table J.4.

Table J.2. Plots showing histograms and distribution of residuals (whole dataset) OR: Occupancy rate.

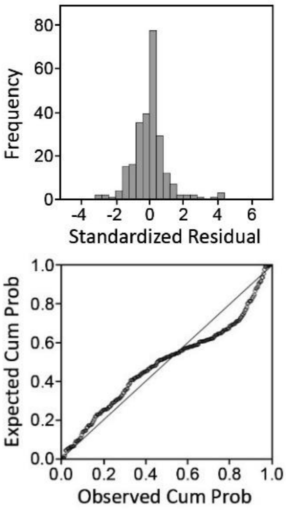
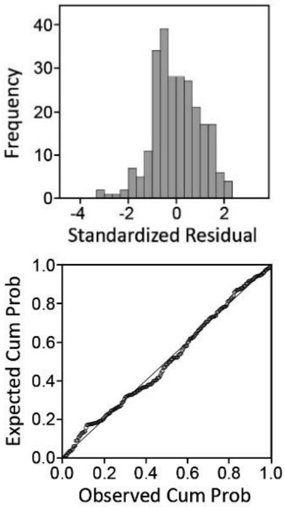
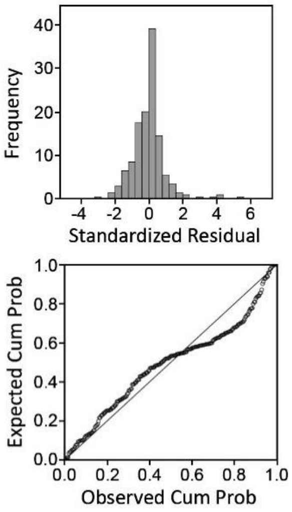
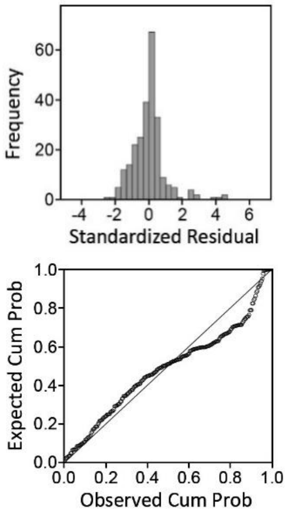
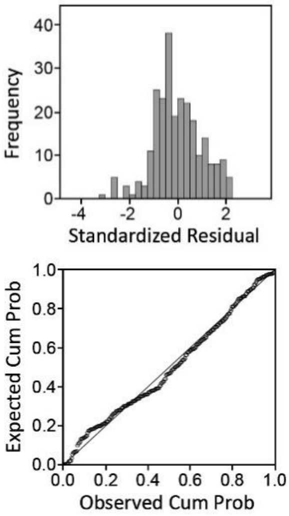
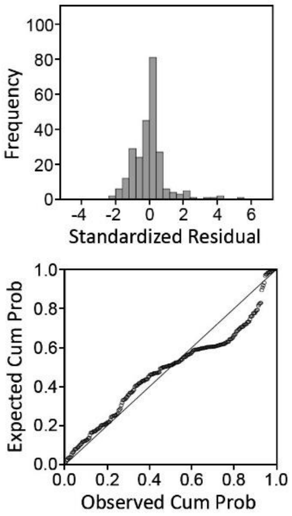
	OR-EX1	**OR-EX2**	**OR-EX3**
Daylight Factor			
Horizontal Illuminance			

Table J.2. Continued.

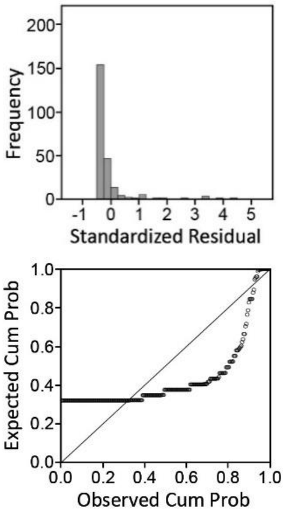
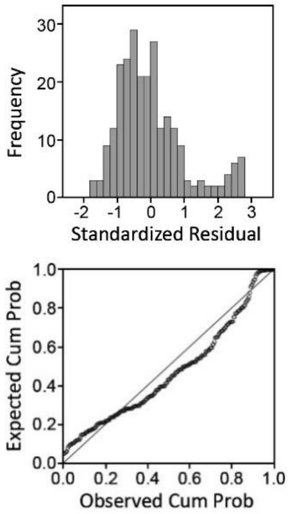
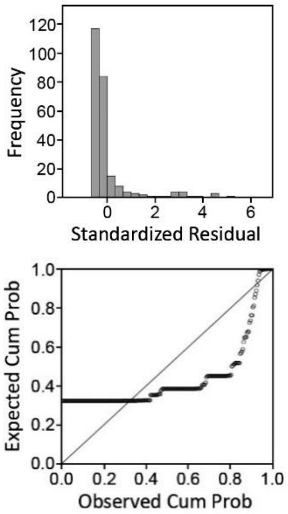
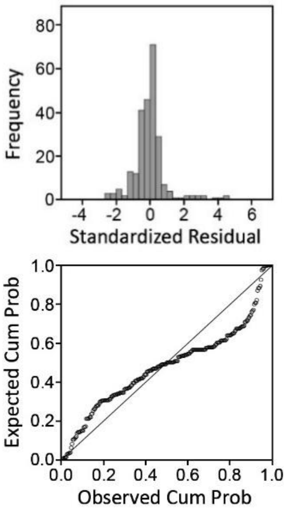
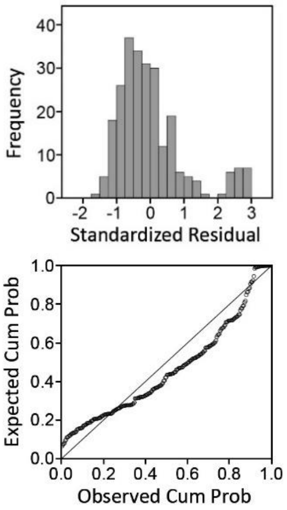
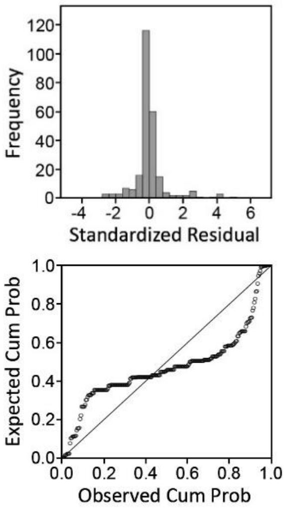
	OR-EX1	OR-EX2	OR-EX3
Daylight Autonomy (300)			
UDI (300-3000)			

Table J.3. Plots showing histograms and distribution of residuals (WSA dataset) OR: Occupancy rate.

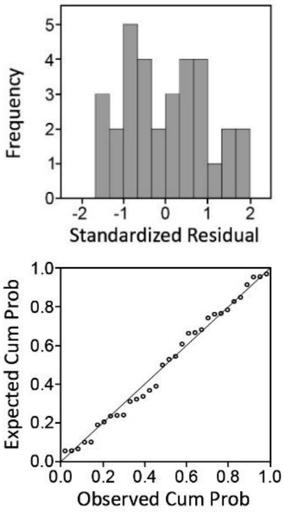
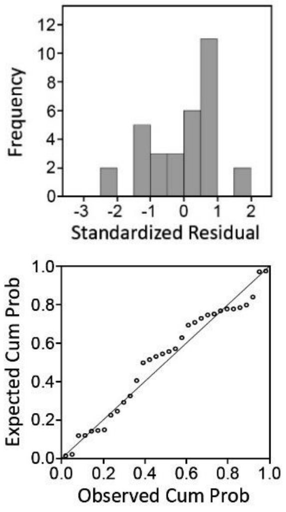
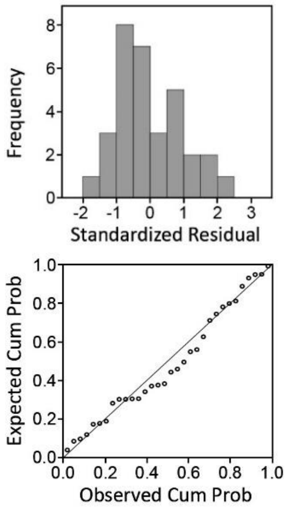
	OR-EX1	OR-EX2	OR-EX3
Daylight Factor			

Table J.3. Continued.

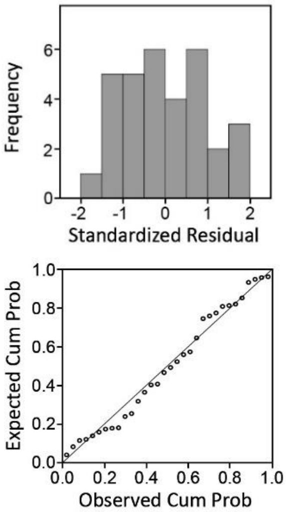
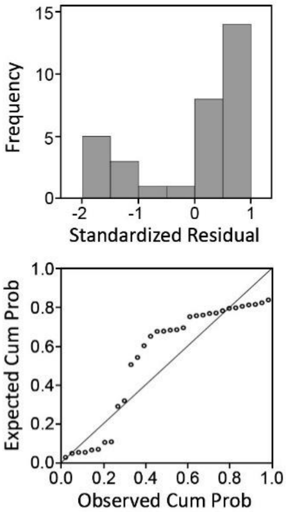
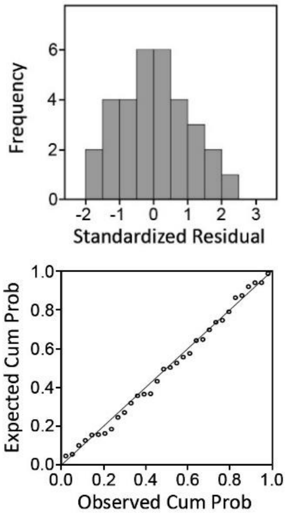
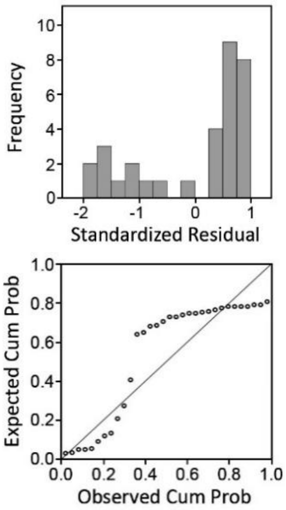
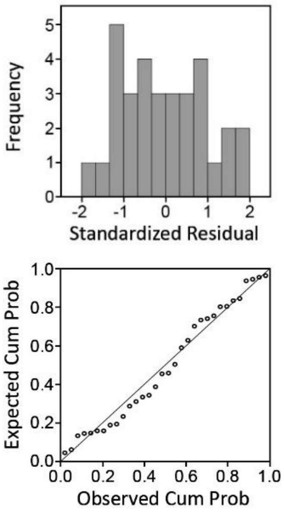
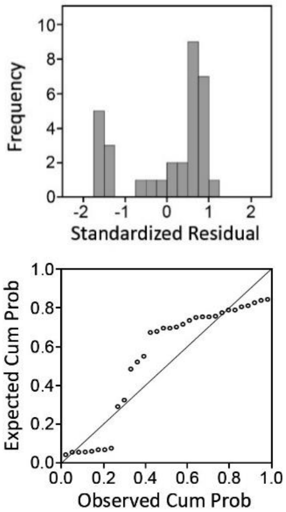
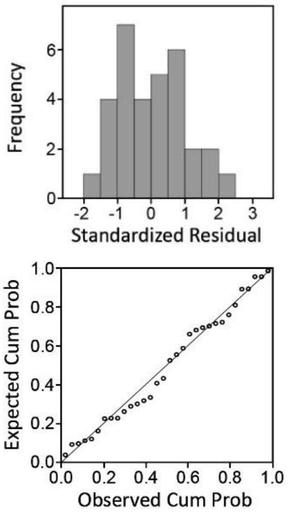
	OR-EX1	OR-EX2	OR-EX3
Horizontal Illuminance			
Daylight Autonomy (300)	**N/A**		**N/A**
UDI (300-3000)			

Table J.4. Plots showing histograms and distribution of residuals (CSA dataset) OR: Occupancy rate.

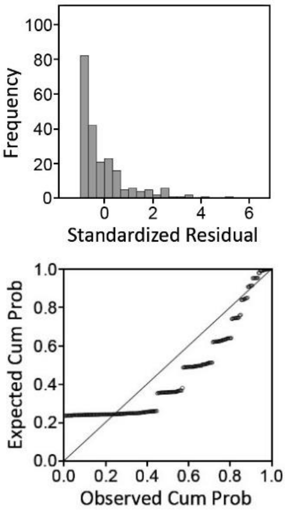
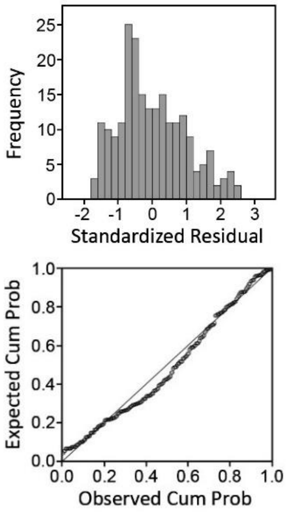
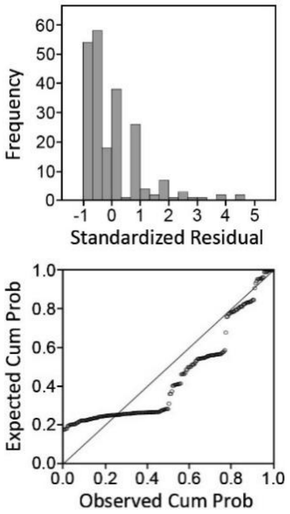
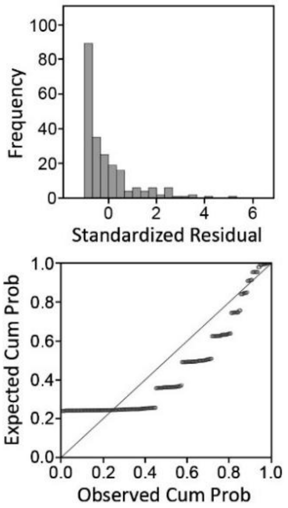
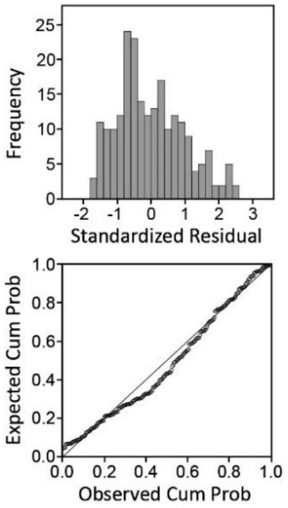
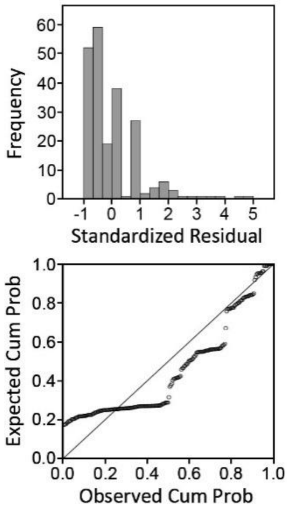
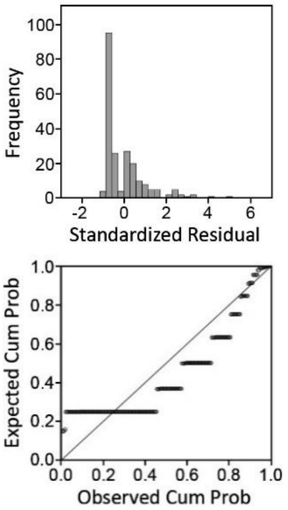
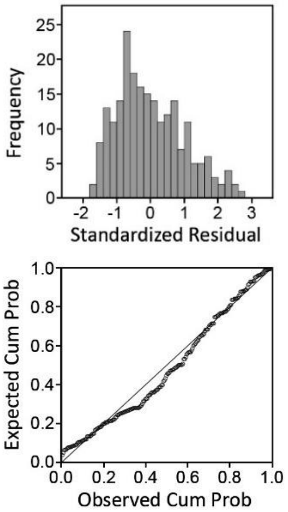
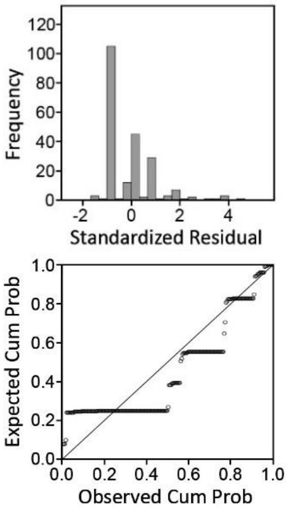
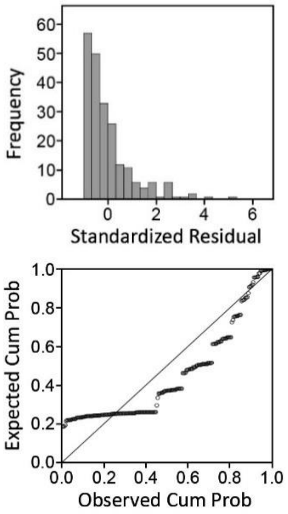
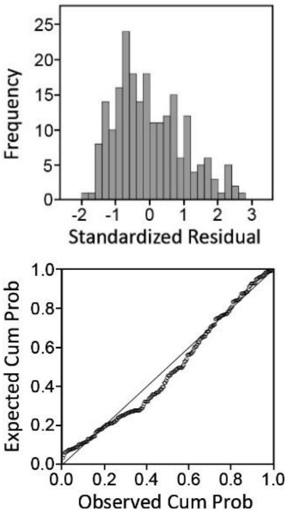
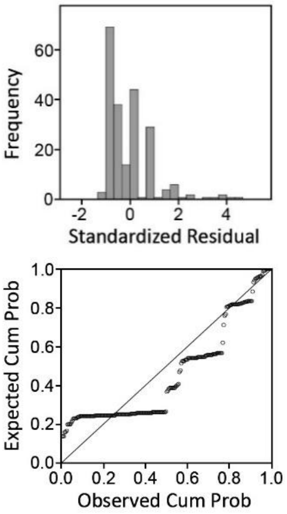
	OR-EX1	**OR-EX2**	**OR-EX3**
Daylight Factor			
Horizontal Illuminance			
Daylight Autonomy (300)			

Table J.4. Continued.

	OR-EX1	OR-EX2	OR-EX3
UDI (300-3000)			

The normality assumption is that residuals follow a normal distribution, which means the histogram of the values forms a bell-shaped curve and the corresponding normal probability plot is approximately linear (Field, 2005). It can be seen in Table J.1 that the residuals for the whole dataset are either normally distributed or very close to it, with the exception of the daylight autonomy plots where the distributions depart substantially from the normal distribution (EX1 and EX3). When the whole dataset is split into WSA and CSA subsets, however, the plots reveal variations in the distribution of residuals. From Table J.2, it can be seen that the histograms of horizontal illuminance, daylight autonomy and useful daylight illuminance do not produce a bell-shaped curve for EX2 dataset, indicating non-normality. The normal probability plots seem to confirm this since there are deviations from the ideal straight line, corresponding to discrepancies between the observed and expected values. From the plots presented in Table J.3, it appears that the residuals follow a normal distribution for EX2, whereas for EX1 and EX3 the distribution is highly skewed, indicating the residuals are far from normally distributed.

From the evidence issued in this section it is possible to conclude with a reasonable degree of certainty that the residuals from some of the datasets are normally distributed. Therefore, statistical tests chosen for these datasets assume normality. In other cases, the assumption of normality is rejected and non-parametric tests are used as a means of comparison.

APPENDIX K. GLOSSARY OF TERMS

This appendix provides definitions and explanations of technical terms used in this thesis. The following glossary of terms has been produced from the lighting standards and guidelines (CIBSE/SLL, 2012; IESNA, 2000), and the CIE International Lighting Vocabulary (CIE 17.4:1987). Other sources included the following: Baker and Standeven (1994), Larson and Shakespeare (1998), Perez et al (1990) and Tregenza and Sharples (1993).

Adaptive opportunity: The opportunities provided by a building for occupants to make themselves comfortable. Examples of actions which people might take to make themselves comfortable are the use of controls (windows, blinds) or movement within a space or between spaces to find the conditions that suit their needs.

Daylight coefficient: Daylight coefficients embody the geometric relationships that determine daylight illuminance. Each coefficient is the ratio between the luminance of a patch of sky, and the illuminance in the building due to the light from that patch. The sky can be divided into zones of altitude and azimuth, and the daylight coefficient found for each zone. The total daylight illuminance at a point is then the sum of the products of the mean luminance of each sky zone, the subtended area of the zone, and the corresponding daylight coefficient:

Diffuse radiation: Solar radiation which reaches the Earth as a result of being scattered by the air molecules, aerosol particles, cloud and other particles of the atmosphere. If not stated otherwise, diffuse sky radiation refers to radiation received on a horizontal plane from the whole hemisphere.

Direct radiation: That part of extra-terrestrial solar radiation (solar radiation incident at the outer limit of the Earth's atmosphere) which as a single collimated beam reaches the Earth's surface after selective attenuation by the atmosphere. If not stated otherwise, direct beam radiation refers to radiation incident on a plane normal to the direction of incidence.

Glare: Condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts.

Global radiation: The sum of direct and diffuse radiation. If not stated otherwise global radiation refers to radiation incident on a horizontal plane.

Illuminance: The amount of light that reaches a point on a given plane in an interior, or the flow of light, that strikes a unit surface area of one square metre. Standard unit for illuminance is Lux (lx) which is lumens per square meter (lm/m^2).

Irradiance: A measure of the amount of light energy incident on a unit area of surface per unit time. The unit of measurement of irradiance is watts per square meter.

Luminance: The amount of light reflected from a surface in a given direction. Standard unit for luminance is candela per square meter (cd/m^2).

Perez all-weather sky model: A mathematical model used to describe the sky luminance distribution. The model is derived from the CIE Clear Sky, but includes the facility to control the luminance distribution through a set of three parameters to reflect the local insolation conditions (solar zenith angle, sky clearness, and brightness). These are influenced by the ratio of normal to diffuse incident radiation.

Pyranometer: An instrument for measuring solar irradiance upon a surface; if mounted horizontally, it measures global irradiance. The instrument is usually used to measure global irradiance but by suitably shading the sensor from the direct solar beam it may be used to measure diffuse radiation.

Ray tracing: A method based on following one-dimensional rays, where each ray is defined by an origin point and a vector direction. In a rendering algorithm, each ray is followed until it intersects a visible surface, where new rays may be spawned in a recursive process. In forwards ray tracing, light is followed from the light sources to the final measurement areas. In backwards ray tracing (as in Radiance), each view ray is traced from the point of measurement to the contributing light sources.

Solar altitude: Solar altitude describes the elevation of the sun in the sky (celestial sphere) relative to an observer, as the angle between the plane of the observer`s celestial horizon and a line from the observer to centre of the sun. Solar altitude and solar zenith angles are complementary and have a sum of 90 degrees.

Solar azimuth: Solar azimuth describes the position of the sun in the sky (celestial sphere) relative to the observer`s location, in terms of its angle east or west of a line running north-south on the celestial horizon.

Solar zenith angle: The angle between the zenith and the line joining the observer and centre of the sun. Solar altitude and solar zenith angles are complementary and have a sum of 90 degrees.

Test Reference Year (TRY): Typical year of weather reference. The TRY is composed of a sequence of meteorological data schedules, measured in reality and selected within a historical series of at least ten years, through a method of selection of a statistical nature. This leads to the creation of a vast amount of hourly data that merge into a year-type, used for models of analysis and the dynamic simulation of the distribution of daylight.

Work plane: The level at which work is done and at which illuminance is specified and measured. This is typically a horizontal plane located at desk height.

Zenith: The point on the celestial sphere directly above the observer.

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