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Claudia Moscoso Paredes

Daylighting and Architectural Quality

Aesthetic Perception of Daylit Indoor Environments

Doctoral thesis

Claudia Moscoso Paredes

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of Philosophiae Doctor
Faculty of Architecture and Fine Art
Department of Architectural Design, Form and Colour Studies

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To Øyvind and Bianca.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) in partial fulfilment of the requirements for the degree of Philosophiae Doctor (PhD). The presented thesis contains work carried out as part of the research of the Light & Colour Group at the Department of Architectural Design, Form and Colour Studies, Faculty of Architecture and Fine Art.

The work presented in this thesis is of a multidisciplinary nature, including architectural and daylighting studies, environmental aesthetics, and experimental simulation.

Being Peruvian, I had no large daylight variability during each season, and of course, there were no special light phenomena (e.g. Nordic lights) present in my life until I moved to Norway. Nevertheless, I could enjoy a pleasant room bathed in the fascinating spectral distribution of colours of a sunset during the summer months, and then the same room as saddened and monotonous as a result of the grey overcast skies of Lima during winter. This peculiar variance in the aesthetic perception of a space created by light produced a constant curiosity in me. My architectural studies and later professional experience cemented my interest for daylight in architecture. It was after my professional experience when I discovered that daylight can be a paramount element in architectural design capable of producing touching and evocative feelings in humans. Thus, in my doctoral studies, investigating architecture, daylighting and environmental studies has been, without a doubt, a rewarding challenge full of various emotions and states.

It was 2010 when I started the work presented here. It has been five years since I started the PhD research; in which a one-year intermission was taken to work on a new ‘project’– I took a break from my scientific research to allow room for baby research. It is then, a special feeling to complete this chapter in my life by putting a full stop to the work that has been with me for such a long time. The experience has taught me so much. It is my hope that the following pages can also be of use to interested readers.

Acknowledgements

First and foremost, I would like to thank God for all the blessings He has conceded me throughout my life. During my PhD research, I have been blessed to count with the support of a number of amazing people, to whom I would like to express my gratitude. The fulfilment of this thesis would not have been possible without their contribution.

My biggest thanks go to my dear supervisor Barbara Matusiak, who believed in me from the start, giving me the opportunity to be a PhD candidate under her supervision, and helping me in more ways that I can account for. Despite her tight and busy schedule, Barbara has always been available for guidance, and for interesting and fruitful discussions about lighting research, becoming a large source of inspiration and support. I will be forever grateful, Barbara.

I extend a heartfelt thanks to my co-supervisor Professor Peter Svensson, for all the constructive discussions, for reading countless versions of my articles, for encourage me to always pay attention to experimental design and statistical analyses, and for patiently sharing his time, thoughts and knowledge with me in different stages of my research project.

I am forever indebted to the Light and Colour Group, in special to Arne Valberg, Kine Angelo, and my fellow PhD colleagues Veronika Zaikina, Ania Sochocka and Shabnam Arbab, for being the wonderful people they are. For all the help in my experiments, for the lunches, for the shared tea-times, for the professional and non-professional discussions, for always listening, for speaking the same 'lighting' language, and for the understanding, I am deeply thankful. Without all of them, my time in the university would not have been as 'bright and colourful' as it was.

My sincere gratitude goes to Krzysztof Orleanski, who so generously supported me by lending me his stereoscopic imaging equipment, and for teaching me and helping me with different technical issues.

I would like to express my gratitude for the support from Professor Alex Booker, the Head of the Department of Architectural Design, Form and Colour Studies, for his openness and his willingness in dealing with different work-related issues. Very special and warm thanks go to Sarah By, not only for providing me endless help and answering the million questions I always had for her in the most positive attitude, but most of all, for her sincere friendship throughout the years. I also acknowledge the support and help regarding PhD issues to our PhD coordinator, Maja Todoroska.

During my PhD time, I have collected fond memories of my fellow PhD colleagues on the 4th and 8th floor, who were not only willing to selflessly support my experiments by signing up as experiment participants, but who were also an enjoyable breath of fresh air in the middle of busy and heavy academic days.

I would also like to acknowledge my colleagues at the Department of Architectural Design, Form and Colour Studies and the administrative staff of the Faculty of Architecture and Fine Art who have also generously provided help not only in my experimental sessions, but also by helping me with needed administrative issues.

Nothing of what I have accomplished so far in my life would have happened without the support and endless love of my parents and my brother. I am who I am because of them. *Queridos papá, mamá y Joseph: Ustedes están en mi pensamiento todos los días de mi vida, en cada paso que tomo y en cada meta que logro. Gracias por aceptar mi decisión de mudarme tan lejos y de no hacerme sentir tan culpable por eso. Gracias por todos los tipos de apoyo que me han brindado siempre. A ustedes mi cariño y mi agradecimiento eterno*.

Last, but definitely not least, with all the love in my heart, I thank the most important people of all, the two persons who this thesis is dedicated to: my dear husband Øyvind and my sweet daughter Bianca. Bianca only needs to smile and hug me for the whole world to be better. Part of my working discipline has been because of her, because of my desire to become the mother she deserves to have. Øyvind has always been my fan number one, cheering me, believing in me, giving me strength, supporting me in sometimes inexplicably ways, and lovingly understanding me in times when I cannot even understand myself. *Tusen hjertelig takk, min kjære*. *Jeg kunne ikke ha klart det uten deg.*

Claudia T. Moscoso Paredes
Trondheim, Norway
January 2016

Abstract

The present thesis concerns the field of daylighting in architecture. In particular, this thesis examines the topic of the aesthetic perception of daylit indoor environments.

Most daylighting studies seem to use photometrical measurements to describe the light in a space. Moreover, most studies seem to focus on comparing metrics to establish an adequate illumination for optimal visual and task performance. However, lighting considerations should go further than merely visual and task performance guidelines; good lighting should also contribute to the aesthetic perception of any environment. This is an important distinction to establish: a room with enough light for performing tasks can be described as an 'adequately illuminated room', whereas a room that also provides a pleasant visual environment can be considered a 'well-lit room'. Yet little literature investigating the aesthetic quality of architectural spaces lit by daylight can be found.

Therefore, the present study seeks to explore how different daylighting designs affect the aesthetic perception of indoor built environments. The fields of architecture and daylighting are taken as starting points. In addition, the aesthetic perception of environments entails studies of environmental psychology, e.g. environmental aesthetics and measurement of environmental perception. Daylight and aesthetic quality are thus terms of paramount importance in the present research.

In the scope of the work presented here, two types of daylighting design have been considered in the study: windows as the most basic daylight collectors in buildings (primary daylighting design), and daylighting systems as advanced measures to collect and distribute daylight deeper in interiors (advanced daylighting design). To examine the aesthetic quality of an architectural space, nine aesthetic attributes were selected: Pleasantness, Excitement, Order, Complexity, Legibility, Coherence, Spaciousness, Openness, and Spatial Definition.

Considering that humans spend most of their waking time indoors, and that most of this time is spent at home and at the workplace, two small environments were the focus of the presented work: a student room and a single office unit.

Experimental research using a mixed method approach was selected as the research strategy. Thus, two main experiments were carried out to investigate: *i.* the effects of windows on the aesthetic quality of a student room, where three different window sizes were considered in a room lit under overcast sky conditions; and *ii.* the effects of daylighting systems on the aesthetic quality of a small single

office, where two types of venetian blinds and two types of light shelves were considered under overcast sky and clear sky conditions.

The summarised results confirm that daylighting design (within the scope of the present research; i.e. daylight delivered by windows and/or daylighting systems) has a significant impact on the aesthetic impression of a small room. Moreover, the collective findings of the present work suggest that photometric measurements are not always the perfect predictors to judge the nine selected aesthetic attributes. Although photometric studies are necessary, other parameters not connected to lighting metrics (e.g. the location of light patches in the room and the physical and geometrical characteristics of the daylighting systems) impact the aesthetic perception of a small room and should be considered.

Furthermore, the study presents a new experimental method that can be used in daylighting and aesthetics studies. This experimental method is based on the use of 3D or stereoscopic images of environments, taken with two cameras and projected full-scale on a silver screen. The method was tested in an experimental procedure and analysed using a method comparison statistical model. The findings show that stereoscopic imaging is a valid and accurate method for use in daylighting studies.

Daylighting in relation to environmental aesthetics is still an incipient body of knowledge, as there is still much that we do not know. The aim of the presented work was set to shed new light on different aspects of daylighting studies, such as the aesthetics of a lit environment. The presented results provide new knowledge that could serve as a departure point for the development of new theories and assumptions that could improve the understanding of this interdisciplinary topic.

Publications

<u>Scientific Articles</u>

- Moscoso, C., Matusiak, B. and Svensson, U.P. 2015. Impact of window size and room reflectance on the perceived quality of a room. *Journal of Architectural and Planning Research*. In Press.

- Moscoso, C. and Matusiak, B. 2015. From windows to daylighting systems: How daylight affects the aesthetic perception of architecture. *Proceedings of the 28th CIE Session*. Manchester, UK. Volume 1 Part 1, p. 297 – 306.

- Moscoso, C., Matusiak, B., Svensson, U. P. & Orleanski, K. 2015. Analysis of Stereoscopic Images as a New Method for Daylighting Studies. *ACM Transactions on Applied Perception*. Vol. 11 Issue 4. Article No. 21. DOI >10.1145/2665078

- Moscoso, C. 2013. Virtual environments to study daylight and colour. Towards a new approach of advanced research method. *In:* MATUSIAK, B. & FRIDELL ANTER, K. (eds.) *Nordic Light and Colour*. Trondheim, Norway: NTNU – the Faculty of Architecture and Fine Art. p. 95 -104.

- Moscoso, C. and Matusiak, B. 2013. Virtual environment as a tool for daylighting studies. *Proceedings of the 12th European Lighting Conference - Lux Europa 2013*. Krakow, Poland.

<u>Other publications</u>

- Valberg, A., Andorsen, B.H., Angelo, K., Matusiak, B., and Moscoso, C. 2015. *A guide to light and colour demonstrations*. NTNU – Faculty of Architecture and Fine Art. ISBN – 978-82-7551-117-9

- Moscoso, C. and Matusiak, B. Vindusstørrelse, dagslys og persepsjon av rom. 2015. Magazine: *LYS – Magasinet for belysning og lysdesign*. 2/2015, June 2015. p. 30-32.

- Moscoso, C. and Matusiak, B. 3D bilder som en ny metode for dagslysstudier. 2014. Magazine: *LYS – Magasinet for belysning og lysdesign*. 3/2014, October 2014. p. 40-42.

Oral presentations and contributions

- From windows to daylighting systems: How daylight affects the aesthetic perception of architecture. 28th Session of the CIE. Manchester, UK. July, 2015.

- Aesthetic judgements in daylit indoor environments. Full-scale laboratory experiments. Nordic Light & Colour International PhD course. Trondheim, Norway. March, 2015.

- Achromatic colours and their effect on architectural quality attributes. Forum Farge. Gjøvik, Norway. March, 2014.

- The impact of light and colour on the perceived quality of architecture. SYN-TES Seminar n. 6. Trondheim, Norway. May, 2011.

- The impact of light on the perceived quality of architecture. Studies with advanced visual equipment. VELUX 1st Daylight Academic Forum. Lausanne, Switzerland. May, 2011.

- The impact of light and colour on the perceived quality of architecture. Lyskultur Academic Conference: Lyskvalitet vs. Ny Teknologi. Trondheim, Norway. March 2011.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

'W*ithout light, there would be no life on Earth. Electromagnetic radiation (EMR) across a very wide spectrum heats the planet sufficiently for biological activity; EMR across the range from ~380 to ~780nm is responsible for most plant life and, most importantly to us, stimulates photoreceptive cells in the retina of most creatures with eyes*' (de Kort and Veitch, 2014). Although this statement summarises the most important contributions of light to human life; in general terms, the author would like to emphasise two crucial points that served as motivators for the present work.

First, light is essential in the visual experience of the world. Our visual system is intrinsically related to light. In order to interact with our physical surroundings, we first need to see and register a large amount of information, such as space boundaries, surfaces, colour, furnishings, openings, and texture (Boyce, 1976). Light is the channel that allows us to perceive the information of the environments, which will be further processed at a later stage (Valberg, 2005).

Second, light affects humans' health and well-being. Light is directly related to humans' circadian rhythm (i.e. the human biological clock). This system adapts the functioning of the body to 24-hour light and dark cycles, according to which the human body regulates its sleep patterns, body temperature, internal clock, and stress hormones (see Figure 1.1). Daylight (in terms of spectral composition and the total amount of light) is crucial to the functioning of this cycle.

Light passes through the retina to specific neural and hormonal centres in the brain (see Figure 1.2). Moreover, eyestrain, fatigue, irritability and muscular aches are health-related conditions caused by intense visual effort due to inappropriate lighting (Wyckmans, 2005). Additionally, light is used as a medical treatment for specific health conditions, such as the early treatment of neonatal jaundice (Maisels and McDonagh, 2008), which involves the exposure of new-born babies to intensive phototherapy. Diverse skin conditions and mood- and sleep-related conditions such as seasonal affective disorder, depression, and circadian rhythm sleep disorders are examples of medical ailments with treatment plans in which light plays a crucial role.

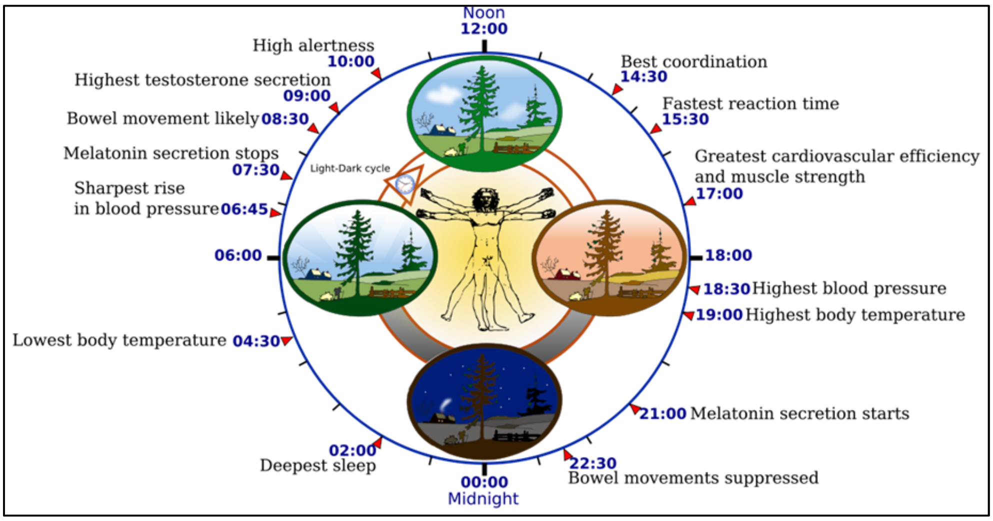

Figure 1.1: Some features of the human circadian rhythm[1]

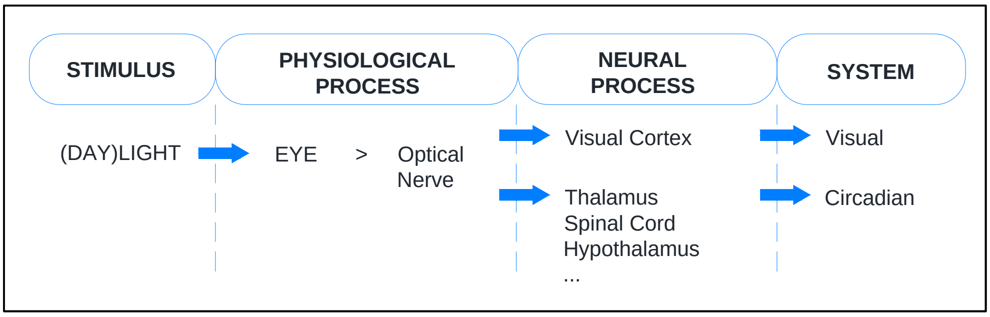

Figure 1.2: Simplification of the neuroanatomy that resolves the sensory capacity of vision and the nonvisual regulation of circadian physiology by light. Figure adapted by the author from Brainard and Bernecker (1996).

[1] "Biological clock human" by NoNameGYassineMrabetTalk - The work was done with Inkscape by YassineMrabet. Informations were provided from "The Body Clock Guide to Better Health" by Michael Smolensky and Lynne Lamberg; Henry Holt and Company, Publishers (2000). Landscape was sampled from Open Clip Art Library (Ryan, Public domain). Vitruvian Man and the clock were sampled from Image human body.svg (GNU licence) and Image:Nuvola apps clock.png, respectively.. Licensed under CC BY-SA 3.0 via Wikimedia Commons – http://commons.wikimedia.org/wiki/File:Biological_clock_human.svg#mediaviewer/File:Biological_clock_human.svg

Furthermore, in the Preamble to the Constitution of the World Health Organization (1948), health is defined as much more complex than just the absence of disease:

'Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity'

Considering that humans spend most of their waking time indoors, interactions with their built environment (via occupation and/or settlement) that are considered pleasant should produce a state of well-being. As pointed out by Veitch and Galasiu (2012), to live in a place that is judged to be attractive may be considered a psychological good in itself. Other research findings also suggested that the aesthetic of a place that is considered to be high quality contributes to psychological and physical health (Evans et al., 2000, Evans et al., 2001, Nasar, 2000, Gifford and Lacombe, 2006). Additionally, a field simulation study on lighting quality conducted by Boyce et al. (2006), suggested that luminous conditions lead to the appraisal of the environment, the selection of lighting preferences and effects on humans' moods, which in turn affects their health and well-being (see Figure 1.3). Thus, there is, little doubt of the large range of benefits that light has on humans' lives.

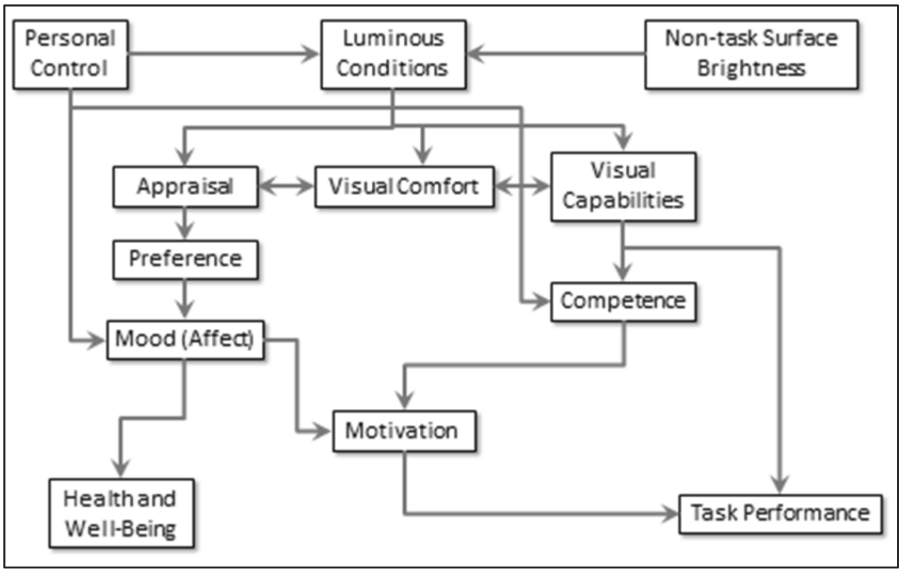

Figure 1.3: Linked mechanism map hypothesised to link luminous conditions with health, well-being and performance. Adapted from Boyce et al (2006).[2]

In conclusion, why do we need to worry about lighting? Because, among other benefits, light affects our health and well-being, and it has the potential to modify

[2] Copyright Clearance Center – Rights Link® from SAGE – Lighting Research & Technology: "Permission is granted at no cost for use of content in a Master's Thesis and/or Doctoral Dissertation."

the perceived visual quality of a luminous environment. Furthermore, why do we need to worry about the aesthetic perception of daylit environments? Because these environments can positively (or negatively) affect our well-being and health. The challenge lies in producing well-lit rooms that can enhance the perception of visual quality. Thus, the present work is based on three keywords and their interplay as motivators: *Daylight, Environment,* and *Aesthetic Quality*.

When discussing the quality of a daylit indoor environment, many researchers agree that lighting quality involves objective and subjective parameters. Among these parameters, good lighting quality is defined when lighting provides appropriate viewing conditions to support visual and task performance and when it contributes to the aesthetic perception of the space (Veitch and Newsham, 1998a). These two parameters are in accordance with the daylighting recommendations presented by Hopkinson et al. (1966): *i*. to provide sufficient illumination for work performance and, *ii*. to provide a pleasant visual environment. Moreover, Boyce (1976) argued that perception and performance cannot be separated. On one hand, he explains, the perception of a place is affected by the ease with which a task can be performed. On the other hand, the motivation to perform a task can be affected by the perception of the space. Hence, the positive perception of a space is recognised as essential for good lighting quality.

Yet, although many researchers have discussed the conditions necessary for good lighting quality, and although the literature proposes that aesthetic judgements are parameters of lighting quality in a built environment, very little has been published on the aesthetic perception of daylit indoor environments (see Section 2.5). Although the effect that lighting has on the aesthetic perception of an indoor environment can be considered evident and logical, to date the topic largely remains unexplored. Thus, the present work was designed to acquire new knowledge about daylighting and its impact on the aesthetic perception of a built indoor environment.

1.2 Objectives and assumptions

This research project aims to explore how different daylighting designs affect the aesthetic perception of an indoor built environment. The fields of architecture and daylighting are taken as starting points. In addition, due to its strong link with the research, the field of environmental aesthetics was also used in the studies. The following sub-sections will delimit the main objective, research questions, conceptual assumptions and points of departure for the present dissertation.

1.2.1 Main objectives

The main objective of the present work is to provide new knowledge about the effects of daylighting on the aesthetic judgements of a small indoor environment. The main objective can be divided into two sections, defined by two different types of daylight collectors: windows (as primary daylighting design) and daylighting systems (as advanced daylighting design). Each of these daylight collectors is tested to evaluate its effect on the selected aesthetic attributes.

Additionally, as discussed in the introductions of Papers I and II (see Sections 3.2 and 3.3), due to the variability of daylight and the difficulty of performing daylighting studies, a methodological concern emerged for the present thesis. Hence, another significant objective was to validate the new simulation method, which allows for the use of stereoscopic images as a tool in daylighting and aesthetic studies.

Thus, the objectives of the present dissertation are:

a. To shed new light on the impact of windows and daylighting systems on the aesthetic judgements of small indoor environments.

b. To compare the different effects of three window sizes under overcast sky conditions in terms of nine aesthetic attributes.

c. To compare the different effects of four daylighting systems (two types of venetian blinds and two types of light shelves) under overcast and clear sky conditions in terms of nine aesthetic attributes.

d. To study the validation of a new simulation method that can serve as a tool for daylighting and aesthetic studies.

1.2.2 Research questions

The motivation described in Section 1.1, the state-of-the-art that is studied and presented later in Section 2.5, and the objectives of the present PhD dissertation generated the following main research question:

How does daylighting design affect the aesthetic impression of a built environment?

This question attempts to target the importance of daylighting design on environmental aesthetics. However, the question can be considered to have a generic and large connotation. Thus, in order to classify and manage the different research steps in a systematic fashion, three sub-questions were derived from the main research question:

1. *To what extent does window size affect the aesthetic judgements of a small room?*

2. *To what extent do different daylighting systems affect the aesthetic judgements of a small room?*

3. *Within the scope of research, which daylighting system is preferred for eliciting positive aesthetic judgements of a small room?*

The first sub-question deals with the primary daylighting design: windows, which serve as basic daylight collectors. Along the window size as an experimental independent variable, other independent variable was selected (i.e. room reflectance); in order to test and compare the effects of window size in two rooms with different conditions.

When windows cannot collect daylight deep in the interior of a room, daylighting systems are used. Hence, the second sub-question concerns the advanced daylighting design: daylighting systems.

The third sub-question emerged from the researcher’s own curiosity and it was designed to compare the selected daylighting systems.

As discussed below (Section 1.3), experimental research (performed using two experiments) was conducted to answer these questions.

Furthermore, the difficulty of conducting ‘real life’ experimental research due to the sparsity of necessary resources, time and logistics means that it is difficult for experimenters to conduct such research (see Sections 3.2 and 3.3). By making use of imaging simulation technology (in the scope of the study, stereoscopic imaging - see Section 3.1), a researcher has the ability to control the experimental variables and deal with resources, time and logistic issues more appropriately.

However, a common criticism of these types of studies is that it may not be possible to apply them in real settings unless the simulations reflect a realistic range of conditions in real environments. In order to validate any simulation method, it must be tested and compared with studies in real environments. An additional research question, based on this methodological concern, was then formulated:

Can stereoscopic imaging be considered an accurate experimental method in comparison to experiments in real environments when used in aesthetic and daylighting studies?

A pilot study and a main experiment were conducted to answer this question with a methodological aim. Stereoscopic images were compared to real environments with similar conditions.

1.2.3 Conceptual assumptions

'Question: A tree falls in the forest when nobody is around to hear it. Does it make a sound?

Answer: It depends on whether you take "sound" to mean compression waves in the air or auditory sensation.'

- Clyde Laurence Hardin. Introduction of Colour and Light: Concepts and Confusions. 2012.

By analysing Hardin's example of the sound of a tree could make (Arnkil et al., 2012), the reader will notice that this example deals with a philosophical problem. How can people describe a conscious sensation in a specific and true manner? Should we define sound as a physical or psychological phenomenon?

The same dilemma may be applicable when referring to light. Light is *something* that all persons with healthy vision perceive. However, the definition of light can have different meanings according to the academic background of the person defining it. In addition, depending on how someone wants to use, monitor, or measure light, different approaches can be applied. For example, in a discussion between a lighting engineer and an artist, conflicting understandings of light can produce disagreements.

In an effort to disentangle the confusing terminology of light and colour, Fridell Anter (2012) offered an analysis and classification of the different approaches most commonly used to identify light and colour as well as the methods used to quantify and describe them. Hence, Fridell Anter (2012) argued that there are two primary approaches to dealing with light and colour, both of which are described in the list below. In line with the main focus of the dissertation (i.e. daylight), the definitions of light according to each approach (based on Fridell Anter (2012)) are:

a. *The perceptual approach*, which describes light as the phenomenon that allows humans to see and interpret their surrounding environments (including surfaces, spaces, and physical objects). This approach is based on how people experience light and thus cannot be directly quantified. For scientific efforts (e.g. analysis and communication of light), the experience of light requires attentive observations. These in turn can represent concepts like *brightness*, *light level*, *light distribution*, *shadows*, *reflections*, *glare*, and *colour of light*.

b. *The physical theory approach,* which defines light as electromagnetic radiation energy, or more specifically, as the part of the electromagnetic spectrum that elicits a visual response in humans (see Figure 1.4). Light (or visible radiation) is thus considered to be limited to wavelengths between 380 and 760 nm (Valberg, 2005). Wavelengths below and above this are called *invisible radiation*. Specifically, wavelengths below 380 nm (are referred to as ultraviolet radiation), and wavelengths above 760 nm (are referred to as infrared radiation). The range of wavelengths that are considered to be included in the concept of visible radiation varies among sources. For example, some scientists work with wavelengths span as narrow as 420-680 nm (Laufer, 1996). Other researchers claim that under controlled laboratory conditions, children can see ultraviolet rays of 310 nm and adults can see infrared rays of at least 1050 nm (Lynch and Livingstone, 2001). Electromagnetic radiation is emitted from a source in small amounts of energy called *quanta* or *photons*. Related concepts used for scientific purposes include: *wavelength*, *electromagnetic spectrum*, *light energy*, *transmission*, *absorption*, *refraction*, and *diffraction*.

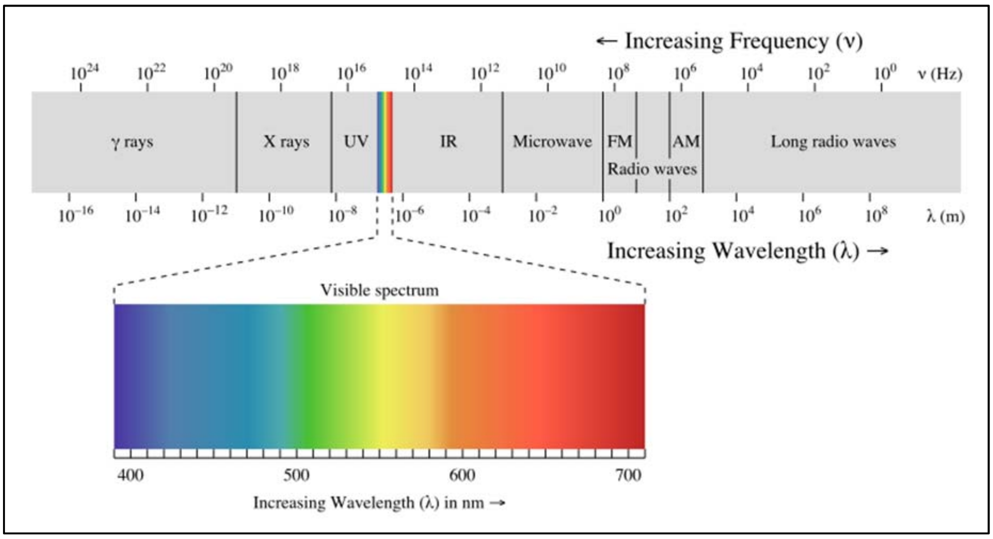

Figure 1.4: The electromagnetic spectrum.[3]

Additionally, a third approach merges both the perceptual aspects and the physical theory, as an attempt to bridge the gap between the conscious sensory experience and the scientific data of the physical world. In other words, it uses physical stimuli to describe and quantify perception. This third approach is referred as:

c. *The psychophysical approach,* describes light making use of the V-lambda V (λ) curve, which is a theoretical model that relates human visual sensitivity to different wavelengths. The photopic curve V (λ) is the typical daylight response curve, and the scotopic curve V' (λ) is the typical night adjusted response curve. The V (λ) curve or luminosity function was established by the International Commission of Illumination (CIE for its French name, *Commission Internationale de l'Éclairage*). Although the V(λ) curve has been questioned and revised a few times (Liljefors, 2010), as presented by Fridell Anter (2012), it is still considered the best tool available to quantify how light is perceived by the human visual system from physical radiation. This is done using photometric measurements, which specify the capacity of radiant energy to evoke visual responses. Logically, all photometric concepts are based on the V (λ) curve. Concepts used with scientific purposes are: *luminous flux*, *luminous intensity*, *illuminance* and *luminance* (see further explanation of these concepts in Section 2.3.3).

[3] Wikimedia Commons - Creative Commons License - http://en.wikipedia.org/wiki/File:EM_spectrum.svg

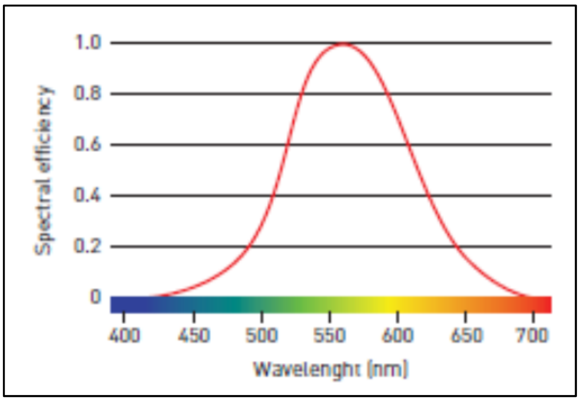

Figure 1.6: Figure of the luminosity function-V (λ) curve: photopic curve. From (Fridell Anter, 2012).[4]

1.2.4 Points of departure

a. Aspects of light

The previous section described different approaches for addressing light and work related to light, each of which fulfils different scientific needs. However, the third approach, i.e. the psychophysical approach, raises many questions, including whether it is truly possible to measure human perception with physical instruments. There seems to be a consensus that photometric quantities have an acceptable correlation with visual perception. A quick search of the annals of journals that include lighting research in their scope yields a large range of research using photometric concepts. Yet some believe that photometric tools should be revised and developed to better correspond to perceptual observations.

Still, as pointed out by Fridell Anter (2012), those taking a psychophysical approach should have an understanding of the differences between physics and perception. She argued that these understandings should not be dismissed from each other; rather, there should be an awareness of all the differences in an attempt to bridge the gap between the fields. Finally, she recommends that terms with specific definitions should only be used for their original purposes, e.g. perceptual concepts to describe perceptual observations.

[4] Permission to use the image granted by Karin Fridell Anter on the 15th of June, 2015.

The author shares this opinion, and thus a main departure point for the present work is the use of photometrical units as a means of monitoring the light conditions of the perceived studied environments. Some references to perceptual concepts related to lighting (e.g. glare) are also discussed as part of the visual perception of an environment. Thus, perceptual and psychophysical terms are addressed where appropriate throughout the dissertation.

b. Interdisciplinary approach

Lighting research is by nature an interdisciplinary activity. Visual perception, circadian rhythm, environmental experience, and spatial studies are terms that are strongly linked to light and lighting. However, as noted by de Kort and Veitch (2014), each of those terms can be used by researchers in diverse domains. For example, vision scientists and neuroscientists often discuss visual perception; chronobiologists and medical physicists study, among other topics, the human circadian rhythm; psychologists study the impact of environmental experiences on humans; and architects, interior architects, lighting designers, and illumination engineers also study the interaction between space and light.

Considering the research interest that spurred the PhD project, two main fields serve as a basis for the present thesis: daylighting studies (encompassing physics and optics) and environmental studies (focusing on environmental aesthetics). Therefore, in addition to lighting studies, some of the theories included in the present thesis include environmental studies (i.e. human environmental preferences) as part of the background in relation to lighting studies.

c. Selection of environments

Humans spend most of their waking time indoors, i.e. around 80-90% (Klepeis et al., 2001). This percentage includes both time spent at home and at the workplace and accounts for an average of around 20 hours a day (Hellweg et al., 2009).

Nonetheless, there seems to be surprisingly little research that focuses on the impact of windows (as daylight collectors) on the perception of the interior of any building type (Veitch, 2011). Even less research focuses on daylighting systems and their effect on the aesthetic perception of any space.

Thus, the author was inspired to study the spaces where people usually spend most of their time, i.e. home and workplace. Following this motivation, the selection of an environment became evident for the research: a single office unit was then set to be one of the studied environments, as it undoubtedly represents a common private workplace.

During the first year of the present project, newspapers indicated that there was increasing demand for student housing facilities in the city of Trondheim (Kilnes, 2011), a phenomenon that has continued in the following years (Kvitrud, 2013). This was hardly a surprise as a previous PhD work identified a steady rise in the number of students in western countries (Thomsen, 2008). In her PhD dissertation, Thomsen (2008) argued that providing living spaces to students should not be the only focus, but that '*other concerns are related to questions on how to accommodate students and what is suitable housing for these temporary residents. The type of housing, the standard and the architectural design are important issues in this context*'. Due to the lack of literature and research focus that connects both daylighting and environmental aesthetics of student rooms, the selection of the first environment to study was not a difficult decision. Hence, the other environment to study was set as a student room.

1.3 Research strategy and research design

According to Creswell (2009), when planning a study, a researcher should involve three components. These components refer to:

i. *the philosophical worldview*, which is the researcher's reflections on the preliminary assumptions of a study;

ii. *the selected strategy of inquiry*, which is directly associated to the researcher's philosophical worldview; and

iii. *the research methods*, which transform the selected approach into practice.

Thus, a logical first step for preparing a plan to conduct research is clearly establishing the philosophical ideas that may have an impact on the research and its outcomes. Different philosophical worldviews could influence the truth, values, reality and knowledge that a researcher uses and finds. Exploring these philosophical ideas is a relevant departure point that allows a researcher to determine what he or she believes and which research method would be the most appropriate.

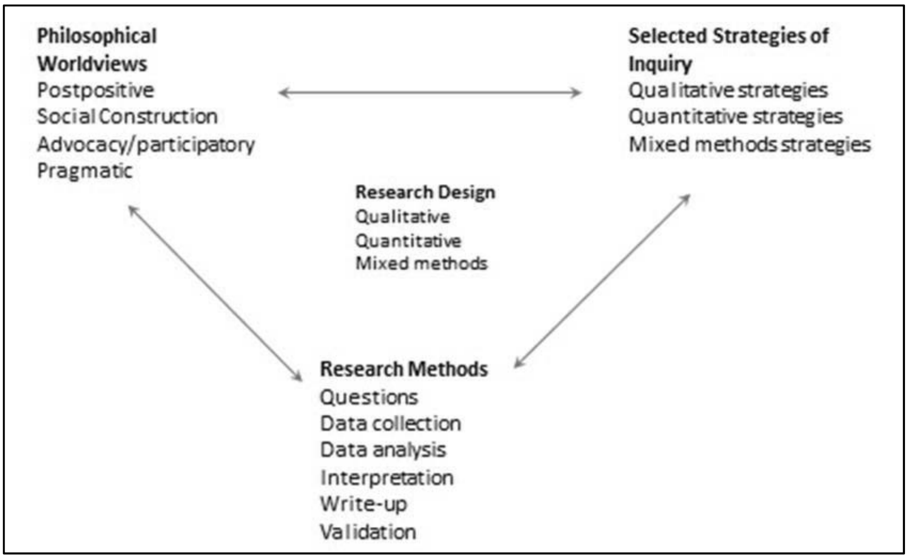

Figure 1.7: A framework for research design: the interconnection of philosophical worldviews, strategies of inquiry and research methods. Adapted from Creswell (2009).[5]

[5] Permission to use the image granted by SAGE Publications, Inc. USA.

1.3.1 Philosophical worldviews

It is not surprising that architecture as a discipline lacks scientific research tradition. Architects and architecture students are mostly trained to design buildings. Studies about theory of knowledge and research methods are little or none in several architecture schools. Mo (2003) pointed out that this lack of research tradition results in a plurality of research, in which different methods and approaches are taken from different disciplines. This results in studies with fundamental problems, such as the use of inadequate research methods for the questions to be answered.

As stated in the previous section, the understanding of different philosophical worldviews is the first step when designing a research study. This can establish a framework for the ideas, reflections and beliefs of the researcher regarding the preliminary assumptions of a specific study. These beliefs will later on guide research action. In architectural and social research books, these worldviews are often referred using different terms such as *paradigms* (Mo, 2003, Groat and Wang, 2002) or *ontologies and epistemologies* (Bryman, 2012).

Different philosophical worldviews can be found throughout literature concerning the philosophy of science. From the ones that are widely mentioned in the literature, and acknowledging that the comprehension of these will dictate the appropriate worldview to bring to inquiry, seven philosophical worldviews are highlighted and briefly discussed:

i. *Positivism,* was considered a philosophy of science in the origins of sociology as a discipline (Mo, 2003). Positivism took from the natural science and applied to the social science, presenting measurements, analysis, and predictable patterns. This means that it studied what one could observe and measure. Positivism dominated a large period of science and is considered as difficult to discuss, due to the different ways in which researchers see it. For example, some define it as a categorical position still valid in scientific research, while others describe it as a trivial collection of data (Bryman, 2012) (see further discussion in Section 1.3.3). However, it was characterised by objectivity (i.e. holds *objectivism* as an ontological orientation), and for presenting the principle of *deductivism* (i.e. theory testing). This means that researchers attempted to prove a theory by manipulating and observing in an objective manner. Thus, this worldview is predominantly related to the use of quantitative and/or experimental research.

ii. *Interpretivism,* originated as a response to positivism, arguing that the social world is ontologically different from the natural world (Hughes and Sharrock, 1997). This means that the relation between people and the natural science requires the intervention and the methodological tools of social science to understand the subjective meaning of the interrelation. It is mainly oriented to an inductive approach (i.e. the generation of theory), making use of qualitative methods as research strategy. Based on this worldview, researchers maintain an interactive link between them and the participants or setting of the study (Groat and Wang, 2002). According to Bryman (2012), Interpretivism influenced, and thus includes as intellectual heritage, the philosophical worldviews of *Hermeneutics* (essentially a theological term with applications to social science, as the study and interpretation of humans and social actions) and *Phenomenology* (discussed below).

iii. *Phenomenology,* stands as an anti-positivist worldview. It critiqued positivism for taking natural science as an ideal in social science, and argued that science must see things as they are. This means that phenomenology seeks the comprehension of knowledge in a holistic way, examining the relation between people and the added world elements in different contexts. It became more philosophical than empirical, addressing how we constitute reality, i.e. *'the study of what reveals and manifests itself'*(Mo, 2003). Although Phenomenology presents many parallels to Interpretivism, Phenomenology disputes the subjectivity claims of Interpretivism, claiming that we cannot get beyond the conscious and immediate experience (Hughes and Sharrock, 1997). Phenomenology is typically qualitative, and it describes and legitimates case study methods (Mo, 2003).

iv. *Post-positivism*, emerged not as a revision of the positivist worldview, but as a rejection of the principles of positivism. While positivist claimed that objectivity can be attained in research procedures, post-positivists argued that all observations are fallible and present errors, and thus objectivity is a goal that can only be realise in an imperfect way. This means that post-positivism believe that a reality can only be known with some level of 'probability' (Groat and Wang, 2002). Post-positivism is characterised by determination, reductionism, empirical observation and measurement and theory verification. This means that post-positivism determines what influences the findings in experiments. It also reduces the scope of ideas, transforming them into a manageable set of ideas that can be controlled (e.g. variables and hypotheses). The acquired knowledge in post-positivism philosophy is mainly based on empirical observations (e.g. an experiment in which the participant's behaviour becomes crucial). Finally, a fundamental assumption of this philosophy is that knowledge is conjectural. This means that researchers do not focus on proving a hypothesis, but rather they reveal a failure to reject the hypothesis (i.e. null hypothesis) with a level of probability (Phillips and Burbules, 2000). In simpler words, post-positivism calls for the use of the scientific method and requires the collection of data that are measured numerically and analysed statistically. Hence, due to the nature of this philosophy and its deductive approach, this worldview is most appropriate for quantitative research.

v. *Social constructivism,* is also called constructionism or social constructionism. It originated from an interpretivist way of thinking and thus shares philosophical roots with interpretivism and phenomenology. However, social constructivism is considered distinct from interpretivism, because similar to phenomenology, questions the focus on the subjective values of interpretivism. Social constructivism sees society as both subjective and objective reality and seeks to apply a '*logical empiricist methodology to human inquiry*' (Andrews, 2012). Although Groat and Wang (2002) indicated that constructionism, interpretivism and phenomenology are terms used interchangeably used by different authors, social constructivism is considered to have emerged from phenomenology. It is characterised by the pursuit of understanding, multiple participant meanings, social and historical construction, and theory generation. Thus, social constructivists seek to understand the world in which people perform their daily activities. This worldview is based on the idea that there are multiple subjective and objective meanings of participants' experiences, which calls for a study of the complexity of these multiple views rather than forcing researchers to choose a limited number of ideas to study. The participants' meanings are based on social and historical interplay with others. This means that the aim of this worldview is to understand interactions between humans (i.e. people making sense of the world based on social interactions) and the historical and cultural contexts that can have an influence on participants. Constructivist researchers recognise that the outcomes are directly influenced by their own background and assumptions, and therefore they include themselves in the research in order to socially construct realities and acquire interpretations of the realities. The main difference between social constructivism and post-positivism is that the former does not start with a theory but uses an inductive approach (i.e. uses observation to generate a theory). This worldview is appropriate for qualitative research.

vi. *Advocacy/participative*, has a philosophical parallel with other worldviews including: *transformative* and *emancipatory*. It emerged during the 1980s and 1990s in response to a strong disagreement with the post-positivist position. The discomfort was originated in the feeling that post-positivism impose theories based on research focusing on racial, ethnic, gender and western-focused biases (Groat and Wang, 2002), and it did not account issues of social justice or marginalized individuals (Creswell, 2009). As a result, it is characterised by political connotations, an orientation towards empowerment issues, collaborative objectives and desire to establish changes. This advocacy/participative worldview claims that research objectives should be associated with and included in political agendas. The needs of people who are ‘powerless’ in a society, either because they are marginalised or disenfranchised are considered important; empowering people to make changes in their communities. It is based on collaboration via the participants, who are not seen as mere study cases but as experts and fellow researchers. This worldview aims to collect information in order to acquire results in the form of action and change. The advocacy/participative worldview is generally used for qualitative research. However, it can also serve as a foundation for quantitative research.

vii. *Pragmatism*, originated during the latter quarter of the 19th century. In contrast to post-positivism, pragmatism is not founded on preliminary conditions, but focuses on actions and consequences. It is characterised by the consequences of actions, is problem-centred, pluralistic and oriented to real-world practice. Pragmatic researchers are not committed to any particular way of thinking about reality. Instead of focusing on methods, a pragmatic researcher focuses on the research problem and uses all available approaches (e.g. quantitative and/or qualitative) to solve that problem. This means that the biggest concerns are the *what* and *how* of research. Pragmatic researchers understand many methods and may mix them to obtain the best solution to the research problem. Due to the nature of this worldview, researchers usually use mixed methods approaches.

Other interdisciplinary directions such as *Structuralism* (i.e. focus on relations and connections between units rather than the units themselves, holding positivism as the ideal), and the heavily criticized *Postmodernism* (which research view is unclear) are discussed by Mo (2003). However, a deeper discussion of these worldviews is not considered necessary at this point, for further information of these interdisciplinary directions please refer to Mo (2003).

1.3.2 Research strategies

The second step of planning a research study is selecting the strategy of inquiry, or the research strategy. To support the researcher's chosen research method for this thesis, a short overview of the other methods (i.e. qualitative, quantitative and mixed) are described and discussed in the following sub-sections.

A list of strengths and weaknesses of each method is presented at the end of the description of each method. It is important to mention that the discussion is directly related to the scope of the research and thus presents a limited selection of weaknesses and strengths. However, interested readers can find further information in Groat and Wang (2002), and Creswell (2009).

a. Quantitative approach

Quantitative research has been described as '*a means for testing objective theories by examining the relationship among variables*' (Creswell, 2009). This approach seems to have many parallels with experimental research (Groat and Wang, 2002). It is characterised by experimental designs that involve a treatment (independent variables), the measurement of outcome variables (dependent variables) and a focus on causality (even when this might not be possible to attain). But, as its name expresses, one could say that the main characteristic of this method is the ability to quantify data. It uses a deductive approach, which allows a theory to be tested (via hypotheses) based on empirical observations and experiments.

As described above, it is important to acknowledge the weaknesses and strengths of this method, in order to decrease the number of possible negative influences on the research outcomes. Based on Groat and Wang (2002), the weaknesses and strengths that can potentially mediate with the present research are:

i. Quantitative methods' weakness:

- *Reduction of a complex reality to identify a cause*. Critics of this method claim that laboratory settings cannot represent real-life settings and consequently cannot provide applicable results. These critics recommend that the phenomena should be observed in natural settings, as there could be other variables influencing the object under study (see Section 2.2.3).

ii. Quantitative methods' strengths:

- *Potential for establishing causality / Ability to control all aspects of an experimental design enables the attribution of causality*. This point can seem to contradict the weakness discussed in the previous paragraph. Groat and Wang (2002) argued that it is not always possible to identify cause as '*pure objectivity is impossible*'. Nevertheless, having control over independent variables and identifying extraneous variables (i.e. variables that can interfere with the effects of the independent variables on the dependent variables) protects against possible bias. The ability of the researcher to have control over different variables allows them to identify uninteresting variables that can mediate between the independent and dependent variables. This can reassure the validity of the results.

- *Potential for generalising results to other settings and phenomena*. By keeping a log of the experimental design, the replicability of the experiment in other contexts becomes available to other researchers. The ability of the researcher to have control over the different variables again becomes a factor as it allows for the generalisation of results or the achievement of external validity (see further discussion in Section 1.3.4).

b. Qualitative approach

Qualitative research has some inherent characteristics, such as researcher dependence, narrative of observation analysis, open-ended status and prolonged contact in studies (Groat and Wang, 2002). Its inductive approach allows observation to lead to generalisation, and in some cases, to the creation of theory. The generative approach depends on the researcher's interpretation of the meaning of the collected data.

i. Qualitative methods' weaknesses:

- *Challenge of dealing with vast quantities of data*. The collection, management, analysis and interpretation of large quantities of unstructured data are major, time-consuming challenges for any researcher.

- *Credibility of qualitative data can remain suspect*. Post-positivist researchers may doubt the validity and credibility of qualitative data, probably due to the characteristic previously discussed (i.e. vast amounts of unstructured data).

ii. Qualitative methods' strength:

- *Flexibility in design and procedures allowing adjustments in process.* Because qualitative research lacks a theory at the beginning of research, one of its major strengths is the ability to make changes and adjustments as the research continues.

c. Mixed methods approach

Mixed methods research combines both qualitative and quantitative methods. This is done to strengthen studies by using more than just one approach, allowing the study to benefit from the strengths of both approaches. Among its main characteristics are the development of a rationale for mixing methods and the integration of collected data at different stages of the research (Creswell, 2009).

i. Mixed methods' weaknesses:

- *Potential lack of connection and coherence*. The potential answers to qualitative open-ended questions are limitless. This could make it difficult to connect participants' opinions to the dependent variables of the study.

- *Need for level of sophistication in mixed methods research design*. In order for the connection between quantitative and qualitative methods to work correctly, the researcher must have a clear, developed idea of how the different parts of each approach may be used to obtain particular information. At the same time, the approaches should be specific enough to complement each other. This level of strategy development required for each approach might seem overwhelming and can lead to errors.

ii. Mixed methods' strengths:

- *Potential for maintaining coherence by emphasising dominant design / less dominant design can provide depth and validity*. The less dominant approach is put in a secondary position, allowing the focus to be on the main objective of the study. This also allows the less dominant approach to provide supporting information to confirm the results. This systematic approach allows a researcher to maintain coherent logic in a research study.

- *Potential to maximise strengths and minimise weaknesses of each approach*. The quantitative approach could have difficulties to obtain information; thus, the qualitative approach can act as a complementary method for gathering missing information. Conversely, large amounts of data that are obtained by the qualitative approach can be controlled by the quantitative approach.

1.3.3 Positioning as a researcher: Conducting a mixed method research

Lighting research follows traditionally the scientific method (i.e. a quantitative approach). However, qualitative methods are also used in human-centred approaches (Wänström Lindh, 2012). Additionally, as discussed in Section 1.2.4, lighting research is an interdisciplinary field with a diverse range of scientific traditions and practice that can lead to conflicting opinions. This divergence of viewpoints has created mutual criticism between, for example, researchers advocating for experimental research and researchers standing by qualitative research, or between post-positivists and constructivists. In a PhD seminar held at the Faculty of Architecture and Fine Art at the Norwegian University of Science and Technology, where this research was conducted, an oral statement was printed in the memory of the author: '*It is considered fashionable to be a constructivist; to be called a positivist means that the researcher is acting as he/she can measure everything*'. This opinion illustrates the ongoing conflicting discussion about the selection between two research approaches. For example, constructivists (or advocates of qualitative methods) question the validity of data acquired from reduced environments in laboratory settings and the simplification of results obtained from statistical analyses. On the other hand, post-positivists (or advocates of quantitative methods) question the subjectivity of complex studies based on the researcher's own interpretations and the acquisition of solid answers from large studies with many uncontrolled research variables. Undoubtedly, this discussion meets no end, and it appears not as it will be resolved in the near future.

In the author's opinion, both quantitative and qualitative methods deserve respect and attention from scientists in different disciplines. A deep understanding of the strengths and weaknesses of each method and the acknowledgement of the differences between them can lead to informed decision-making regarding a research method. In this regard, research methods should be selected primarily based on the research question/problem to answer/solve. Different problems demand different approaches to achieve a solution; where one method can help answer a question, another method might not.

Hence, the author's criteria for selecting a research method for the present PhD project were developed after carrying out a literature review of philosophical worldviews, research methods design, and performing a review of the state-of-the-art of the lighting research regarding aesthetic evaluations of environments. Nevertheless, it is important to remember the main research objective of the present dissertation: to offer results that can shed new light on the effects of daylighting on aesthetic judgements of an indoor environment. Thus, the central focus was on acquiring information instead of focusing on single research methods. Consequently, the view for this research lies in the philosophical tradition of *Pragmatism*, where the objective of which is to use all the available approaches to achieve new knowledge.

As discussed in Section 1.3.1, the pragmatic worldview opens the door to multiple methods; in fact, it aims to engage with more than one single method (Creswell, 2009). In that regard, the most suitable method for this research project appeared to be a mixed methods approach. Certainly, the use of different research methods (i.e. quantitative and qualitative) might allow for a more complete collection of information using different strategies. As discussed by Reinharz (1992), and presented in Groat and Wang (2002), '*Combining the strengths of the experimental method with the strengths of other methods is probably the best way to avoid its weaknesses while utilizing its power. Similarly, combining the strength of research with the power of other forms of persuasion is probably a useful approach for creating change.*'

The primary analytical characteristic of hypothesis testing in this study, i.e. seeking expected connections between daylight and aesthetic judgements, seems to justify the use of quantitative methods. Hence, the strengths of quantitative methods are used via experimental research to establish a relationship between daylight deliverers (acting as independent variables), and the selected aesthetic attributes (acting as dependent variables) (for a detailed discussion about the selection of aesthetic attributes, see Section 5.1 – Paper V).

Furthermore, using the strengths of qualitative methods allows for deeper sources of information for variables that could have an influence on the experimental outcomes. For example, the use of open-ended interview with a group of participants can provide some insight that could have mediated their responses and thus could have an impact on the results. Another advantageous characteristic of qualitative research is its use of multiple strategies. In addition to the open-ended interviews, photographs, and an experimental log based on the experimenter's observations could serve as sources of information with qualitative value when analysing the results.

Due to the aim of the research, the author considered the quantitative methods (via experimental research) to be the logical predominant method to be used so that the preliminary assumption (i.e. daylight/daylight collectors affects the aesthetic perception of an indoor environment) could be tested first. In addition, the use of qualitative methods would serve as secondary method providing a supporting role in the data collection procedures. The qualitative method (via face-to-face open-ended interviews) allows a detailed exploration of the outcomes.

The strategy of inquiry used in the present work was the one referred to as *Concurrent Embedded Strategy* (Creswell, 2009). This particular strategy is concurrent because the data collection of both quantitative and qualitative methods happens simultaneously. This means that in the present work the qualitative data collection was not carried out after the complete set of quantitative data was collected and analysed; rather it was collected between the experimental sessions. The strategy is embedded because the qualitative approach was nested within the predominant method (i.e. quantitative approach). In this way, the embedding of the qualitative approach (via interviews) addressed different questions (see Appendix B) than the ones in the quantitative approach (via questionnaires).

According to Creswell (2009), the use of this particular strategy of inquiry is advantageous because: *i*. it provides the benefits of both quantitative and qualitative approaches, allowing the researcher to gain perspectives from the different types of data, and *ii.* it allows a simultaneous collection of data, making the study manageable for the time and resources available. Finally, the comparison and/or integration of the data from the two approaches is usually achieved in the discussion section of the report of the study.

Thus, the selected strategy used in this PhD work is a mixed method research using a concurrent embedded approach with a quantitative method as the predominant method and qualitative as supporting method, i.e. research design: *'QUAN + qual'*.

The collection of the quantitative data is described in each paper included in this thesis. The collection of the qualitative data was carried out using semi-structured interview protocols using five open-ended questions. However, some interviews included insights and new questions that emerged from previous interviews or data collection. The interviews were selected as qualitative approach because they enabled to explore the rationales behind the evaluations of the experiment participants, and allowed a deeper understanding of their evaluations. It is important to indicate that the qualitative interviews were conducted for the two experiments of the present PhD work. Although the interviews are briefly discussed in paper II, the interview protocol was the same as the one described in detail in paper IV (see Section 2.4).

1.3.4 Research design: Validity

Two crucial terms that motivated the present research are *Daylight* and *Aesthetic Quality* (see Section 1.1). Within the selected research method (i.e. mixed methods, with the quantitative method being of paramount importance) there is a logical need to measure (and thus control) the stimuli that are under study, which allows the observed outcomes to have meaning. In other words, the daylight collectors that are acting as stimuli should be able to be measured. Likewise, the aesthetic attributes acting as observed outcomes should also call for measurement. This demand for measurement and control emerges from the need to ensure validity in any research study.

As indicated by de Kort and Veitch (2014), lighting research that reveals internal procedures in order to produce practical applications of the results requires both internal and external validity. In quantitative methods, internal validity refers to the extent to which conclusions are due to the independent variables, and external validity refers to the extent to which conclusions may be extended beyond the experimental setting.

Additionally, Veitch and Newsham (1998a) pointed out that in order to establish cause-and-effect relationships between lighting conditions and the observed outcomes, internal and external validity are not the only elements that should be maintained. Other research control practices, such as statistical conclusion validity (i.e. statistical tests address the research hypothesis), should also be planned for in the research design.

Regarding the present dissertation, daylight can be measured using physical and photometrical procedures (see Section 1.2.3) and instruments, e.g. a lux meter, which measures illuminance, and a luminance meter or luminance camera, which measures luminance. In addition, daylight collectors, such as the ones used in the present research study (i.e. windows and daylighting systems), can be and have been adequately and specifically described.

In the present PhD work, the dimensions of the windows and daylighting systems, number of glazing panes, material properties, reflectance, room surface colours and translucence of materials are physical characteristics that are carefully described in detail. Moreover, since the research deals with daylight and not artificial/electrical light, the selected studied lighting conditions include two general sky types (i.e. overcast sky in the first experiment and both overcast and clear skies in the second experiment) that could be extended beyond the experimental setting. Naturally, a partially covered sky would have created uncontrollable variables, which are unsuitable for a scientific study. Thus, the appropriate lighting conditions became evident. Furthermore, all photometrical measurements were carried out using the same instruments at fixed and marked points in the studied environments (see Papers III and IV).

Measuring aesthetic quality holds a more complex domain. Quality is a subjective term with a definition that varies depending on the person who uses it and the field in which it is used (for the definition of quality used in the present dissertation, please refer to the Glossary). Still, quality is commonly considered to be an abstract concept, and thus receives criticism for its inability to be measured (Veitch and Newsham, 1998a). However, in the social sciences, intangible entities such as quality are considered constructs, and measurement rules can be established to better understand these constructs (Ghiselli et al., 1981), as presented by Veitch and Newsham (1998a). In the specific case of aesthetic quality attributes, these can be (and have been) measured using different rating scales (see Section 2.2.3). In addition, the use of open-ended interviews with participants acted as a supplementary response modality to confirm the participants' questionnaire answers and gather extra information. The strength of the numerical results became more robust by confirming the responses using two different measures.

Good scientific practice also requires detailed statistical reporting to validate the obtained results and allow the re-analysis of the data for meta-analytic purposes (Veitch and Newsham, 1998a). In this regard, the present dissertation attempts to comprehensively and precisely describe the statistical tests and techniques that are used. For example, a report of the overall means (*M*), and the standard deviations (*SD*) of the participant groups of each experiment are given. Finally, the reasoning behind the selection of each statistical test has been expressed in sections entitled '*Analysis strategy*' prior to the reporting of the numerical and statistical outcomes.

1.4 Outline of dissertation

The main basis for the present work is the five scientific articles found in Chapters 3, 4 and 5, making this dissertation an article-based thesis. In addition to the scientific articles, Chapters 1 and 2 supply a connection between the articles by providing the introduction, research design and theoretical foundation for the conducted work. This was made in accordance with the current PhD regulations in *§10.1 Thesis requirements*, provided by the Norwegian University of Science and Technology.

As the reader will notice, the scientific articles are placed within the main body of the dissertation and are not provided as appended articles at the end of the dissertation. This was done in order to offer a better connection between the different stages of research: experimental method testing, primary daylighting design, advanced daylighting design, and conjunct analysis of the summarised results.

It is, however, important to note that because the black and white room experiment is represented in four articles and the daylighting systems experiment is represented in two articles, some repetition and overlapping occurs.

In order to aid the readability and understandability of the text, the main concepts and theories (according to the author) are discussed in general terms. For readers interested in further and more detailed reasoning, recommendations for literature and their sources are provided in appropriate places within the present dissertation.

The dissertation starts with *Chapter 1: Introduction*, in which the research field is introduced and the objectives, research questions, conceptual assumptions and points of departures are given. Additionally, different research approaches are discussed, the validity of the research design is examined and the position of the researcher regarding the selected research strategy is given. Finally, the articles selected for this dissertation are listed and the candidate's and co-authors' efforts in each article are identified and described.

Chapter 2: Theoretical Background presents the definition and use of main concepts and theories, which are divided into three fields of research: visual perception, environmental studies and lighting studies. Due to the strong focus of the work on light and perception, visual perception opens the chapter to discuss the physical and physiological processes of vision, and its direct relation to light, e.g. basic physical and perceptual concepts of light. This section provides an overview on the theories and concepts that discuss 'how do humans see?' and 'the importance of light to human vision'. After understanding on how humans see, studies about the relation between man and the visual environment follow in section 'Environmental studies', in an attempt to understand the theories behind the question 'how do humans relate to the visual environment?' The next two sections discuss light and colour in relation to architectural environments, by reviewing concepts and/or theories addressing the relation between light, colour, and the visual environment. Naturally, these sections are limited to contain the most relevant concepts that are directly related to the present research; for example, stereoscopic vision is included in visual perception due to its association with the presented methodological study. Although the last two sections of this chapter belong to the same field (i.e. daylighting), they are separated to discern basic concepts of daylight and colour from the application of daylighting design in buildings. The first four sections of the chapter deal with an overview of established concepts and theories, while the last chapter section (i.e. Section 2.5) introduces the state-of-the-art by mapping out the field of previous interdisciplinary research focusing on aesthetic judgements in lighting studies.

Chapter 3: Experimental Method presents a brief overview of the simulation techniques used in lighting studies and describes the methodological framework for using stereoscopic imaging as a daylighting research method. In addition, two scientific articles with methodological aims are included in this chapter. The first article refers to the experimental set-up and pilot study, and the second article refers to the complete data set of the main methodological experiment. The validation of the stereoscopic image method as a research method for daylighting and aesthetic studies is analysed and discussed.

Chapter 4: Findings includes the two main articles describing the core of the present dissertation: the main findings which connect aesthetic judgements with daylighting design. The first article deals with the primary daylighting design, windows, by examining three different window sizes. The second article deals with advanced daylighting design, examining four types of daylighting systems.

Chapter 5: General Conclusions provides the last article of the present work. The article joins, summarises, and critically analyses the results of the two articles presented in chapter 4. The reasoning behind the creation of this joint article was to point out similarities and connections between the relation of the selected aesthetic judgements and daylighting design. In addition, this chapter concludes the thesis by presenting the main conclusions, classified by research topic. Finally, proposals for developing the research field beyond doctoral studies are offered.

Summary sections are provided at the end of each chapter in order to gather the necessary information in a synthesized course.

The dissertation ends with the complete *References* list, the *Glossary* of the terms most used in the study and the *Appendices*, which include one sample of the written questionnaires given to the participants of both experimental studies, and one sample of the semi-structured open-ended interviews also used in both experimental studies.

1.5 List of papers

The present dissertation is based on five scientific research papers. The full version of each of the articles is included in the appropriate chapter. Most of the articles have been published or accepted for publication in international scientific journals. One paper was published as a part of a book, and another paper was published in the proceedings of an international scientific conference.

These independent articles were developed during the author's doctoral studies and were produced to report the results of different stages of research. They supply in-depth information for each of the experimental settings with a relatively high degree of technical detail.

The list below describes the five scientific articles, including their place of publication and general reference information. In addition, according to the current PhD regulations in *§10.1 Thesis requirements*, provided by the Norwegian University of Science and Technology, the roles of the co-authors of each paper are described. Thus, the papers that support the empirical findings of the present PhD work are:

Paper I

- Reference information:

MOSCOSO, C. 2013. Virtual environments to study daylight and colour. Towards a new approach of advanced research method. *In:* MATUSIAK, B. & FRIDELL ANTER, K. (eds.) *Nordic Light and Colour*. Trondheim, Norway: NTNU – the Faculty of Architecture and Fine Art. p. 95 - 104.

- Status: Peer reviewed. Published.

Paper II

- Reference information:

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- Roles of the co-authors: The second and third co-authors helped define the scope of the experimental design, provided support when analysing the statistical results and contributed by performing quality assurance and proof reading.

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1.6 Summary

The first chapter has exposed the motivation that inspired the research activities of the present dissertation. As indicated, the main focus of the work presented in this dissertation is to shed new lights on the effects of daylight on the aesthetic perception of built indoor environments.

By daylight, two types of daylight collectors are considered within the scope of the research: windows as primary daylighting design and daylighting systems as advanced daylighting design. The aesthetic perception of environments entails studies of environmental psychology (e.g. measurements of environmental perception). Daylight and aesthetic quality are thus terms of paramount importance in the present research.

Due to the interdisciplinary nature of lighting studies, different fields claim usage and knowledge of different terms (i.e. perception, physics and psychophysical studies). In order to avoid discrepancies, and as a way of solving theoretical and practical questions, this chapter provides the different conceptual assumptions and approaches, and mentions the departure points for the research work, e.g. the differentiated use of perceptual and psychophysical terms where appropriate.

In order to establish the most suitable research methods and techniques for the present work, and to answer the research questions, an overview and discussion of different philosophical worldviews and research strategies is provided. After such discussion, this chapter presents the logic used by the author to determine the positioning as a researcher. In sum, the author claims that the philosophical worldview of *pragmatism* leads to the selection of mixed methods research as the most appropriate strategy for the presented work.

Finally, as pointed out by Veitch and Newsham (1998a), the lack of knowledge regarding aesthetic perception in lit environments is caused not only by the little attention it has received by research, but also by the poor performance of some lighting studies. To ensure scientific validity and reliability, Section 1.3.4 provides a general explanation of the measures taken to report the scientific practice carried out during the years when this PhD dissertation was performed.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 Visual perception

Among the five human senses that are traditionally recognised, sight is probably the most powerful sense for connecting a person with the surroundings. Approximately 60% of all the nerve fibres that connect sensory organs to the brain are located in the eyes (Valberg, 2005). It is consequently not surprising that sight is the sense which, via the visual system, has more capacity to receive, interpret and understand information than any other of the senses.

One of the most basic concepts in the science of vision is that visual perception is directly related to the light reflected from objects. Thus, to perceive the visual totality of a room, three elements become necessary at a first stage: the eye, the objects and light. Light allows us to process information about our surroundings. Later, the processing of information leads to an interpretation of what we see. This process is called visual perception. In order to understand how we perceive our surroundings, it becomes necessary to understand basic concepts related to how visual perception works.

2.1.1 Fundamental visual factors

Visual perception cannot be defined simply by *what we see*. Three different processes are involved in the science of vision. These are the physical, the perceptual and the cognitive processes. These three processes will be briefly described in this section as a simplification of the broad understanding of how visual perception works. Many disciplines, such as physics, psychology, neuroscience, and biology, have an ongoing research focus on the science of vision. Due to this interdisciplinary nature, visual perception can be studied at different levels dissimilar to the ones exposed here. However, these three processes cannot be omitted when discussing visual perception.

Physiologically speaking, in simple words, light goes through the pupil while the lens focuses the image on the retina. The retina is a layer of tissue located at the back of the eyeball that receives different kinds of light information along parallel tracks. This information is received by different kinds of neurons connected to photoreceptor cells located in the retina: rods and cones. Although the retina is less than half a millimetre thick, it contains many layers. Photoreceptor cells are found at the outermost layer of the retina. This means that the light passes through different layers and other types of cells before reaching the rods and cones. Although both rods and cones absorb light, they differ regarding their sensitivity to light and the type of information they carry. The rods, about 95% of the photoreceptors, are located in the periphery of the retina (Valberg, 2005). They are more sensitive than cones and function in scotopic vision (i.e. low light conditions). The cones are located in the centre of the gaze and function in photopic vision (i.e. high light conditions). Within the retinal layers the retinal ganglion cells are also encountered. Conventional ganglion cells lacking melanopsin do not present intrinsic light responses, whereas retinal ganglion cells containing melanopsin present intrinsic light responses (Hattar et al., 2002). These light-sensitive cells are called *intrinsically photoreceptive retinal ganglion cells* (ipRGCs). However, unlike the rods and cones, the ipRGCs do not contribute directly to vision, but are responsible for helping human circadian rhythms remain on a diurnal light and dark pattern cycle and for initiate other non-image-forming visual functions, such as the pupillary light reflex.

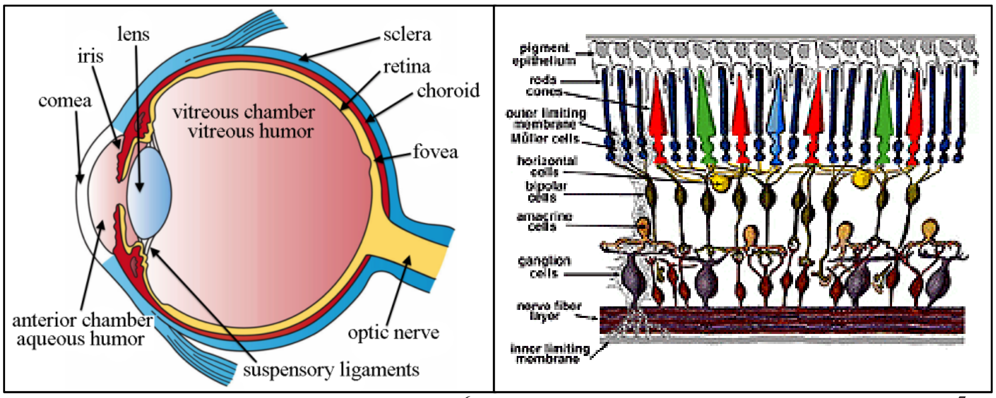

Figure 2.1: Anatomy of the human eye[6] *and schematic cross section of the retina*[7].

At this point, it is important to remember that *what we see* is not limited to the visual scenes collected in our human physiological stages. The information acquired by the visual system needs to be processed. This is when the perceptual process starts.

[6] "Three Main Layers of the Eye" by Artwork by Holly Fischer - http://open.umich.edu/education/med/resources/second-look-series/materials - Eye Slide 3. Licensed under CC BY 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Three_Main_Layers_of_the_Eye.png#mediaviewer/File:Three_Main_Layers_of_the_Eye.png

[7] "Simple organization of the retina" by Helga Kolb. "For non-commercial, academic purposes, images and content from the chapters portion of Webvision may be used with a non-exclusive rights under a Attribution, Noncommercial, No Derivative Works Creative Commons license." Source: http://webvision.med.utah.edu/imageswv/schem.jpeg

The retina cells send neural signals via the optical nerve, first to the primary visual cortex of the brain (also known as V1, located in the occipital lobe) and then to higher cortical regions (V2 to V5, located in the parietal and temporal lobes). The information extracted from an environment is thus processed in the visual cortex, and scene details such as pattern recognition, colour perception, spatial organisation, motion and depth are perceived. A useful model of visual perception was first presented by Ungerleider and Mishkin (1982). This model divides the kinds of information processing into two areas of the brain: the dorsal stream and the ventral stream. These are more commonly known as the *Where System* and the *What System* respectively. The *Where System* is responsible for the perception of motion, space, position, depth, and figure/ground segregation. This system is colour-blind, has a lower acuity than the *What System* and operates quickly. The *What System* is responsible for object and face recognition and colour perception (Livingstone, 2008). An example of this division can be explained through a common human experience. We are travelling in a car and have a first glance of a known person. We still do not know who that person is, but we know his location. Our head then turns rapidly back to that person's position to recognise his face. The *Where System* has already told us where that person is because it operates faster than the *What System*. The *What System* is slow, and that is why it takes longer to recognise the face of the person. Our visual perception is already processing the information we receive through our eyes.

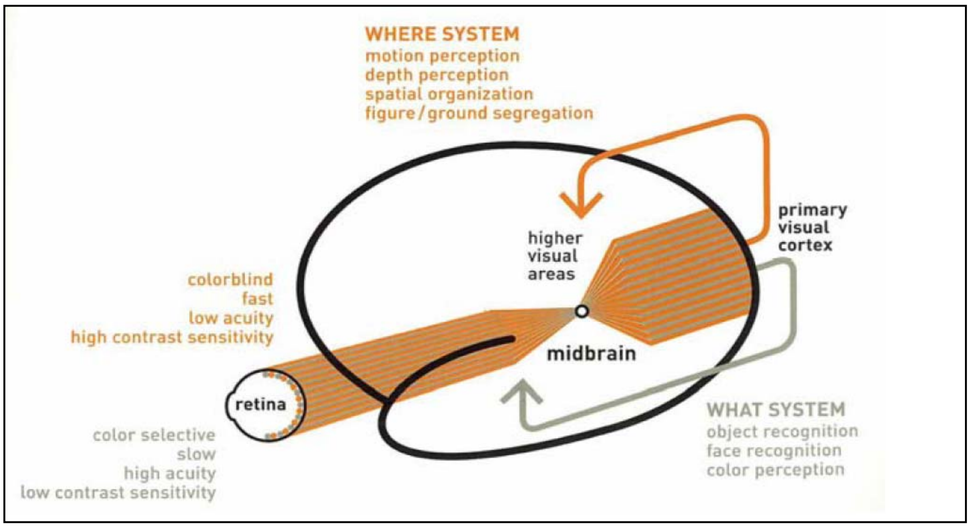

Figure 2.2: 'What and Where Systems'. From Livingstone (2008).[8]

[8] Used by permission. Permission to use the image granted by Margaret S. Livingstone, on the 15th of June, 2015.

Finally, after the information is processed in the visual cortex, and once a scene has been identified and recognised, the cognitive process can use the stored information from past experiences to acquire the meaning of what a person sees. This means that, for example, two healthy persons with no functional visual impairment can perceive the same kind of information through the visual system (eye and brain). However, due to the different experiences, memories, context, and knowledge of each person, the information can be understood in two different ways.

After understanding the fundamental visual factors, and for the purpose of the present research, it seems essential to understand how humans perceive light and colour.

2.1.2 Perception of light

A person experiences light, not as a characteristic of an object but, as a phenomenon falling upon an object. Whether from natural or artificial sources, light is considered the linkage that allows the visibility of our surroundings (Arnkil et al., 2012). In physical terms, *light* is the part of the electromagnetic spectrum that is visible to the human eye. The visible range of the electromagnetic spectrum stretches from 380 to 760 nm (Valberg, 2005) (see Figure 2.3).

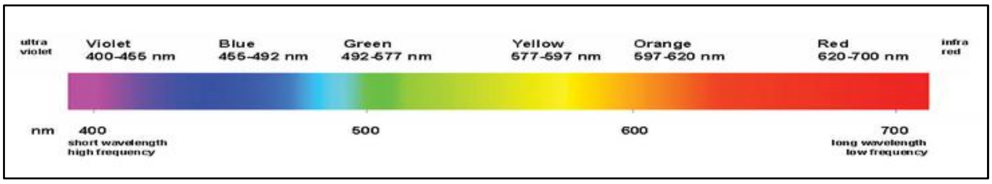

Figure 2.3: Visible light of the electromagnetic spectrum.[9]

As discussed in Section 1.2.3, when referring to physical and psychophysical aspects of light, many physical and photometric terms are currently used to register different measures of light, e.g. luminance, illuminance, wavelength, luminous flux, luminous intensity, refraction, diffraction. However, by referring to the perception of light, subjective terms, such as brightness, darkness, and shadows, cannot be measured (Fridell Anter, 2012). Moreover, descriptions of the perceived brightness of objects do not naturally correlate with luminance measurements. This means that higher luminances will not necessarily make a scene look brighter and conversely, lower luminance levels will not automatically make a scene look

[9] Used by permission. Source: https://physick.wikispaces.com/Electro+Magnetic+Radiation+and+the+Spectrum. Author: Heather Massicotte, Permission to use the image given by Bradley Langdale, physics wikispaces; on 17th of June, 2015.

darker. The perceptual aspects of light applied to this research, such as brightness and glare, have been concisely discussed in Papers I, IV and V. The concepts of brightness and glare are briefly explained in the following sub-sections.

a. Brightness and darkness

In a perceptual approach, brightness is the concept used to describe the *perceived* light reflected from an object. Thus, this should not be confused with the photometric term *luminance*, which quantifies the emitted or reflected light from a specific area (for a deeper understanding of luminance, see Section 2.3.3). The intensity of the perceived light, (e.g. a surface appears more or less bright) is one of the aspects of the overall visual perception. The perception of brightness depends not merely on the light intensity that the retina receives but also on how the eye adapts to the prevailing lighting conditions and on the simultaneous contrast between the central field of vision and the surrounding area. Darkness, on the other hand, is considered to be the opposite of brightness and refers to the low intensity or absence of perceived light.

Visual illusions are examples of brightness/darkness as cognitive attributes. The Cornsweet illusion (Cornsweet, 1970) is an image used as a visual illusion (see Figure 2.4). The left area of the figure seems to be darker than the right area. Conversely, the right area of the figure seems to be brighter than the left area. The reader is encouraged to cover the middle of the figure using two fingers. The perception should be changed. This illusion demonstrates that two surfaces with the same luminance distribution can be perceived as having different brightness.

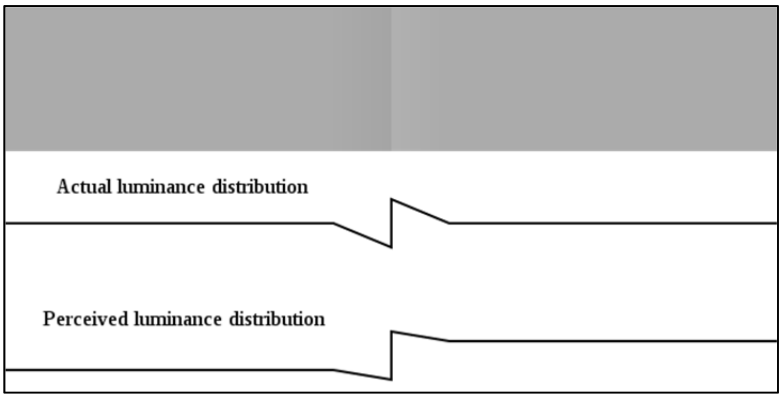

Figure 2.4: Cornsweet Illusion[10].

[10] "Cornsweet illusion explanation" by Fibonacci - Own work. Licensed under CC BY-SA 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Cornsweet_illusion_explanation.svg#mediaviewer/File:Cornsweet_illusion_explanation.svg

b. Glare

Glare has been defined as visual noise that interferes with the perception of what we want to see. A more complete definition was given by the CIE (1983), which defines glare as '*the condition of vision in which there is discomfort or a reduction in the ability to see details or objects, or both, due to an unsuitable distribution or range of luminances or to extreme contrast in space or time*'. In more recent years, the definition has been updated and simplified: '*visual conditions in which there is excessive contrast or an inappropriate distribution of light sources that disturbs the observer or limits the ability to distinguish details and object'* (CIE, 2002).

This definition indicates the two types of glare: disability glare and discomfort glare. Disability glare decreases the visibility of objects; a person experiencing disability glare usually squints or looks away. This kind of glare occurs when an object with a very high luminance level is seen in contrast to a background with a low luminance level. When this happens, the light scatters inside the eye and produces a luminous contrast in the retinal image (IESNA, 2000). This is also known as a luminous veil across the retina (i.e. veiling luminance). Disability glare can be estimated by calculating the veiling luminance, L_v (Holladay, 1926). Discomfort glare, as its name indicates, produces discomfort without decreasing visual performance. This type of glare occurs when there is a luminance variation in the visual field altering the central and peripheral visual field (Matusiak, 1998).

Disability glare is more related to outdoor scenes with full sunlight and on the road at night with lights from opposite vehicles. Discomfort glare is more related to indoor environments, and thus it is the type of glare that receives more attention in research. It is not surprising that several formulas based on empirical studies have been developed and described to calculate glare probability, such as the *British Glare Index* (Hopkinson et al., 1966), and the *Daylight Glare Index* (Chauvel et al., 1982).

The interest in discomfort glare has not diminished over the years. New glare index formulas, such as the *Visual Comfort Probability (VCP)* system, which is mostly used in North America (IESNA, 2000), and the *Unified Glare Rating*, which is mostly used in the rest of the world (CIE, 1996), have been developed in the last years. Furthermore, the *Daylight Glare Probability* proposes a tool to evaluate the probability that a person will feel discomfort glare due to the daylight coming from windows (Wienold and Christoffersen, 2006).

2.1.3 Perception of colour

As discussed in Section 2.1.1., rods and cones are photoreceptor cells existing in the human eye. A person with normal vision has three different types of cones, each responding best to different ranges of the visible wavelengths of light. The three cones are referred to as long-, middle- and short-wavelength cones. Although their peaks are located in different regions of the spectrum, these three cones are also commonly referred to as red, green and blue cones (see Figure 2.5). This is called trichromatic colour vision, and it was first proposed by the English physicist Thomas Young (1773-1829) and developed further by the German physician Hermann von Helmholtz (1821-1894). The Young-Helmholtz's three-receptor theory suggests that all colour perception originates in the excitation of these cones with different intensities; for example, yellow would be perceived by the equal excitation of red and green processes, and white by all three together. Currently, the Young-Helmholtz's theory is considered the first physiological stage in colour perception.

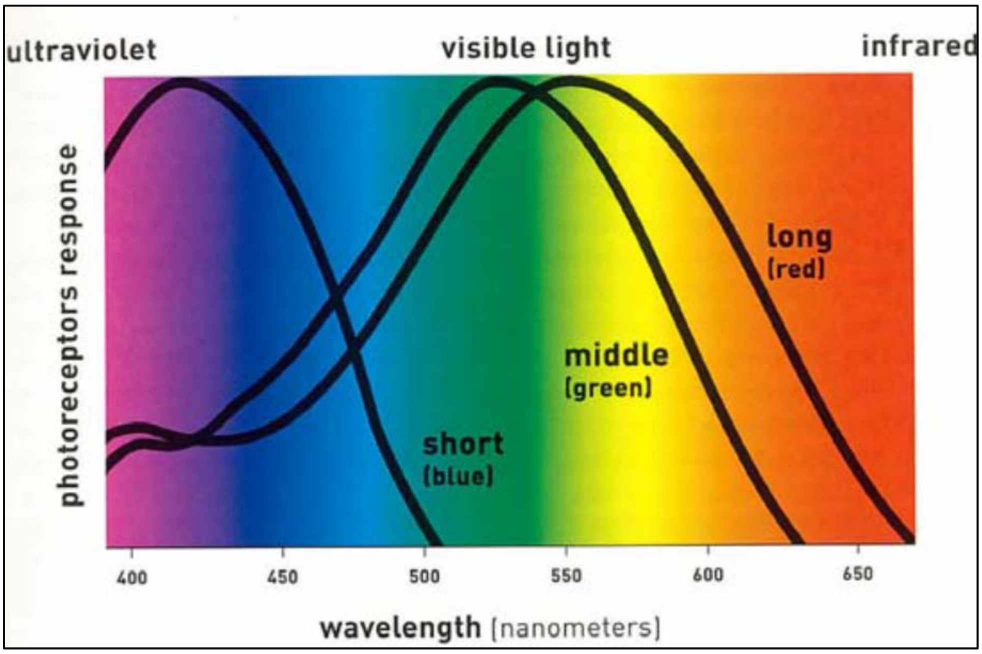

Figure 2.5: The response of the three cone types to different wavelengths of light. From Livingstone (2008).[11]

Another colour theory is the one referred to as the opponent colour theory, proposed by the German physiologist Ewald Hering (1834-1918). Hering argued that there were four chromatic (i.e. yellow, red, blue and green) and two

[11] Used by permission. Permission granted by Margaret S. Livingstone, on the 15th of June, 2015.

achromatic (i.e. black and white) elements to base colour perception. The theory suggested that the interpretation of colour happens in an opposite manner (i.e. blue – yellow, red – green and black – white).

Although these two theories were opposed for a long time, today they are both considered to be valid. Hering's theory is thus a complementary stage in the visual perception process, where the receptors' reaction to light could be transformed into four colour-coding signals (Valberg, 2005). These signals are then sent as neural impulses via the optic nerve, optic chiasma and the visual tracts to the primary visual cortex (V1), where the three-colour stimuli are processed. Colour information is then sent to the second area in the pathway, the V2, further to the V4, and finally to the ventral stream.

Nevertheless, it would be audacious for the author to limit the explanation of colour perception to only two physiological colour theories and the summarised explanation of the neural pathway. There is no doubt that there is still a gap in knowledge between physics and perception related to colour vision. Furthermore, concepts related to what colour really is, and thus how it is registered, differ among several disciplines. Different colour phenomena and terms (e.g. simultaneous colour contrast and synaesthesia) remain the subject of research. However, due to the scope of the present research, a deeper explanation of the colour vision process is considered not needed at this point. Interested readers are highly encouraged to consider further reading in Valberg (2005). The perceptual aspects of colour are, however, discussed further in Section 2.3.4.

2.1.4 Adaptation

Humans are not in a fixed state in natural everyday conditions. Light conditions are constantly changing, not only due to daylight fluctuations of intensity and colour but also when people move between indoor spaces with different artificial lighting and colour temperatures. The capacity of the human eye to adapt to changing light levels and colours of light is referred to as light adaptation and chromatic adaptation, respectively. In other terms, this means that the eye acts as a filter that neutralises light fluctuations and adjusts to the dominant light condition. In a physiological understanding, the eye pupil gets smaller in bright light and bigger in low light, varying in diameter between 2 mm in strong daylight and 8 mm in darkness (Valberg, 2005). In addition, the photosensitive cells located in the retina (i.e. rods and cones) bleach out and regenerate their pigments to adapt from dark to bright and from bright to dark. However, Valberg (2005) argued that only less than 10% of the cone pigments are bleached, making the neural contribution the most important to the adaptation process.

According to Valberg (2005), the adaptation to low levels of brightness (i.e. bright to dark) could take up to one hour. In this time, people become dark-adapted and make use of scotopic vision (luminance below 0.001 cd/m^2). In contrast, adaptation from dark to bright takes only a few seconds and makes use of photopic vision (luminance above 3 cd/m^2).

Chromatic adaptation is an aspect of photopic vision. Similarly to light adaptation, the eye neutralises colour changes in light and adjusts to the prevailing colour condition. This means that the perceived colour of an object will be kept constant, a phenomenon that is called colour constancy. In simpler terms, for example, a ripe banana will always look yellow to us whether it is located under a white artificial light source or under daylight during a sunset with reddish colour conditions.

Figure 2.6 shows the process of adaptation to low light levels. The Y-axis refers to the lowest luminance a group of experimental participants could detect, and the X-axis refers to the time they sat in darkness.

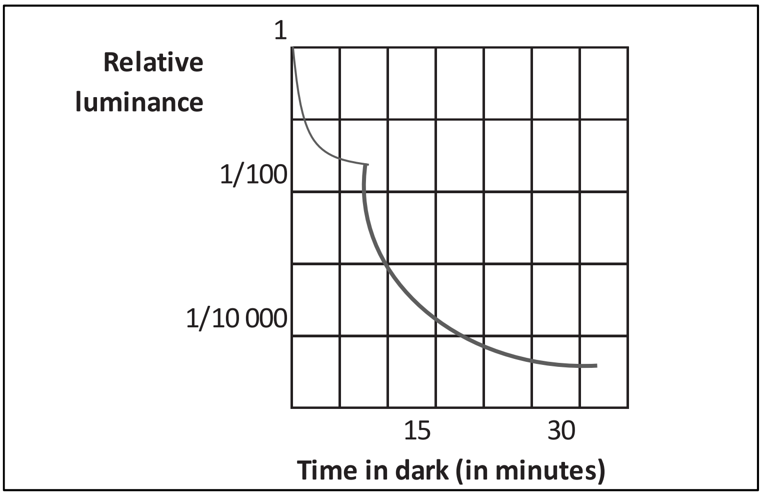

Figure 2.6: Adaptation to low levels of brightness. Adapted from Tregenza & Wilson (2011).[12]

2.1.5 Binocular vision and stereopsis

Binocular vision in humans refers to the simultaneous use of the two eyes. This allows for a wide field of view (i.e. around 208°). Due to the position of the eyes to each side of the nose, there is a sector of about 30° to each side called the *monocular sector* (Valberg, 2005). This means that this sector can only be viewed

[12] Used by permission. Permission to use the image granted by Taylor & Francis Group, on the 6th of August, 2015.

by one eye because the nose interferes with the visual sector of the other eye. In between the two monocular sectors, the binocular sector is found (see Figure 2.7).

Stereopsis refers to the perception of depth, or 3D perception. This term is directly related to, and based on, binocular vision, as a person must make use of the two eyes to perceive depth. In addition, the position of the eyes (i.e. on the front of the head, not on the sides like some animals) generates visual field overlapping. This means that each eye receives a slightly different image because objects are seen from slightly different viewpoints. These vision differences between the two images (i.e. binocular disparity) contribute to depth perception (Cauwerts, 2013).

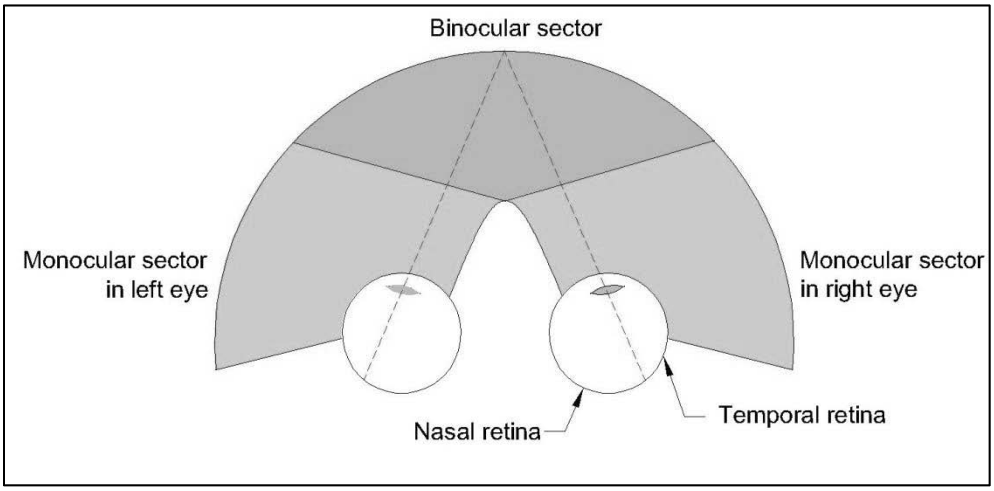

Figure 2.7: The field of view of the two eyes. The binocular sector refers to the area that is seen by both eyes while looking straight ahead. Figure adapted by the author from Valberg (2005).

2.2 Environmental studies

Environmental psychology is a relatively young and growing field of research that uses theories and assumptions from the field of psychology to study the interaction between man and the physical environment. Note that the term environment includes both built (e.g. buildings, public spaces) and natural environments (e.g. forests, wilderness areas).

Since the 1960s, both practicing and research environmental psychologists and social scientists focused on how the man changes his environment and, conversely, how the environment changes the man's behaviour (Gifford, 2002). The goal of this field seems to achieve of a better understanding of this interaction to mitigate environmental problems and create more humane environments. Empirical studies of this particular field have resulted in the development of diverse theories, which are briefly explained in the following sections.

2.2.1 Person – environmental psychology

According to Gifford (2002), environmental psychology theories are diverse and still developing. Due to this fact, he believes that, although today's theories are accurate, they only partially explain human behaviour in a built environment. Indeed, an overview of different authors generates a large list of theories addressing the person-environment interaction.

Gifford (2002) summarised six types of theories:

i. Stimulation theories (with a focus on arousal, overload, underload and stress theories) describe how humans adapt to certain levels of environmental stimulation;

ii. Control theories (with a focus on personal control, boundary regulation and reactance theories) describe the need for humans to control the stimuli present in an environment;

iii. Behaviour setting theory describes the importance of the settings (environment fixed activities) for an expected pre-determined behaviour;

iv. Integral theories (with a focus on transactionalism, interactionism and organismic theories) describe the complexity of everyday person-environment relations;

v. Operant theories, which attempt to modify human behaviour that could be affecting the environment in a negative manner; and *vi.* Environment-centred theories (also referred to as green or ecopsychology), which focus on the earth's natural environment.

Additionally, Nasar (2000) discussed two kinds of theories to explain environmental preferences:

i. Berlyne (1971) argued that preference is dependent on arousal (interest) with a particular complexity. Low complexity would produce low preference. As complexity increases, the preference increases, up to a certain point called the optimum level of arousal. Too much complexity can decrease the preference.

ii. Gaver and Mandler (1987) argued for the concept of atypicality. According to their analysis, humans tend to categorise known objects and details of a scene into *schemas*. When a person experiences a scene that fits his or her schema, it becomes boring and the preference decreases. Conversely, atypical features of their schemas increase novelty and preference.

Furthermore, Cold et al. (1998) pointed out a group of conceptual models showing cognitive processes that lead to environmental preferences:

i. Colman et al. (1986) indicated that too little or too much of a previously experienced quality can lead to low preference due to a lack of control or a lack of interest, whereas a certain amount of the experienced quality can lead to high preference.

ii. Canter (1991) indicated the importance of people's purpose for being and acting in a place. At the first stage, human behaviour is guided by 'rules of place', referring to the generally expected roles of people at a determined place. Later, the behaviour is guided by 'cognitive ecology', which refers to internal decision-making regarding the upcoming events at the place and the behaviour that will be used to fulfil these activities.

iii. Küller (1991) theorised that a successful emotional activation process is balanced between the input components (i.e. physical environment, ongoing activities, individual resources and social environment) and the human outcomes (i.e. control, adaptation and compensation).

iv. Kaplan (1987) explained the importance of aesthetic perception. According to this theory, people need to notice, understand, evaluate and act on environments that could benefit or threaten their survival.

Kaplan's theory, although not the latest in chronological terms, was purposely placed last in order to expand further on its meaning. This particular theory emphasises the visual quality of an environment. This model explains that humans need a scene's available information at a first stage to recognise and understand the environment and at a second stage to explore and act in situations that can threaten or benefit their survival. This model proposes two dimensions in each of these two stages. There are four scene attributes, described as *cognitive affordances* (Gifford, 2002). *Coherence* and *Legibility* enable the understanding of the environment at a present and future perception respectively. Likewise, *Complexity* as an immediate perception and *Mystery* as a future perception enhance the people's desire to get involved in the environment.

	Understanding	**Exploration**
Immediate	Coherence	Complexity
Inferred, predicted	Legibility	Mystery

Figure 2.8: Kaplan's preference model. Adapted from Cold (1998).[13]

These four scenes' visual attributes provide knowledge about new environments that are being assessed. As previously discussed, humans have the need to understand what they see and get involved with the environment, and the information available in the scene is crucial for meeting these objectives. For example, environments judged as coherent allow a person to make sense and organise the scene; legible environments allow a person to feel comfortable about finding their way in the environment; environments judged as complex provide enough visual richness to keep a person occupied and not bored; and environments judged as mysterious allow a person to have curiosity and encourage him or her to explore the scene further. The empirical studies presented by Gifford (2002), postulate the notion that scenes with more mystery, complexity and coherence are preferred more.

Two other theories of environmental preferences are relevant for the present study. The '*prospect and refuge*' theory was proposed by Appleton (1975, 1988), and describe the need of environments to contribute to basic human psychological needs by providing the feeling of safety. According to this theory, the environments need to supply people the ability to observe and/or predict opportunities (prospect) without being seen in order to feel safe (refuge). In 1991,

[13] Used by permission. Permission to use the figure granted by Birgit Cold, on the 24th of June, 2015.

this theory was applied to architecture studies and popularised among architects. Based on this theory, Hildebrand (1991) analysed the power of the houses designed by the American architect Frank Lloyd Wright. Hildebrand discussed that the sheltering ceiling and roofs, the position of the indoor environments in relation to the outdoors, and the psychological comforting effects of the house elements such as the fireplaces were examples of the Wright's houses as architectural expressions covering the inborn human needs of prospect and refuge. Moreover, Hildebrand expanded the theory by providing other aspects to the needs, such as the human's love of complexity, which promises opportunity (related to prospect), and the love of order, which provides a control of the environment (related to refuge).

The other theory is called '*permeability theory*' and was proposed by Stamps (2007). In his theory, environmental preference is influenced by the feelings of spaciousness and safety. Similar to the Kaplan's theory and to the prospect and refuge theory, the permeability theory pointed out the need of humans to feel secure in an environment that can benefit their survival. A permeable environment presents openings through which one can observe the world, and a spacious environment admits a secure distance in which one can evaluate the surroundings.

In sum, many theories and conceptual models are available as a basis for research that focuses on environmental studies. However, the Kaplan model seems to have a parallel with lighting studies and the collection of information from a scene. The objective of the present research, as discussed previously, is to understand how the aesthetic assessment of a scene is influenced by different daylighting conditions. Hence, the Kaplan model seems to suit this research. Still, there is a need to obtain a deeper theoretical understanding of aesthetic attributes and judgements, which are presented in the following Section 2.2.2. The relation of aesthetic judgements with lighting studies is discussed in Section 2.5.

2.2.2 Perceived quality of architecture: Aesthetic judgements

In 1943, American psychologist Abraham Maslow (1908-1970) presented a psychological theory called 'human's hierarchy of needs'. This theory described the stages of growth in humans and the crucial factors for their development (Maslow, 1943). He stated that people have the motivation to fulfil a need after a previous need has been fulfilled. Originally, these 'needs' were divided into five stages, ranging from most urgent to least urgent: physiological needs, safety, social needs, esteem, and self-actualization. Later, in 1970, he expanded his five-stage model to include cognitive and aesthetic needs, not as additional stages in the 'hierarchy of needs', but as additional aspects of motivation.

As discussed previously in Section 1.1, the motivation to perform a task can be affected by the perception of a space (Boyce, 1976). Whether they are considered to be a human need or a motivating factor, there is little doubt that aesthetic judgements are part of the visual totality of an environment. In addition, there appears to be a scientific consensus about the impact of the aesthetics of an environment on humans' psychological well-being. For example, Nasar (2000) pointed out that '*the visual character of our surroundings has an important impact on human experience*'. Cold et al. (1998) argued that one could assume that being in an aesthetically pleasant environment will produce a feeling of well-being. Similar statements were given by Noschis (2001) and Veitch and Galasiu (2012): to inhabit a place that not only protects us from cold or hot but that is also considered pleasant, can result in psychological benefits. Going back to the Kaplan model of preference, the visual evaluation of an environment is needed for people to decide whether an environment could threaten their survival. This could be considered a psychological good in itself.

However, not only the four dimensions of the Kaplan model are necessary to evaluate an environment. Research has identified six main types of environmental attributes related to preference, as described by Nasar (2000):

- *i.* Order, refers to environments that have a uniform style and in which disorder and chaos are absent.
- *ii.* Complexity, refers to the visual richness of the environment. An environment with diverse, distinct elements with a satisfactory and coherent interconnection is considered to be positively complex.
- *iii.* Openness, refers to open views. A restricted environment that does not allow access to or views of the outdoors is not considered open.
- *iv.* Naturalness, refers to the existence of natural elements such as vegetation or water. Natural landscapes, such as mountains and forests are usually preferred over built environments.
- *v.* Upkeep, refers mostly to urban features such as wires, poles and signs. Built landscapes such as industrial areas are considered to be incivilities and are least preferred by people.
- *vi.* Historical significance, refers to scenes that have historical importance or simply look historical. Scenes that look old or vernacular seem to be preferred over modern architectural styles.

Naturally, this categorisation made by Nasar (2000), is not exhaustive and does not limit the range of aesthetic attributes available to environmental studies. Several aesthetic attributes have been discussed and described in the literature. Two samples of enlisted attributes are described by Hesselgren (1975) and Flynn et al. (1979).

For the purpose of the present research, the Kaplan's framework for predictors of preference (for its parallel to lighting research) (Kaplan, 1987) and the six variables categorised by Nasar (2000) have served as theoretical basis. The selection criteria for the nine aesthetic attributes studied in this project are described in Section 5.1, Paper V.

2.2.3 Measurement of environmental perception

Environmental perception is a term that includes different concepts. Two of the concepts that are most often referred to in related literature are *appraisal* and *assessment*. These terms are sometimes mistaken for each other. Appraisal means an evaluation which is person centred, focusing on how people think and feel about a specific scene, whereas assessment means an evaluation which is place centred, focusing on the physical properties of a place. For place assessments, people with a specific relationship to the assessed place are usually selected to be the observers (Gifford, 2002).

In the specific case of this research, one objective is to find out how people evaluate different scenes and which scene is most preferred. According to Nasar (2000), this is conceptualised as an affective appraisal. Affective appraisals (i.e. human experiences of the physical environment) unlike many misconceptions, can be quantified by research (Russell and Snodgrass, 1989).

According to Gifford (2002), environmental psychologists make use of a large range of research methods and diverse types of research techniques that are based on different philosophies of science. This has been identified as a *multiple paradigm* (Craik, 1977). Although different books conceptualise, describe and compare research methods, researchers apply them by varying the procedures. This is not surprising as each research hypothesis and research question has particular problematics that require specific settings. In turn, many established research practices are modified in their procedures.

Nevertheless, many research methods are used today for studying environmental perception, including naturalistic observation, interviews, rating scales, personal space, cognitive maps, and laboratory experiments. Considering the scope of this research, a deeper discussion of the two used methods of measurement (i.e. laboratory experiments and rating scales), and a brief discussion of construct measurement and statistical analysis are presented in the next sub-sections.

a. Laboratory experiments

A crucial feature of environmental studies is the ability to count on external validity (see Section 1.3.4). This means that the results obtained from a single study should be able to be applied in settings that are different from the ones in the study, i.e. they should be applicable to populations in different parts of the world. For this reason, laboratory experiments have been a concern for researchers focusing on environmental psychology. For example, Cold et al. (1998) claimed that laboratory research within environmental studies excludes many of the elements that influence environmental evaluations and yields results that are difficult to interpret in real environments. One question is commonly formulated among environmental researchers who are sceptical of laboratory experiments: can results obtained in a laboratory setting be applied to everyday settings?

As a first response, it can be claimed that it is not always possible to perform field studies (e.g. a study examining an environment that has not been built yet), and field studies can be considered complex in terms of variables control. Indeed, Nasar (2000) discussed that onsite tests become limited due to the difficulty of controlling extraneous variables. He points out that the researcher has the advantage of controlling the experimental variables, and that this control allows the researcher to better identify cause. Although Nasar (2000) discussed meta-analysis as a research method, he identified three characteristics that can be well applied to a single experimental research: precision, objectivity, and replicability. The usage of statistical analyses increases precision, the variable selecting procedures increase objectivity and the explicit description, and registration of the procedures provides replicability (Nasar, 2000).

In addition, as discussed by Gifford (2002), either due to specific research objectives or because it is not possible for the research to be conducted in the same environment, some studies are best conducted in laboratories. Yet, one may ask whether it is possible to generalise results obtained from laboratory settings. Some sceptical researchers might say no. However, the results obtained from a small experiment can be a first step towards understanding the problem being studied. De Young (2013) claimed that small experiments '*support innovation and maintain experimental validity all while promoting rapid dissemination of findings*'. Furthermore, he argued that success on a smaller scale can result in an empowering sense of competence, which may lead to a continuation of the experiment's results later or in different settings. For example, in several disciplines, many pilot studies are performed prior to the main experiments. These pilot experiments are the first step towards providing validity, which allows the main experiments to be performed.

Simple guidelines can enhance the effectiveness of laboratory experiments and increase the validity of their results (De Young, 2013); e.g. (Flynn et al., 1973, Flynn et al., 1979, Bech and Zacharov, 2006, De Young, 2013). Carefully designed laboratory experiments can yield results that act as problem-solving indicators and guidelines in environmental studies.

b. Semantic differential scale

The American psychologist Charles E. Osgood (1916-1991) developed a method for measuring the connotative meaning of concepts. The connotative meaning of a concept refers to the cultural or emotional responses that imply particular attributes. The method developed by Osgood was referred to as the *semantic differential* (Osgood et al., 1971). Later, this method was developed further by Küller (1972) and Gärling (1976) to evaluate the impression of an architectural environment.

According to Hesselgren (1975), the semantic differential was also developed to trace the characteristics of an experience, emotions, perceptions or preferences that are associated with the concept that one wishes to rate. Thus, if a significant group of observers have the same associations with the concept; it could result in a quantifiable consensus.

Other rating scales are also used to measure attitudes, e.g. the Likert scale (Likert, 1932) and the Thurstone scale (Thurstone, 1928); and they are mostly used in survey research and to assess the extent of agreement among a panel group that is proposing items for a scale, respectively.

The scaling procedure of the semantic differential scale is as follows: a person evaluates a concept with a pair of bipolar adjectives, e.g. pleasant – unpleasant. The bipolar adjectives are placed at the extremes of a 7-step scale. Five-item scales have also been used; however, the 7-step scale is preferred for attitude evaluations. The observer is asked to place his/her evaluation (by using only one mark) on one of the seven spaces available along the scale. The data gathered from the experiment participants are then analysed. The seven steps are assigned numerical values, usually from 1 to 7. Finally, the mean ratings are plotted among all the numerical values provided by the participants' evaluations.

c. Constructs measurement

As stated in Section 1.3.4, architectural and aesthetical qualities are considered constructs (or theoretical abstractions) in the social sciences and measurement rules can be established to better understand these constructs. According to Kerlinger and Lee (2000), constructs could be defined in two ways: *i.* by other constructs (i.e. *constitutive definitions*), and *ii.* by experimental and measurement procedures (i.e. *operational definitions*).

Constitutive definitions are definitions that describe constructs with other constructs. For example, several aesthetical qualities could share a common aspect. This new aspect receives a name to acquire a ‘hypothetical entity’. Next, this new entity is evaluated using factor analysis to test its ‘reality’ (Kerlinger and Lee, 2000). This means that a factor analysis including all possible scales in a study can indicate redundant scales and/or can categorise and group scales. Operational definitions define how to measure a specific concept or construct in an experimental procedure, and they enable a researcher to create measurement scales.

Although this kind of procedure is well-known and accepted in scientific research, due to various practical considerations in some experimental procedures, this approach is not always possible in experimental research. For example, in the case of the present PhD work, experimental sessions depending on natural light resulted in logistic challenges that directly affected the number of available participants and the time allocated to each experimental session. The sample size thus could not perform a robust factor analysis, which requires a minimum of 10 people for every scale (Kerlinger and Lee, 2000, Veitch, 2001). However, in such cases, a more limited selection of concepts may be used (Flynn et al., 1979, Vogels, 2007). In this scenario, operational definitions were used. Thus, the selection of the aesthetic attributes (i.e. dependent variables) derived from theory, primarily (see Section 2.2.2), and from other research, secondarily (See Section 5.1 – Paper V, for a detailed discussion about the selection of dependent variables).

d. Statistical analyses

Experimental research seeks mainly to study the effects of changes in any selected experimental conditions, i.e. what is the effect of independent variables (experimental conditions manipulated by the researcher) on dependent variables (measurable outcomes in the experiment) (see definitions of both variables in the Glossary). To perform experimental studies, the dependent variables are measured after each time the independent variables are modified. This produces a collection of data that naturally, requires further processing to allow conclusions to be drawn.

Statistical analyses have been widely used in experimental research in which numerical data is gathered. Medicine and psychology are some of the fields that are strongly linked to the use of statistical research studies. This mathematical body of science organises, analyses, interprets, and presents the collected data in experimental research. As pointed out by Creswell (2009), meaningful interpretations can be drawn from the measurements of objective data in well-designed studies in which the validity and reliability have been considered. Indeed, the validity and reliability are pivotal concepts for any experimental research. This, together with the reasoning for the present work, has been previously discussed in Section 1.3.4.

As pointed out earlier, good scientific practice demands detailed statistical reporting to validate the obtained results. Hence, two statistical areas are needed: descriptive statistics and inferential statistics.

Descriptive statistics describes, organises and summarises the sample immediate data, e.g. the overall mean (*M*, i.e. the average of a data set) and the standard deviation (*SD*, i.e. a measure that quantifies the amount of dispersion of a data set around the mean of the data).

Inferential statistics helps to examine the likeliness of a hypothesis (a researcher's prediction) to be true. Inferential statistics use a sample data from a population to attempt to infer what the population might think. Two types of hypothesis are tested to either be confirmed or rejected (see 'Hypothesis testing' below).

Inferential statistics mainly use, but are not limited to:

i. Hypothesis testing (i.e. *alternative hypothesis* and *null hypothesis*), in which an alternative hypothesis is developed by the researcher, assuming that the dependent variable is influenced by the independent variable. The null hypothesis contravenes the alternative hypothesis. If a statistical test explains much of the variation in a set of scores, the alternative hypothesis gains confidence, i.e. a researcher can presume the initial prediction as true - the independent variable have an effect on the dependent variable. However, it would be wrong to assume that the hypothesis is entirely correct. In this case, the statistical test is performed to calculate the probability that the independent variable does *not* have an effect on the dependent variable (i.e. the possibility that the null hypothesis is true). The smaller is the probability (i.e. the p value), the greater is the confidence that the alternative hypothesis is correct.

ii. Error analyses (e.g. *Type I error* and *Type II error*), whilst there are different types of error analyses, such as standard error and sum of squared errors, the Type I error and the Type II error are recognised when working with a null hypothesis. The Type I error is present in a 'false positive', i.e. when a null hypothesis is falsely rejected, for example by using wrong variables. The Type II error is present in a 'false negative', i.e. when a null hypothesis fails to be rejected because, for example, the researcher fails when analysing the results.

iii. Interval estimations (e.g. *confidence intervals*), assess the accuracy of the sample mean (i.e. the mean of the gathered data) as an estimate of the mean that represents the whole population. Boundaries, such as confidence intervals, are studied to calculate the range of values within which the population mean will fall.

According to Field (2009), the last stage of a research process is the analysis of the data through the use of statistical tests. Proper fit of statistical tests with the data is important because it allows the variation in the scores to be explained, thus increasing the confidence in assuming that an initial prediction is true.

Examples of statistical tests include: t-tests, correlation, Mann-Whitney test, Kruskal-Wallis test, one-way independent analysis of variance (ANOVA), one-way repeated measures ANOVA, Friedman's ANOVA, Pearson correlation, Multiple Regression, Factorial repeated-measures ANOVA, Factorial mixed ANOVA, Analysis of covariance (ANCOVA), Pearson chi-square, Logistic regression, Multivariate analysis of variance (MANOVA), Factorial MANOVA, and Multivariate analysis of covariance (MANCOVA). Naturally, each test needs to pass certain theoretical requirements before it is selected to analyse the data.

For a more detailed understanding of the theory and terminology of both descriptive and inferential statistics, including statistical tests in a simple, easy-to-read and interesting form, Field (2009) and Salkind (2014) can be consulted.

As indicated in Section 1.3.4, the reasoning behind the selection of each statistical test for the present dissertation has been expressed in sections called '*Analysis strategy*' prior to the reporting of the numerical and statistical outcomes.

2.3 Daylight and colour in architecture

Daylight acts intertwined with the built environment. The fenestration design of a building will dictate, e.g. the microclimate in the building's interior, the exposure to daylight according to the building's functions, outdoor views, and energy use. Hence, many of the building's performance indicators will correlate directly with the daylighting design. Although energy efficiency has gained strength in recent years, and the fenestration areas and glazing types are now on the agendas of sustainability researchers; sadly daylighting design is still often considered only an issue of façade composition. Daylight is commonly treated as a natural resource capable of shaping a building and its interiors. The shape, texture and colour of both the building as a whole and its interiors become visible through light. Yet, daylight does not only affect energy efficiency and building shape. The effects of daylight have also been found to hold a large range of positive effects in humans.

Daylight is also considered as a generator of positive effects related to physiological and psychological well-being, and to be a crucial factor for health (Cold et al., 1998). Indeed, the discovery of the ipRGCs (see Section 2.1.1) and their connection to the human circadian system means that daylight can be used to achieve healthy lit environments (Veitch, 2011). Motivated by this discovery, the 2004 CIE report offers guidelines for healthy lighting (CIE, 2004). Additionally, due to the relation between daylight and the environment, daylight has been the subject of environmental studies, which have identified daylight as an indispensable source of aesthetic experiences (Cold et al., 1998). In sum, there is little doubt that the relation between daylight and the built environment affects our daily lives in more than one manner.

Furthermore, colour is another element that has a direct relation to indoor environments. The first premise to discuss is that colour and light cannot be considered separately (see Section 2.3.4). In architecture and lighting studies, differently coloured surfaces have an impact on the reflectance of light. In addition, colour has been found to be linked to the need to distinguish surrounding objects (Cold et al., 1998); and it has been found to contribute to positive moods (Küller et al., 2006).

The scope of the present dissertation includes the study of daylight on the perception of built environments. A room can be changed in its aesthetic perception solely by modifying its access to daylight, or the coloured surfaces that reflect light. For understanding dissimilar environmental evaluations, the contrasting lighting conditions studied in the interior of the room are quantifiable. Thus, the following subsections will specifically address some basic concepts of daylighting and colour studies that are relevant to the present study.

2.3.1 Daylight factor components

Daylight falling into a specific point inside a room (usually at table level) can be calculated by considering three different components (see Figure 2.9). According to the definition of daylight factor (see Glossary), the components are not to be used for direct sunlight, i.e. they only indicate the different contributions of daylight under overcast sky conditions.

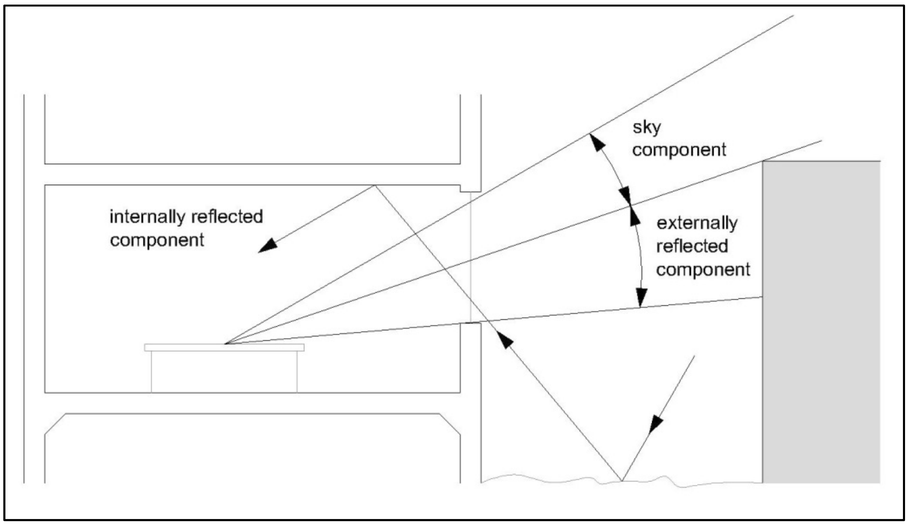

Figure 2.9: Daylight components. Adapted from Baker & Steemers (2002).[14]

i. The sky component (SC) refers to the direct light coming from the portion of the sky that is visible from the selected point. In cases in which a shielding building does not allow visibility of the sky, this component may be omitted.

ii. The internally reflected component (IRC) refers to the light reflected from the indoor surfaces in the room. The surfaces may be illuminated by direct skylight or by the reflections of neighbouring buildings. Additionally, the reflection factors of the interior surfaces of the room play an important role in the contribution of the IRC. For example, white surfaces with an average 80% reflection factor will contribute to the IRC much more than black surfaces with a 4% reflection factor. In specific cases, the IRC can be caused by double reflection, e.g. in a selected measurement point at table level, the light reflected from below this level must be reflected a second time from the ceiling or the walls. Despite this double reflection, and according to Matusiak (2008), due to the downwards direction of daylight,

[14] Used by permission. Permission to use the image granted by Taylor & Francis Group, UK; on the 12th of August, 2015.

the reflection factor of the floor will be of the highest importance. Furniture, especially floor-to-ceiling furniture, and its reflection factors should be considered in the calculation of the IRC.

iii. The externally reflected component (ERC) refers to the light reflected from external surfaces, e.g. shielding buildings. Needless to say, in situations in which there are no neighbouring buildings or external surfaces shielding portions of the sky, the ERC may be omitted. In contrast, in particularly dense urban situations, the ERC becomes more important. The ERC comes from a low elevation angle, almost horizontal, and thus enters the space more deeply than the SC (Baker and Steemers, 2002).

The sum of these three components results in the daylight factor (see Section 2.3.2). Naturally, the contributions of these three components to the daylight factor vary in dissimilar scenarios. As anticipated, the SC is thought to offer the highest contribution. However, in cases in which most of the light comes as reflections from neighbouring buildings, the ERC becomes the component that offers the highest contribution. According to Baker and Steemers (2002), the IRC is fairly uniform throughout the room. Figure 2.10 shows how the relative contributions vary with the distance from the window.

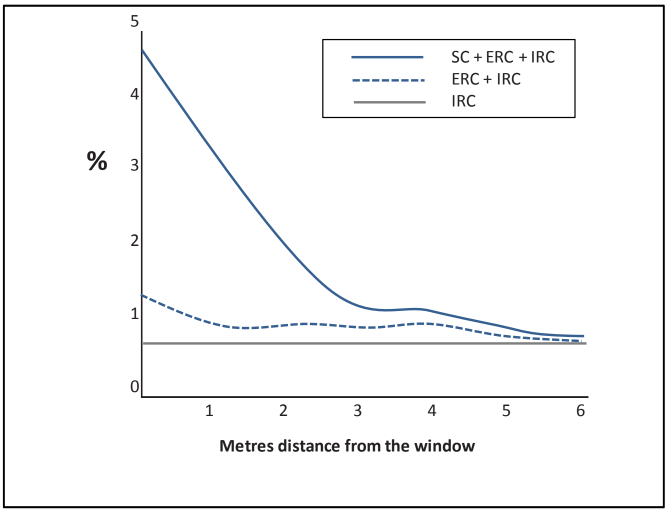

Figure 2.10: Relative contributions of daylight components (i.e. SC, ERC and IRC) in a typical room with an external obstruction. Adapted from Baker & Steemers (2002).[15]

[15] Used by permission. Permission to use the image granted by Taylor & Francis Group, UK; on the 12th of August, 2015.

2.3.2 Daylight factor and calculations

The International Commission on Illumination (Commission Internationale d l'Éclairage - CIE) defines the daylight factor (D) as the '*ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded*'.

In a simplified version, the D is the ratio of the available interior illuminance to the available exterior illuminance under overcast sky conditions. As it is a ratio, the D does not provide information about the absolute level of illuminance. Considering that daylight fluctuations occur continuously, the most reasonable method for calculating how much daylight is present at a selected point is a ratio. Thus, under this definition, the ratio can be calculated using the following formula:

$$D = E_i/E_o \; x \; 100\% \tag{f. 2.1}$$

Where:

E_i is the illuminance at the selected point inside the room
E_o is the illuminance from the unobstructed hemisphere of overcast sky

Formula 2.1 should be used with simultaneous measurements at the selected point inside and outside the room.

However, many other methods have been used to calculate the D, e.g. slide rules and books of tables in the 1930s and graphical methods, mathematical formulae and computer calculation methods in recent years.

When a mean D is calculated, a typical value for a room that is considered brightly lit is over 5% (Baker and Steemers, 2002), whilst a room with a value of 2% is considered to need supplementary artificial lighting (Aschehoug and Arnesen, 1998) and a room with a value of about 1% is considered dark (Matusiak, 2008). Currently, Norwegian regulations related to the building code recommend that the '*requirements for daylight can be verified either by calculation confirming that the* *average daylight factor in the room is a minimum of 2%, or by the daylight surfaces representing a minimum of 10 % of the use area'.* [16] (TEK, 2010).

Nonetheless, Tregenza and Wilson (2011) argued that a correct daylight factor does not exist. They rightly point out that D calculation formulae are based on model assumptions; e.g. the CIE overcast sky represents the real sky, that all surfaces are matt and have uniform reflectance, that the glazing hold a specific transmittance factor and that the room is empty. Indeed, real rooms rarely match those assumptions. Other formulae have been developed considering more characteristics that are appropriate for each studied room. For example, Littlefair (1991) developed an empirical formula for the calculation of an average D:

$$D_m = LT \, x \, A_{lys} \, x \, \Theta / \, A_{tot} \, x \, (1\text{-}R^2) \qquad \text{(f. 2.2)}$$

Where:

D_m	is the average daylight factor, in terms of percentage
LT	is the diffuse light transmittance of the glazing
Θ	is the vertical angle of the visible sky measured from the middle point of the window (°)
A_{tot}	is the total area for all the surfaces in the room, including the windows (m^2)
A_{lys}	is the area of the glass (m^2)
R	is the average reflection factor of all the surfaces in the room

Although Formula 2.2 may be considered more robust than Formula 2.1, other conditions are still not taken into account. A range of methods and formulae to calculate the D are available according to each need. Yet, calculating the D is still considered to be a low-precision procedure (IESNA, 2000). As was briefly discussed before, many rooms and lighting conditions are not part of D calculations, making each case unique. Thus, a simple formula cannot lead to final conclusions. In addition, a D is specified for the current conditions at the time of the measurement; and modifications in the same room, as trivial as they may seem, can affect the results. For example, changing the IRC, by modifying the colours of the wall surfaces, or introducing more furniture into the room may drastically change the D.

Additionally, the D is considered under low daylighting conditions (i.e. overcast sky). A room that met a minimum average D under an overcast sky could be

[16] Author's translation from Norwegian: §13-12 Lys - *"Krav til dagslys kan verifiseres enten ved beregning som bekrefter at gjennomsnittlig dagslysfaktor i rommet er minimum 2 %, eller ved at rommets dagslysflate utgjør minimum 10 % av bruksarealet»*

considered too bright under a clear, sunny sky. Hence, the recommendation for achieving a minimum average D should be taken as a guideline and not as a goal. Additionally, it is recommended that supplementary daylighting studies should be performed for architectural and environmental decisions.

2.3.3 Photometric units

As previously mentioned in Section 2.1.2, light is the visible part of the electromagnetic spectrum, and it can be described with physical concepts, such as wavelength, light energy and power. Fridell Anter (2012) indicated that for the description and comparison of light sources, it became necessary to understand the link between emitted light energy and human vision.

This psychophysical aspect of light includes four main photometric concepts that can be quantified in order to obtain a mathematical description of visual sensitivity. The four photometric concepts are:

i. Luminous flux (symbol – *F*, unit – lumen [lm]), which describes the total flow of light from a source;

ii. Luminous intensity (symbol – *l*, unit – candela [cd]), which describes the flow of light in a given direction;

iii. Illuminance (symbol – *E*, unit – lux [lx]), which describes the amount of light falling on a surface; and

iv. Luminance (symbol – *L*, unit – candela per square metre [cd/m^2]), which describes the amount of light emitted from a particular surface area.

The four units are linked together. The luminous intensity is the luminous flux per solid angle, i.e. the number of lumens divided by the angular size, measured in steradians. Likewise, the illuminance refers to the lumen falling on a square metre and the luminance relates to the luminous intensity emitted from a projected square metre. As indicated, illuminance and luminance are directly related to a selected and projected area, and are probably therefore, the two units that are mostly used in lighting studies. For example, illuminance values are needed to calculate the daylight factor and luminance values are needed to calculate glare. Many lighting standards require illuminance on the working plane (a horizontal surface in a room, usually around 0.70 m - 0.80 m above the floor). Illuminance and luminance values have been considered measures for monitoring lighting conditions in both experiments of the present dissertation.

2.3.4 Colour and light

Fridell Anter (2012) discussed that colour and light are perceived by all people with healthy vision; however, under different specific contexts, colour and light can evoke different terms, concepts and meanings. She rightfully argued that depending on a person's background, a colour can be described by physical notions (e.g. chromatic), perceptual notions (e.g. chromaticness), or psychophysical notions (e.g. chromaticity coordinates).

Regardless of whether they are described physically, perceptually or psychophysically, colour and light cannot be considered separately in any of the mentioned aspects. From a physical point of view, colour and light belong to the same single spectrum and are indivisible. Perceptually speaking, the appearance of colour is directly affected by the light falling on a coloured surface. In contrast, lighting conditions can also be affected by the reflecting light of all surfaces. Finally, in psychophysical terms, colorimetric measurements need to be made with the standardised daylight simulator of D65. Undoubtedly, colour and light share a strong association.

Within the scope of the present research, i.e. studying the perceived quality of a room, the focus is on the perceptual aspects of colour. A brief introduction to how colour is perceived has already been given in Section 2.1.3. However, the given text refers only to the physical and cognitive phases related to colour vision. The way in which people describe a perceived colour is a different topic.

Generally speaking, humans tend to come to an agreement when describing a colour. Two persons with similar colour vision would likely agree on the colour of a common ripe banana, for example. They will surely say its colour is *yellow* or *yellowish*. Depending on their tradition and culture, humans can define a single colour as, for example, *green*, *greenish*, *olive green* and *strong green*. Yet, with these subtle variations, the meanings can differ among people. Such ambiguity is not useful, practical or precise when used for scientific purposes.

To better understand perceived colours, different colour systems attempt to build a conceptual understanding of colour. For architectural purposes, the objective is to achieve a colour guide capable of describing colour according to perception in order to ensure standardisation, match colours accurately, and visualise chromatic relationships (Tregenza and Loe, 1998). Yet, Anderson Feisner (2006) indicated that humans see colour in so many different ways, that no single system has been capable of fulfilling all the needs of colour theory. Indeed, colour systems differ greatly, and depending on the case, some colour systems may be more appropriate to use than others.

The world's oldest drawn colour system was created in 1611 by the Finnish priest and philosopher Aron Sigfrid Forsius (1550-1624). Forsius' system was drawn as a sphere, placing black at the top, white at the bottom, and the colours red, blue, green and yellow at the surface (Rihlama, 1999).

Later, many other systems were developed, such as Aguilon's diagram (1623), Fludd's colour wheel (1631), Kircher's two-dimensional colour table (1671), Waller's colour grid (1689), Newton's colour wheel (1730), Mayer's colour triangle (1745), Harris' colour wheel (1766) and Lambert's three-dimensional colour pyramid (1772)(Rihlama, 1999).

Yet, in 1810 a colour system placed more focus on how colour is perceived by humans. This system was created by the German poet, philosopher and writer Johann Wolfgang von Goethe (1749-1832), and it is probably the most famous colour system from the 18th century. In the book *Theory of Colours* (1810) (Goethe, 1970), Goethe shares his assumptions about the nature of colour perception and how colours are perceived by humans. Probably one of his best remembered theories is the Colour Wheel, on which he suitably arranged colours in a symmetric colour wheel, and argued that '*the colours diametrically opposed to each other in this diagram are those which reciprocally evoke each other in the eye. Thus, yellow demands purple; orange, blue; red, green; and vice versa: thus again all intermediate gradations reciprocally evoke each other; the simpler colour demanding the compound, and vice versa*' (Goethe, 1970).

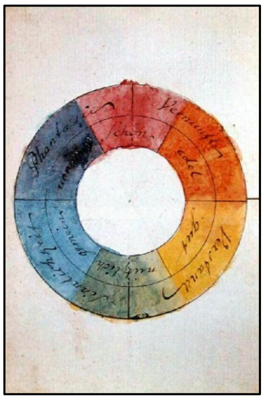

Figure 2.11: Goethe's symmetric colour wheel.[17]

[17] "Goethe, Farbenkreis zur Symbolisierung des menschlichen Geistes- und Seelenlebens, 1809" by Original uploader was Luestling at de.wikipedia - Transferred from de.wikipedia; transferred to Commons by User:Andrei Stroe using CommonsHelper.. Licensed under Public Domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Goethe,_Farbenkreis_zur_Symbolisierung_des_menschlichen_Geistes-_und_Seelenlebens,_1809.jpg#mediaviewer/File:Goethe,_Farbenkreis_zur_Symbolisierung_des_menschlichen_Geistes-_und_Seelenlebens,_1809.jpg

Subsequently, other colour systems were developed, such as Wünsch's three primary lights (1792 –further developed by Thomas Young, Herman von Helmholz and Albert H. Munsell), Runge's colour solid sphere (1810), Chevreul's hemispherical colour solid (1861), Rood's double pyramid (1879), Charpentier's colour cube (1885), Höfler's double tetrahedron and colour octahedron (1905), Munsell's colour system (1915), Ostwald's double colour cone (1915), Pope's colour solid (1929), the CIE chromaticity diagram developed by Wright and Guild (1931), Johansson's colour solids (1937), Frieling's active colour pentagon (1939), Hickethier's colour cube (1940), Rihlama's colour wheel (1965), and the Natural Colour System (1969). This chronological list of systems is a summarised version. For further information about each of these systems, interested readers are encouraged to read Rihlama (1999).

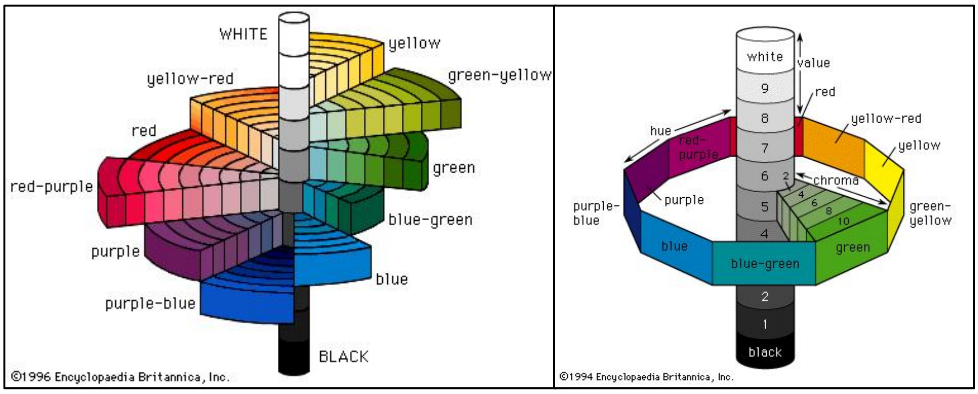

Figure 2.12: Munsell's colour tree (left)[18] *and Munsell's colour system: hue, value, and chroma coordinates (right)*[19].

Of these systems, three of them hold higher degrees of recognition. The first is the Munsell's colour system created by the American professor Albert Henry Munsell (1858-1918), which is based on a colour solid arrangement with three colour dimensions: hue, value and chroma (intensity of colour) (see Figure 2.12). His solid presents a trunk describing a grey scale, with black at the bottom and white at the top. Around the trunk, several layers of colour wheels are placed. The primary colours are red (R), yellow (Y), green (G), blue (B) and purple (P). In this system, each colour hue receives a code that is located in the Munsell's colour wheel. The code is defined by letters relating the hue, and numbers from 1 to 11 corresponding

[18] Used by permission. "Munsell colour system: Munsell color tree". Art. Encyclopædia Britannica Online. Web. 09 Mar. 2015. <http://global.britannica.com/EBchecked/media/61524> Permission to use the image granted by Britannica Customer Service, Encyclopædia Britannica (UK) Ltd.

[19] Used by permission. "Munsell colour system: hue, value, and chroma coordinates". Art. Encyclopædia Britannica Online. Web. 09 Mar. 2015. <http://global.britannica.com/EBchecked/media/1068/The-hue-value-and-chroma-coordinates-of-Munsells-colour-solid> Permission to use the image granted by Britannica Customer Service, Encyclopædia Britannica (UK) Ltd.

to the scale from black to white, and the chroma is designated by a number from 1 to 15. Due to its coding, which permits accurate colour description, this system is still in use, mostly by paint, dye and ink manufacturers (Anderson Feisner, 2006).

Second, the CIE colour system (i.e. the CIE chromaticity diagram) was a product of a precise colour matching system based on light (Anderson Feisner, 2006). To define a colour in the CIE chromaticity diagram three coordinates are used: X, Y, and Z; where the value Y is normalised to be a photometric unit describing the light reflection percentage of the colour. Although different photometric units can be used, very often the tristimulus value Y is normalised using cd/m^2 for luminance. The coordinates X and Y are usually plotted in a coordinate system with axes at right angles, which is called the chromaticity diagram (see Figure 2.13) (Valberg, 2005).

A very didactic explanation of the CIE chromaticity diagram was given by Rihlama (1999): '*The coordinates refer to the chromaticity diagram in which the completely pure colours are situated on a curve shaped like an extended horse shoe. Pure purple colours are on the purple line joining the ends of the horse shoe. When going towards the white point in the centre of the area bordered by these lines, the saturation of the colours decreases. The grey scale is thought to be situated perpendicularly towards the surface in such a way that white is at the white point, greys above it, darkening towards the top, and black at the apex. Theoretically there are an infinite number of differences in lightness between white and black*'.

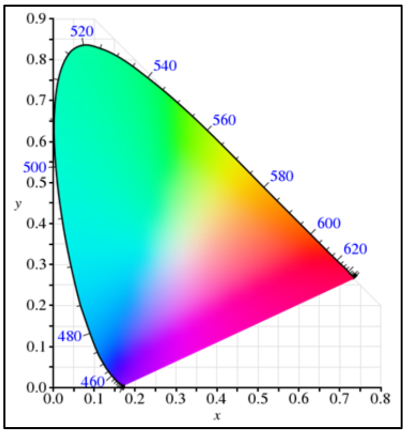

Figure 2.13: The CIE 1931colour space chromaticity diagram. The outer curve with numbers in nanometres describes the wavelengths of the spectrum.[20]

[20] "CIE1931xy blank" by BenRG - File:CIExy1931.svg. Licensed under Public Domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:CIE1931xy_blank.svg#mediaviewer/File:CIE1931xy_blank.svg

This means that by having the pure colours situated in the curve, a colour hue can be defined by the *X* and *Y* coordinates. From the selected colour point, a line is traced to the white point and subsequently to the curved line. The curved line indicates the wavelength and hence the hue. The saturation of the colour is given by the ratios of the distance between the curve point and the white point, and between the colour point and white point (see Figure 2.14).

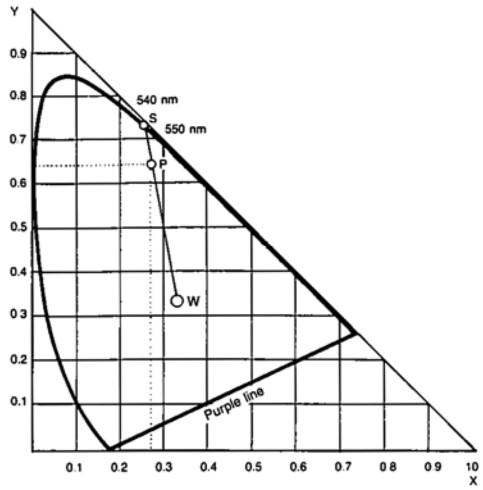

Figure 2.14: Definition of a colour in the CIE chromaticity diagram. With the help of the X and Y coordinates, colours can be plotted on the diagram. 'Pure monochromatic colours are situated on the curve and on the line joining its end; the saturation of these colours is 100 percent. A colour P can be depicted as a point with coordinates x = 0.27 and y = 0.65'. From Rihlama (1999).[21]

As Anderson Feisner (2006) pointed out, matching colours with barely perceptible differences can accurately be defined by the CIE system, eliminating differences in people's interpretations. To this day, the CIE system is the most widely used system for colourimetric studies. Wider explanations of the CIE colour system and chromaticity diagram, are presented by Valberg (2005), and Rihlama (1999).

Finally, the Natural colour system is a '*logical colour notation system which builds on how humans see colour*' (NCS, 2015). This means that the Natural colour system is based purely on perception. As indicated on more than one occasion, the scope of the present dissertation includes perceptual quality, and thus the dissertation uses the Natural colour system as a means for monitoring colour conditions in both experimental studies. For this reason, the concepts and description of the system are further expanded in the following section.

[21] Used by permision: Seppo Rihlama, Colour World, picture 47 / Rakennustieto Publishing, Helsinki Finland. Permission to use the image granted by Kristiina Bergholm, Rakennustieto Oy/ Rakennustieto Publishing, on the 16th of June, 2015.

2.3.5 NCS: Natural Colour System

The Natural colour system (NCS) was developed by Thomas Hård, considered the founder of the NCS. Professor Gunnar Tonnquist, expert in physics, photometric and colour measurement; and Dr. Lars Sivik, expert in psychology and perceptual responses of colour, were part of Dr. Hård's team, which after 15 years of research, finally produced the first NCS Colour Atlas (NCS, 2015). The NCS was published by the Scandinavian Colour Institute (Swedish name: *Skandinaviska Färginstitutet* AB), now known as the NCS Colour AB. It is now the Swedish national standard for colour.

According to Hård et al. (1996), the NCS is a general system based completely on the capabilities and limitations of humans' visual experience and requires no previous physical or physiological knowledge. They defined the system as general, allowing colour description according to each particular situation, i.e. depending on how humans see the colour and the illumination situation. In this way, the NCS system allows people to distinguish colour differences (*colour discrimination*) and define colour names (*colour identification*), thus treating the colour experience as part of the holistic visual experience (Fridell Anter, 2012).

The NCS is based on Hering's colour opponent theory (see Section 2.1.3) and thus, operates with six elementary colours: white, black, yellow, red, blue, and green. The NCS system uses three terms to define a colour: hue, blackness, and chromaticness. The latter two are used together to define the nuance of a colour.

Hue is defined by the NCS as how similar the colour is to the chromatic colours yellow (Y), red (R), blue (B), and green (G), and it is placed in the NCS colour circle. The *nuance* is determined by the blackness (how dark the colour is) and the chromaticness (how chromatically strong the colour is) of a colour, and it is placed in the NCS colour triangle (Hård et al., 1996, NCS, 2015). The NCS colour circle is symmetrical. The colour yellow is placed at the top quarter of the circle, and the colours red, blue, and green are placed at the subsequent quarters of the circle in a clockwise manner. The NCS colour triangle is formed by white, black, and a chromatic colour, each of which is placed at one of the triangle's edges. These define the whiteness, blackness, and chromaticness of a colour, respectively (see Figure 2.15). The blackness edge is placed at the central point of the circle to form a tri-dimensional solid, matching the chromaticness vertex with the NCS colour circle's diameter.

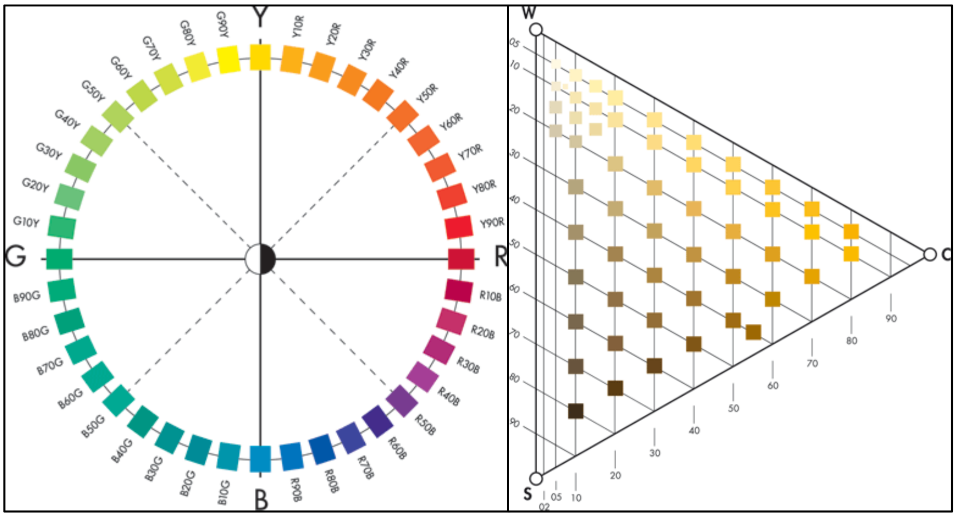

Figure 2.15: The NCS colour circle (left) and NCS colour triangle (right)[22].

Hence, a perceived colour can be defined by an NCS colour notation. To denote the numerical value for hue, chromatic colours should be given as they appear in the circle in a clockwise direction; e.g. an orange that is an equal mixture of yellow and red should be noted as Y50R; and a green with just a tint of yellow would be G10Y. Consequently, to denote the numerical value of the nuance, four digits should be given. The first two digits correspond to the blackness and the second two correspond to the chromaticness; e.g. in the notation 2070, 20 refers to the blackness and 70 to the chromaticness. Although the whiteness is not given explicitly in any NCS colour notation, it can be easily calculated. The sum of the blackness, whiteness, and chromaticness always equals 100%. Thus, in the notation 2070, the whiteness is 10%. As a result, a typical NCS colour notation first describes the nuance and then the hue of the colour, e.g. 2070 Y50R.

Within colour studies, the concept *nominal colour* is used. Fridell Anter (2012) discussed this term as the '*perceived colour under standardised viewing conditions*'; and argues that a colour code printed in an NCS colour sample can denote a nominal colour. Placing a colour sample directly on an object allows one to take a visual colour measurement of the given surface (see Figure 2.16). For this method to be reliable, it should be used in most prevailing daylight situations (excluding dawn, sunset, and dark weather) and under light with a similar wavelength composition to daylight to avoid metameric effects (Fridell Anter, 2000).

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[22] NCS - Natural Colour System®© property of NCS Colour AB, Stockholm 2015. References to NCS®© in this publication are used with permission from NCS Colour AB. Source: http://www.ncscolour.com/en/natural-colour-system/logic-behind-the-system/

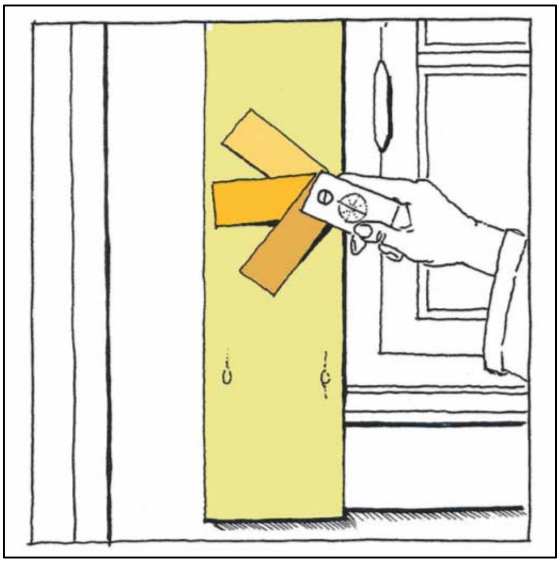


Figure 2.16: Visual method for determining nominal (inherent) colour. From Fridell Anter (2012).[23]

In addition, the NCS colour atlas offers information about the reflectance factor of any given colour. The reflectance factor, Y_l, given by NCS is the CIE tristimulus value, Y, measured with an integrating sphere-type photospectrometer with an included specular component. This method of measurement prevents differences due to the influence of the gloss level of the measured surface (diffuse or glossy surfaces) (SIS, 1998). For the purposes of the present dissertation, the NCS was the selected colour system for registering the colour and reflectance conditions of the room surfaces used in experiments 1 and 2 (see Sections 4.1 and 4.2).

2.3.6 Achromatic colours

As is evident in their name, achromatic colours are colours with no chroma. Chroma defines the purity of a hue and describes the strength of a colour's hue. Under this definition, the colours black, white, and the gradations of grey are considered achromatic colours.

Yet, one could question whether black and white should be considered colours. Just as colours may be described differently by different people (i.e. physical, psychophysical and perceptual, see Section 2.3.4), black and white are often disregarded as colours by some people, while others consider them to be colours. For example, a physicist would reflect on colour as light theory and would

[23] Used by permission. Permission to use the image granted by Karin Fridell Anter on the 15th of June, 2015.

probably answer that black is not a colour, but white is. An artist would consider colour to be pigments and say that white is not a colour, but black is. Thus, the answer to this question is left to each person to answer themselves.

As previously stated, the NCS system was based on Hering's colour opponent theory; and according to Hering, white and black are basic visual qualities in the same way as yellow, red, blue, and green (Hård et al., 1996). Additionally, Hård et al. (1996) claim that both chromatic and achromatic colours constitute '*humans' conceptions of the simple and unambiguous colour sensations that we carry with us as a kind of inner reference system*'. The author agrees with this postulate, and considering that the NCS system is the colour system selected as a tool in this dissertation, black and white will hereafter be considered achromatic colours.

White and black are denoted in the NCS system in form of N, in which N means 'neutral' (Fridell Anter, 2000). Given that the hue is given as an alphanumerical code in an NCS colour notation, this is replaced in its totality by the letter N; e.g. 5000-N.

2.4 Daylighting design

Humans spend around 80-90% of their time indoors (Klepeis et al., 2001, Baker et al., 2001, European Commission, 2003). Additionally, daylight produces diverse positive effects on human beings: an objective view, thus, is to bring daylight to the interior to satisfy human needs; not only as a means for task illumination, but also, as a means for promoting psychological health and mental well-being (see Section 2.3).

Depending on the type of building and its location (both locally and globally), the collection of daylight in interiors can have different parameters. The climate, the urban density surrounding the building, the function, dimension and physical characteristics of the interior space, and the operational hours of the space are some parameters to consider when designing a well-daylit room. A successful daylighting design can mark the difference between an '*adequately illuminated space*' and a '*well-lit room*'. The following sub-sections summarise important strategies for satisfactory daylight collection.

2.4.1 Daylight openings: Side-lighting and roof-lighting

Daylight can be collected via vertical openings (side-lighting) or horizontal/sloping openings located on the roof of a building (roof-lighting).

A window (a vertical opening in a building's façade) is probably the most basic way to collect daylight in an interior space. Not only do windows admit daylight, they also are a provider of views of the outdoors, air, information about the weather, and time and relief from claustrophobia and monotony; all of which are desired characteristics (Collins, 1975). Although it is preferred to have windows in a space rather than having a room without windows; windows can cause negative effects in rooms such as glare and solar overheating (Arnesen, 2002). Certainly, side-lighting can have limitations and challenges. For example, the light distribution in a sidelit space changes dramatically throughout the room. The daylight factor falls off swiftly at the farthest place from the window (Baker and Steemers, 2002) (see Figure 2.17). Naturally, the closer a person is to the window, the greater illumination the person will experience. This demands that some tasks and activities occur close to the window to benefit from the higher illuminance.

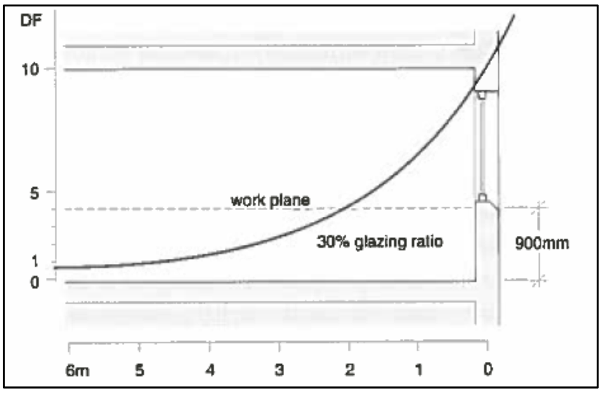


Figure 2.17: Rapid fall of D with distance from window wall. From Baker & Steemers (2002).[24]

Furthermore, the location, size, and shape of the windows are factors that also play a critical role in the distribution of the daylight. Generally, a window located higher on the window wall will offer better daylight distribution than a window placed at a lower height in a window wall (Baker and Steemers, 2002). An explanation was given by Arnesen (2002); she discussed that windows placed in high positions diminished the daylight level around the window's perimeter, making the luminance distribution of the room more even.

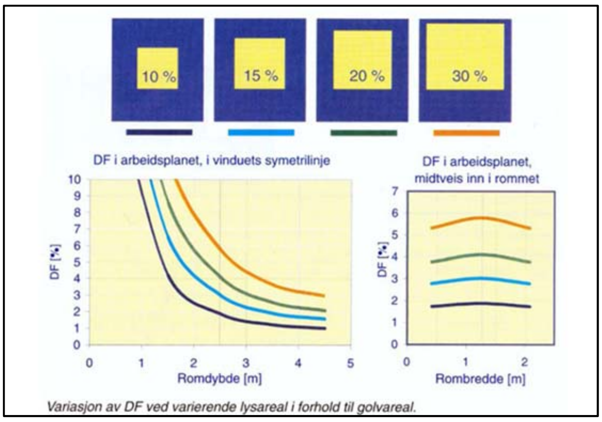


Figure 2.18: Comparison of the D of four different window sizes. The chart to the left refers to the D in the working plane, in the window's line of symmetry. The X axis refers to the room's depth. The chart to the right refers to the D in the working plane, midway into the room. The X axis refers to the room's width. From Aschehoug & Arnesen (1998).[25]

[24] Used by permission. Permission to use the image granted by Taylor & Francis Group, UK; on the 12th of August, 2015.

[25] Used by permission. Permission to use the image granted by Lyskultur, on the 14th of August, 2015.

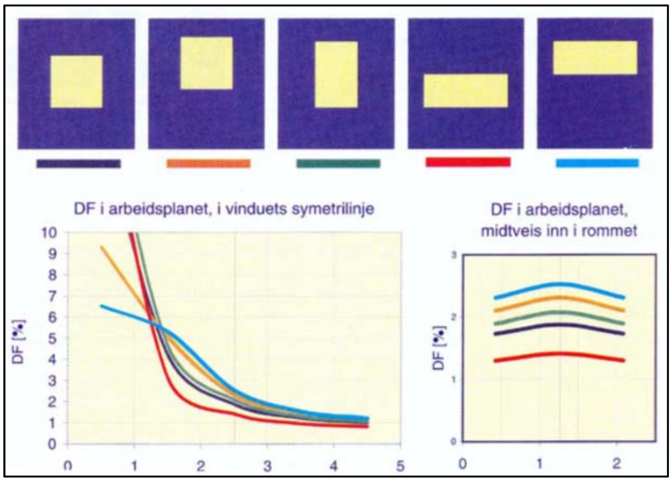


Figure 2.19: Variation of D for different window positions and geometries. The glass area represents 10% of the floor area. The chart to the left refers to the D in the working plane, in the window's line of symmetry. The X axis refers to the room's depth. The chart to the right refers to the D in the working plane, midway into the room. The X axis refers to the room's width. From Aschehoug & Arnesen (1998).[26]

As anticipated, larger windows offer higher daylight levels than smaller windows (see Figure 2.18). This is due not only to the increased size of the opening, but also to the higher position of the window (Arnesen, 2002).

Nonetheless, as discussed before, other factors, such as climate and sky type, also play a role in daylighting design. Thus, larger windows may not be the most appropriate solution for every room. If one wishes to study the daylight factors of a large and a small window, it is logical to assume that the larger window will offer higher D values. However, it is important to remember that the daylight factor is used for testing under overcast sky conditions. If a large window is placed in a room with the belief that the daylight factor values will be higher, one should also consider that under clear and sunny sky conditions that same room will probably suffer from overheating and glare.

Moreover, when the light levels are unsatisfactory in the deeper areas of a room, roof-lighting can contribute to even daylight distribution, as the depth of the room is no longer a limitation. Roof-lighting provides greater illuminance than side-lighting on horizontal surfaces (Tregenza and Wilson, 2011). Naturally, this can only be applied to one-level buildings or the top level of a multiple-level building. Roof-lighting design is not limited to a horizontal opening in the roof; the

[26] Used by permission. Permission to use the image granted by Lyskultur, on the 14th of August, 2015.

geometries of the openings and the position of the glazing in relation to the opening vary according to the desired daylight penetration. Roof-lights can also be placed in vertical and tilted positions. For further information about different roof-light configurations, readers are recommended to consult CIBSE (1994).

Similar to windows, roof-lights have their own challenges, especially regarding overheating. According to the climate and sun elevation angles, roof-lights should be oriented in such manner to minimise direct sun penetration and avoid a greenhouse effect.

2.4.2 Daylighting systems: Function and classification

As previously discussed, windows are the most basic way to collect daylight in interiors. In cases with large, deep floor plans, roof-lighting can contribute to daylight penetration in the deeper areas, but this can only be done for certain types of buildings or on certain levels of buildings. In order to collect daylight deeper into the interiors of spaces where roof-lighting is not possible, daylighting systems can help achieve well considered daylighting design.

Moreover, daylighting systems are mainly used to diminish thermal discomfort due to solar overheating and visual discomfort, which result from the glare produced by fenestration. This is usually achieved by controlling and redirecting direct sunlight onto the ceiling. In addition, they seek to distribute light uniformly across the room by reflecting the redirected light into deeper areas of the room. As noted by Kolås (2013), the two benefits of improved daylight distribution are: '*i.* increased energy saving potential by reducing the need for electric lighting; and *ii*. improved lighting quality and visual comfort for the building occupant'.

In common terms, daylighting systems can be divided into two types: shading systems, and daylight redirecting systems. However, a much more detailed classification was provided by the International Energy Agency, Task 21 (IEA, 2000) in the form of a 'system matrix', in which daylighting systems were classified as:

i. Daylighting system with shading:
- Systems primarily using diffuse skylight and dismissing direct sunlight.
- Systems primarily using direct sunlight.

ii. Daylighting systems without shading included:
- Diffuse light guiding systems, which redirect light to the interior of the room.
- Direct light guiding systems, which redirect sunlight to the interior of the room, controlling glare and overheating.

The system matrix given by the IEA offers information about different daylighting systems, including the climates in which the daylighting systems are suitable to be used, and diverse performance criteria, such as glare protection, outdoor views, and homogeneous illumination. The complete system matrix containing the classification of the daylighting systems can be found at IEA (2000).

It should be noted that this classification was made 15 years ago, and thus, more recent research have resulted in the development of new daylighting systems and new classifications. For example, Nair et al. (2014) divided daylighting systems into four types:

i. Light guiding systems:
- Direct light guiding systems.
- Diffuse light guiding systems.

ii. Light transport systems:
- Collectors.
- Closed light transportation guides (subdivided into: Multiple specular reflection, Total internal reflection, and Convergence systems).
- Light distribution systems.

iii. Light diffracting systems.

iv. Hybrid and integrated systems.

Similar to the IEA system matrix, this classification offers information about the suitability of the climate and performance indicators such as integration, durability, maintenance, availability, efficiency, light output, and transportation.

As the reader can understand, the list of daylighting systems is too extensive to be discussed in detail in the present dissertation, and thus detailed information can be found in the previously given references.

Within the scope of the present research, two daylighting systems were selected and used in experiment 2 (further discussed in Section 4.2): light shelves and venetian blind systems. The criteria for selecting these daylighting systems were:

a. Location of studies: The experimental work was carried out in Trondheim, Norway (latitude: 63°26’24’’ N), where daylight is typified by overcast skies and low solar altitude. Light shelves and venetian blinds were among the daylighting systems that are suitable for northern climates (Arnesen, 2002).

b. Light distribution: Both systems increase daylight levels in the deeper areas of a room, by reflecting light towards the ceiling. More detailed information about the advantages of light shelves and venetian blind systems are discussed in Sections 2.4.3 and 2.4.4.

c. Availability: Venetian blinds are probably the most commonly used daylighting (and shading) system in buildings. In some cases, they can also be quickly manufactured.

d. Installation practicality: Both systems can be easily installed in the interior of a room without altering the building’s façade or structure, and without intervening spaces adjacent to the room.

2.4.3 Light shelves

Light shelves are usually made of a horizontal or slightly tilted reflective surface placed near a window pane either internally or externally to the building façade; or in some cases, simultaneously both externally and internally. The light shelves are placed above eye level, separating the window into two parts: an upper window section for daylighting purposes and a lower window section for outdoor viewing (see Figure 2.20). Logically, the width of the light shelves is normally similar to the width of the window. In some cases, the large dimensions of a light shelf can be considered to have a significant architectural impact (Baker and Steemers, 2002).

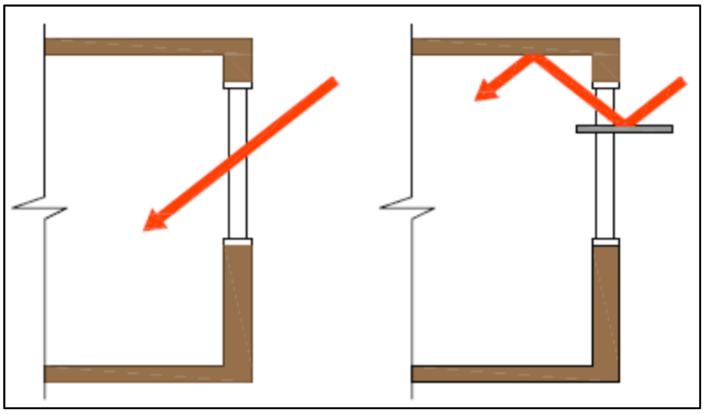


Figure 2.20: Comparison of the light distribution of a room with a light shelf (right) and a room without a light shelf (left).

They are primarily used to redistribute incoming daylight, improve light uniformity and visual conditions in the interior, control direct sunlight in the areas near the window, and reduce glare and discomfort by shading.

Arnesen (2002) argued that different factors are indicators of the performance efficiency of a light shelf. These factors are:

i. Location (internal and/or external): External shelves prevent high angle solar elevations and thus will shade the area closest to the window wall. Internal shelves will diminish the illuminance near the window and shade intermediate areas of the room.

Later studies have reported that under clear sky conditions, internal light shelves offered higher average illuminance than external light shelves (Aghemo et al., 2008).

ii. Design (tilt angle and surface shape): A light shelf can be tilted upward or downward according to specific redirection needs to control its performance. Both tilt positions have benefits and limitations. Daylight collection and reflection deeper into the room will be higher if the light shelf is tilted downwards in relation to the interior, but the shading will be diminished, creating a risk of glare. In contrast, an upward tilt in relation to the interior will reduce daylight collection but result in better shading conditions.

The shape of a light shelf also plays a role in its performance. For example, Beltran et al. (1994) worked with a curved segmented surface as a light shelf reflector to redirect sunlight with changing solar altitudes. A horizontal light shelf may become less efficient when redirecting low solar altitude radiations.

iii. Material surface properties: The type of reflection will be affected by the surface material. As indicated by Arnesen (2002), specular surfaces can guide light into lowly lit areas, and diffuse surfaces will scatter the light reflected from the surface. Additionally, different materials such as mirror, aluminium, methacrylate, as well as white surfaces and matte surfaces were studied and compared as reflective surfaces of light shelves (Claros and Soler, 2001). In their study, Claros and Soler (2001) reported that methacrylate was more effective under high solar altitude conditions.

iv. Window characteristics: Naturally, the daylight input onto the surface of the light shelves is linked to the light transmission properties of the glazing. The width of the window is another factor that sets an additional restriction on light shelves' design (Nair et al., 2014).

v. Obstructions of the sky: Surrounding buildings, urban elements and/or vegetation can obstruct the sky component and direct light radiation. Moreover, not only direct light, but also the contributions from the externally reflected component can influence the performance of light shelves.

vi. Climate conditions: As anticipated, the performance of light shelves is affected by the climate. For example, Baker and Steemers (2002) noted that during sunny conditions in winter, a light shelf can reduce the demand for heating and lighting; and that in summer, direct sunlight penetration through a light shelf is not desirable. In a previous study, it was found that a diffuse light shelf reduced illuminance by 0-20% under clear sky conditions, while illuminance was reduced by 5-30% under overcast sky conditions (Aiziewood, 1993), as presented by Arnesen (2002).

As previously discussed, a light shelf can have a considerable impact on architectural design. Hence, to fulfil its primary goals, i.e. light distribution, glare protection, and shading, its design and implementation should be thoroughly analysed, preferably in the initial stages of a building's construction. Furthermore, the maintenance of light shelves is another factor to estimate. External light shelves can cluster rainfall, snow and air pollution, while internal light shelves can cluster dust. The accumulation of dust and pollution has been discussed as a cause that reduces the performance of light shelves (Edmonds and Greenup, 2002).

According to the IEA (2000), a light shelf '*is a truly classic daylighting system that was known as far back as in the days of the Egyptian Pharaohs*'. They have been used for several decades, probably because they are considered the simplest and most cost-effective passive daylighting system (Nair et al., 2014).

2.4.4 Venetian blind systems

Conventional venetian blinds are a daylighting system mainly used for solar shading and glare protection. In their typical form, they cannot collect daylight deeper into interiors but they can distribute daylight throughout the working plane (Arnesen, 2002). Venetian blinds are composed of multiple, evenly spaced horizontal slats placed one above another. They can be placed on the exterior or the interior side of a window, or between the panes of a glazing unit. The slats are usually suspended by cords, which allow near-180-degree simultaneous rotation of all the slats. When fully closed, the slats overlap, with one side of each slat facing inward. This is also possible because the depth of the slats is generally larger than the distance of the slats. Moreover, the slats can be automatically or manually adjusted to achieve several different tilt angles according to the specific needs of the room.

A second cord (often referred to as the lift or operational cord) passes through one side of the slots across all the slats. When this cord is pulled and fixed, the bottom rail of the blinds moves upward, making the lowest slats press against the next-higher slats, and raising the blinds to a desired height. By pulling the cord fully, the blinds achieve an open or raised position. The slats' surface shape can be flat or moderately curved, with the convex side often facing upwards. According to Kolås (2013), the width of the slats differs according to where they are placed: if placed in the interior, the slats are usually from 10mm to 50 mm wide; whilst exterior slats range from 50 mm to 100mm wide.

Venetian blinds have been used for hundreds of years; the first references to them dates back to the 18th century (Felton, 1794). Their popularity might be attributable to their low cost, simple design, user-friendly operation and non-disruptive appearance in the building envelope. In addition to their solar shading and glare protection properties, venetian blinds can also provide privacy and/or outdoor viewing. When the slats are fully open, the glazing area becomes free of obstructions and allows a full view of the outdoors. Conversely, when the slats are fully closed, room users can benefit from privacy. Naturally, the amount of daylight penetration is directly correlated with the degree to which the blinds are open and/or the tilt angle of the slats.

Although Venetian blinds are mainly considered a shading system, innovative designs modifying the surface material, the orientation and/or the geometry of the slats allow the blinds to have daylight applications, such as light scattering and/or light redirecting properties (Nilsson and Jonsson, 2010). Furthermore, in daylighting studies, conventional venetian blinds serve suitably as base-cases. For example, Littlefair and Motin (2001) discussed that venetian blinds are the most common glare control system, and due to their effect on the luminance distribution in a room, they serve as a reference case in comparison studies with other daylighting systems.

As discussed above, venetian blinds can function as daylighting redirection systems when the surface material and/or the geometry and orientation of the slats are modified. For example, comparison studies report the variation of light reflectance between different slats' surface colours and/or materials (Christoffersen, 1995, Rubin et al., 2007, Nilsson and Jonsson, 2010). Additionally, the geometry design and orientation of the slats have produced novel solutions, such as the daylight redirecting blind system, the fish system, the okasolar system, the retrolux system and the retroflex system. A detailed description of these systems is provided by Kolås (2013).

Two types of venetian blinds were used in the present study: white blinds as the base case (identified as the most common surface finish for blinds by Kolås (2013)), and high reflective blinds. A further description of the geometry, reflectance and position of the blinds can be found in Section 4.2.

2.5 State-of-the-art: Lighting research and aesthetic judgements of an environment

In the previous sections, different theories and discourses have been presented and discussed separately. This is mainly because visual, environmental, and lighting studies are included in well-established and differentiated research fields. Additionally, architectural studies examine diverse research topics, including but not limited to material and construction technology, energy efficiency, building performance, environmental assessments, and colour investigations. However, an interdisciplinary approach that addresses both environmental aesthetics and lighting studies is rarely used.

2.5.1 Lighting research

The focus of lighting research has evolved throughout the years. First, lighting research efforts focused on daylight as an architectural formgiver; to be later dismissed in the second part of the 20th century in favour of artificial light (Reinhart and Selkowitz, 2006). Nowadays, the focus of daylighting research varies between daylight openings as a source of heat loss or daylight as an energy efficiency measure for buildings that are primarily used in the daytime. Fontoynont (2002) pointed out the development of the focus of lighting research in the last decades. He argued that the first priority of lighting studies was visual performance. This means that, in order to perform a specific activity, humans have certain visual demands that should be fulfilled by the lighting conditions. Indeed, most recommendations for satisfactory levels of lighting are directly related to visual acuity and people's performance of activities (CIBSE, 1994, CIE, 2001). A subsequent study focus was visual comfort, specifically on the reduction of glare. Accordingly, recommendations regarding lighting conditions and for avoiding glare are presented in scientific articles, handbooks and standards (CIE, 1996, IESNA, 2000, Boyce and Raynham, 2009). Although both visual performance and visual comfort are crucial to the development of people's activities, other research approaches need equal attention.

Vision, as a physiological process that is related to light, has been widely studied and is, in general and elementary terms, well understood (see Sections 2.1.1 and 2.1.2). However, visual perception involves more than just seeing light falling on an object. As implied by Cuttle (1999), the appearance of the distinctive attributes of a material depends on the present lighting conditions. Moreover, recent discoveries related to retinal ganglion cells (see Section 2.1.1) have spurred lighting research focusing on mood, health and cognition (Veitch and Galasiu, 2012). As noted by de Kort and Veitch (2014), all of these effects influence human behaviour, and hence are also important in environmental psychology studies. Furthermore, they succinctly and rightfully claim: ‘*Not only does light influence behaviour, but our choice to use lighting is behaviour, one that has environmental consequences*’ (de Kort and Veitch, 2014).

A behaviour-based definition of lighting quality was presented by Veitch and Newsham (1998a). They classified the criteria for lighting quality into six categories: visual performance, post-visual performance (behavioural effects that are not visual, such as eating or walking), social interaction and communication, mood (happiness, alertness, satisfaction and preference), health and safety, and aesthetic judgements (appraisals of the appearance of the space or the lighting). Furthermore, this definition of lighting quality was broadened to include architectural and economic considerations (Veitch, 1998) (see Figure 2.21).

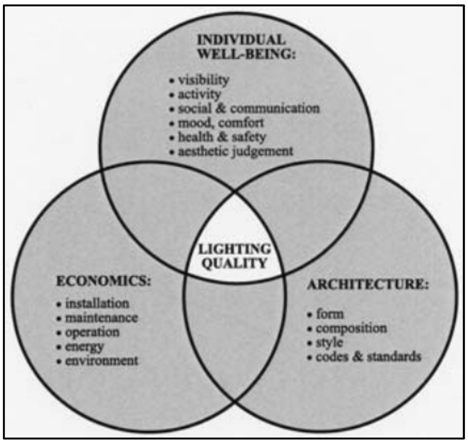


Figure 2.21: Lighting quality: the integration of individual well-being, architecture and economics. From Veitch (1998), ©National Research Council of Canada.[27]

2.5.2 Subjective impressions in lighting research

As noted in figure 2.21, mood and aesthetic judgements are included in the category of ‘individual well-being’, as they contribute to a situationally-appropriate mood, and to the aesthetic appreciation of the space (Veitch and Newsham, 1998a). Many investigations exist in the literature regarding these behavioural responses.

Moreover, it is clear from many studies that brightness is considered intrinsic to lighting research; and it is, therefore, included in certain aesthetic studies.

[27] Used by permission. Permission to use the image granted by Jennifer Veitch, on the 25th of June, 2015. ©National Research Council of Canada.

However, a distinction between aesthetic and cognitive judgements was already established in the 18th century by the German philosopher Immanuel Kant. In the first part of his book, the *Critique of Judgement*, Kant established the basis for aesthetic judgements. He asserted that cognitive judgements are based on perception (e.g. brightness); whereas aesthetic judgements are also based on feelings of pleasure (e.g. beauty). Moreover, research suggests that some areas of the brain are activated differently from aesthetic and cognitive judgements. For example, subcortical regions have a role in aesthetic judgements, but they have none in brightness judgements (Ishizu and Zeki, 2013). The present dissertation agrees with this distinction and chooses to omit brightness as a scale in aesthetic evaluations (see brief discussion in Paper II – Section 3.3).

Nonetheless, other levels of behavioural responses (e.g. mood, preference, satisfaction) can influence how people develop judgements (Isen et al., 1982), presented by Wang and Boubekri (2011). The following sub-section will discuss some investigations of mood and preference in relation to lighting research.

a. Investigations of mood and preference

Different studies have addressed the influence of light on mood. For example, Veitch and Gifford (1996) used a questionnaire package consisting of six different test/scales. Each of the tests contained statements based on different beliefs held by people in relation to light and lighting, such as lighting effects on people, technical aspects of common light sources, and the effects of the physical environment on people. The questionnaire statements were rated using either Likert scale or true/false items. The results found reliable held beliefs about the effects of common lighting conditions on human health, work performance, mood, and social behaviour. For example, they found that a large majority (80.5%) of their study respondents agreed that daylight indoors improve their mood. They discussed that such beliefs predict people's decision regarding the use of lighting.

Keighley (1973a, 1973b) studied different window design options in an office model and their influence on people's satisfaction. The model represented an office of length 17.7 m, and a variable width transformed with mirror-side walls. The height of the room was set to 3.1 m. The different window design options included the number of openings, window height, window area, mullion width, and view type. In addition, the type of view was changed by projecting pictures of cityscape views varying through the different types of windows. The results showed that the window area affected the satisfaction of the participants. For a constant area of opening of 20%, of a 6 m x 3.1 m wall, the preferred window width ranged between 2.8 and 3.4 m, and the preferred window height ranged between 1.8 and

2.4 m. In general, large horizontal windows (i.e. minimum 25% of the wall area) were most preferred, while windows below 10% of the wall area were least preferred.

Rubin et al. (1978) conducted an experiment over three 10-day periods in October, February, and July, in which approximately 700 venetian blinds of office buildings were set in either open or closed position after the workers had left their offices, in order to see whether the workers changed the position of the blinds upon their arrival back to work. The various blind configurations set by the workers were analysed based on the percentage of window coverage and slat angles. Their results showed that blinds were more closed on the southern façade than on the northern façade, suggesting a desire to avoid sunlight penetration and office overheating. Nevertheless, most blinds were set as open, suggesting a strong preference for a view out.

Cuttle (1983) surveyed 471 office workers regarding their preferences of windows in a workplace. A very large majority (i.e. 99%) of the survey respondents claimed that offices should have windows. In addition, 86 % preferred daylighting as their light source. The author noted that the preference over daylighting was due to a belief that electric light was a threat to human health.

Veitch and Newsham (1998b) studied the lighting quality and energy efficiency effects on task performance, mood, health, satisfaction and comfort. The study was performed in a windowless open-plan office with nine different artificial lighting conditions. The participants of their study rated their mood in both the morning and afternoon of the experimental day. Mood was investigated using a questionnaire consisting of 18 semantic differential scales representing three components of mood: pleasure, arousal, and dominance. The results found that time had an effect on mood, in which mood measures decreased in the afternoon. Pleasure presented a larger decline in the scores, in comparison to the moderate decrease of dominance, and the small decrease of arousal.

Boyce et al. (2000) investigated how people use individual lighting control systems and the effects the use of the system has for task performance and mood. The study included three small windowless offices lit by the same type of electric luminaire. Experiment participants working in two of the offices were given a handheld lighting controller in order for them to dim the light of the luminaires if desired. They hypothesised that people could achieve a more positive mood by having control over the lighting system. The '*Positive and Negative Affect Schedule*' (PANAS) (Watson et al., 1988) with a range of values from 10 to 50 was used to measure people's mood, and was administered three times during the experimental day. Similar to the study by Veitch and Newsham (1998b), they found that the participants' mood decreased throughout the day. Statistical analyses concluded that having control over the lighting system does not contribute to a positive mood in people.

Knez and Kers (2000) examined whether mood and cognitive performance were influenced by indoor lighting, gender, and age. An office-like room with false windows was used. The room was equipped with lamps of two type of colour temperature: warm white lighting – 3000 K, emitting a reddish light; and a cool white lighting – 4000 K, emitting a bluish light. The population sample included a younger group of participants (M_{age} = 23.6) and an older group of participants (M_{age} = 65.4), in order to study the effect of age. Both genders were represented in each group. The experiment participants had to self-report their mood using the PANAS scale, using 10 affective adjectives for positive mood and 10 for negative mood. The PANAS scale was administered to them in the beginning and after 90 minutes of the experimental session. The results confirmed their hypothesis: the room light had an impact on the participants' mood. Moreover, effects of age and gender were found. The older males preserved the positive mood better than the older females did, whilst the younger females preserved both the positive and negative mood better than the younger males did. After performing cognitive tasks for 90 minutes, the younger group of participants preserved a negative mood in the warm white lighting, while the older group of participants preserved a negative mood in the cool white lighting. They concluded that indoor lighting can transfer different emotional meanings according to age and gender groups.

Wang and Boubekri (2011) evaluated the mood, preference, and task performance of people in a sunlit workspace. The experiment made used of a multifunctional seminar room presenting a floor-to-ceiling window facing east. The room presented an outdoor view of natural landscape. Window blinds controlled the sunlight penetration at a level of 20 - 25 %. Ten different seating locations in the room were evaluated (two in the sun patch, two on the boundary of the sun patch, three at 1.2 m from the sun patch, and three located at 2.5 m from the sun patch). Regarding the preference of the location of the work desk, 89 % participants chose to sit in what the authors called the 'favourable zone', which described the zone close to the sun patch. From the total sample, 19 % of the participants located their work desk in the sun patch, suggesting glare as a problem. Other reason for the preference of seating close to the window was not only sunlight and view out, but the feeling of control. According to the participants' responses, they wanted to have good visibility to the doorway in order to respond quickly if a person approached the room. Additionally, the PANAS scale was used for the study twice: before and after the cognitive tasks of the study. Statistical results suggested that the sitting location affected the positive mood. The majority of the participants showed a decrease in positive mood after the cognitive tasks, with exception of one position on the boundary of the sun patch, and one position located 1.2 m from the sun patch, which showed a very slight increase. However, on average, the mood decreased less in the participants seating close to the sun patch than the ones seating far from the window and the sunlight. In addition, the seating position located next to the window, in the sun patch, showed a higher degree of mood decrease. The authors speculated this may be due to the visual discomfort produced by the extreme amount of daylight.

b. Investigations of aesthetic judgements

Within environmental studies, aesthetic judgements relate to the perceived appearance of a space. According to Veitch (2001), the understanding of aesthetic judgements as a factor of lighting quality, and the understanding that lighting conditions stimulate a positive evaluation of a space are of great importance because they can result in the development of: *i.* human aesthetic and lighting preferences; *ii.* theoretical categorisations of luminous environments; and *iii.* new hypotheses about information processing in luminous environments. Additionally, Veitch and Newsham (1998a) argued that lighting quality occurs when the humans' behavioural needs are supported by the lighting conditions of a space. Nevertheless, few researchers and studies address this interdisciplinary topic.

Almost twenty years ago, a literature review discussed the efforts of lighting research that studied the effects of lighting on behavioural outcomes (Veitch and Newsham, 1996). The investigation reported that only studies about luminous uniformity and colour examined aesthetic judgements as behavioural outcomes. In contrast, they found few studies that could allow us to reach conclusions about the link between aesthetic judgements and luminance, illuminance, glare, flicker, lighting systems, control, daylighting and windows (see Figure 2.22). It is important to remember that the literature review that resulted in Figure 2.22 was undertaken almost twenty years ago. This means that the understanding of the different areas of knowledge might have changed in the last twenty years. The reader is then cautioned to use this information as referential and not as current insight of the literature.

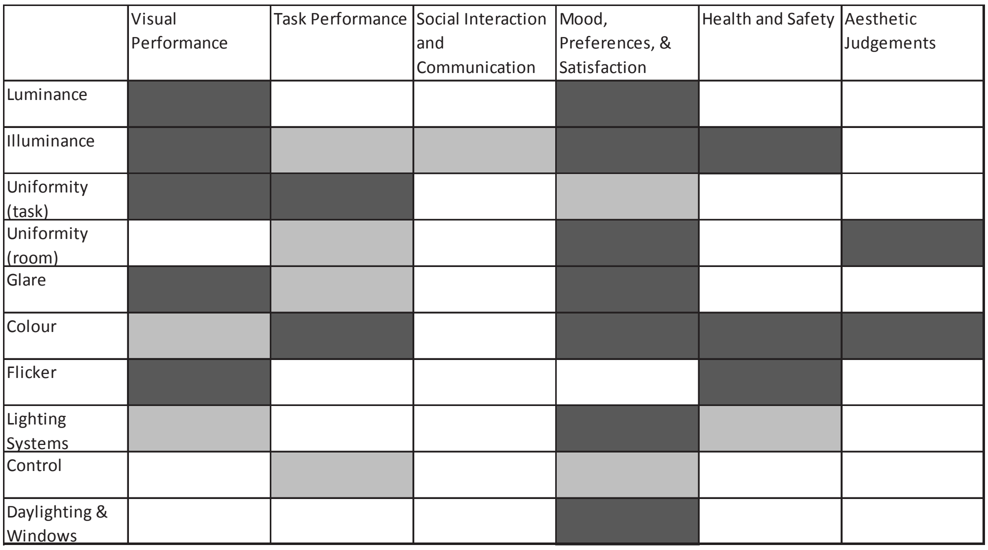


Figure 2.22: Areas of knowledge about Luminous Conditions and Behavioural Outcomes. Shaded areas indicate that a body of scientific knowledge exists between the independent variables (i.e. Luminous Conditions) and dependent variables (i.e. Behavioural Outcomes). 'The darker the shading, the better the understanding of the topic'; 'empty cells reveals areas in which there is too little evidence, or none at all, to reach any conclusion.' From Veitch and Newsham (1996), ©National Research Council of Canada.[28]

Nevertheless, readers can notice the unshaded area at the intersection between 'daylighting and windows' and 'aesthetic judgements' in Figure 2.22. Sadly, almost twenty years after the literature review was presented, it appears as the area of knowledge relating to aesthetic judgements might still be unshaded. In the author's opinion, this is not due to a lack of research interest in visual quality; rather it seems to be that the focus is mostly set on photometrical measurements related to task and visual performance.

The limited interest in aesthetic judgements as part of lighting quality has been sporadically discussed. For example, Pellegrino (1999) noted that there are '*many methods to quantify lighting, whereas there is no comprehensive and widely accepted method for evaluation of its quality*'. Fontoynont (2002) argued that '*the amount of light available is only one of the parameters which defines visual well-being*' and that '*it is becoming indispensable to define descriptors of lighting quality, beyond only the field of performance*'.

[28] Used by permission. Permission to use the image granted by Jennifer Veitch, on the 25th of June, 2015. ©National Research Council of Canada.

Although some attention has been paid to aesthetic judgements as part of the lighting quality, the amount of attention is still not sufficient. The following paragraphs will summarise some of the most important studies examining subjective impressions of the appearance of a space.

Probably the first reference to treat lighting quality in a holistic manner, i.e. looking beyond the working plane for task performance, but also paying attention to the ceiling, walls, and the whole space, was the paper published by Waldram (1954). In the paper, Waldram exposed the 'Design Appearance Lighting Method' as a procedure according to which a lighting installation is preconceived together with architecture and decorations to achieve the desired appearance of a space. This method suggested that the subjective term 'brightness' be used by architects to describe the desired appearance of a lit space. Later on, lighting designers would use a set of luminance/brightness scales to attempt to match the required brightness scenarios of the architect.

Another well-known study including subjective evaluations is the investigation carried out by Flynn et al. (1973). In their study, the appearance of six different lighting scenarios of conference rooms was evaluated by of 34 semantic differential scales. They analysed their results using a factor analysis; and thus reduced the semantic differential scales to three factors: Perceptual clarity, Evaluative impressions and Spaciousness. Similarly, they managed to interpret three dimensions of lighting settings: uniformity, brightness and overhead/peripheral. The lighting settings were related to the factors. Finally, their conclusions included that, e.g. spaciousness is related to uniform lighting and bright walls; and relaxation is related to non-uniform wall lighting. Their study derived in guidelines to study subjective impressions in lighting (Flynn et al., 1979); and although its validity in current times has been questioned, it still serves as a reference material for lighting researchers interested in subjective evaluations.

Hawkes et al. (1979) agreed with the methods used by Flynn et al. (1979), and argued that with such techniques (i.e. semantic differentials, factor analysis, and multidimensional scaling) lighting quality should stop being considered an '*unsolvable riddle*', given that it is '*possible to remove some of the mystery attached to the vague and subjective term "lighting quality"*'.

Loe et al. (1994) studied the relationship between the subjective responses of 18 different lighting settings of a full-scale mock-up of a conference room. Two factors were identified using a factor analysis: visual interest and visual lightness. The results showed that those two factors are directly related to the luminance contrast and the average luminance within a horizontal band that is 40° wide and centred at the normal eye height of a seated viewer. Moreover, they concluded that users not only require sufficient lighting scenarios for task performance, but also desire a lit environment that is considered 'interesting' and 'light'.

In later studies undertaken by the same research group, Loe et al. (2000) continued to investigate what is considered 'the most important area of the field view', i.e. the horizontal 40° band via the standard deviation of the luminance distribution, and the average luminance as two photometrical measurements in order to describe the lighting appearance of a space. The study used eight different lighting scenarios: four basic electric lighting systems and four adding installations together (combination of the four previous lighting systems). Ten bipolar semantic differential scales were used for users' evaluations. Their results suggested that the average luminance and the luminance standard deviation can be used to describe visual lightness and visual interest, respectively.

Other studies do not solely focus on aesthetic judgements of a lit environment as their dependent variable (i.e. the observed outcome) but include the aesthetic evaluations as part of their studies.

For example, in the study conducted by Veitch and Newsham (1998b) (see Page 82), the evaluation of aesthetic impressions of a windowless open-plan office with nine different artificial lighting conditions was included. Twenty-seven semantic differential scales were evaluated. Most of the scales implied three factors: visual attraction, complexity and brightness. Nine scales did not fall into any of the defined factors. Finally, they concluded that, despite using measures selected from the literature and a robust sample size, the measures were too weak to detect significant effects.

Laurentin et al. (2000) investigated the effect of thermal conditions and light source type on visual comfort appraisal. The study included an evaluation of pleasantness of the lighting environment of a room with three light source types (daylight, electric light, and combined lighting) at a constant 300 lx illuminance. The results indicated that environments with daylight only were considered pleasant, and those with electrical light only were considered unpleasant. Additionally, gender differences were found with regard to visual comfort; i.e. in general terms, women tended to rate pleasantness differently than men.

Houser et al. (2002) reported two studies using eleven artificial lighting scenarios for evaluating human subjective responses to spatial distribution of light. The lighting conditions presented a constant horizontal illuminance, with varying horizontal illuminance contribution from up and down the space, i.e. the photometric distribution was the independent factor. In their first study, a paired comparison analysis was used. The second study used 21 semantic differential scales. From their first study, they concluded that humans are able to discriminate different photometric distributions. The second study attempted to progress to more specific conclusions. The majority of their conclusions dealt with the perceivable differences between e.g. changes of ceiling luminance, shadows, and physical settings. Regarding the aesthetic appearance of the room, the results suggested that the indirect lighting made the room appear more spacious; conversely, the room appeared less spacious when only direct light was delivered.

In recent years, a number of PhD dissertations have addressed the topic of visual quality with regard to lighting. For example, Stidsen (2014) investigated the light atmosphere in hospital wards. In her research, she developed an abstract *'Model of light atmosphere',* in which four aspects (i.e. light, user, space and time) attempt to establish a framework for studying light atmosphere. Additionally, based on Küller (1991), she carried out a questionnaire study using eight factors to describe the physical environment: '*Pleasantness*', '*Complexity*', '*Unity*', '*Enclosedness*', '*Potency*', '*Social status*', '*Affection*', and '*Originality*'. These eight factors were investigated under two types of lighting scenarios, in which the illumination was defined by the lighting design and not the luminaire design. The two wards used in her survey were: *i.* ward with lighting design (DW), in which a new lighting concept was installed in a room, consisting of a vertical grid locating artificial luminaires near the walls and achieving a horizontal tripartition of the space in '*high lighting zone*', '*centre light zone*' and '*low light zone*'; and *ii.* a traditional ward illumination (TW), arranged in a control room. For a more specific explanation of her study variables, please consult Stidsen (2014). Her statistical results showed that DW had higher scores in '*Pleasantness*', '*Complexity*', '*Unity*', '*Social status*', and '*Originality*'. '*Enclosedness*' and '*Affection*' ranked higher scores in the TW. Furthermore, her thesis discussed whether the use of e.g. illuminance, composition of colour rendering index (CRI), and a particular colour of light on the Kelvin scale were enough to achieve a '*home-like*' and '*pleasant*' light atmosphere in hospital wards. She pointed out that more knowledge about the emotional and sensory qualities of light is needed and recommended that further research study the socio-cultural aspects of light.

Liu et al. (2015) examined the effect of eight lighting conditions on the perception of atmosphere in a living room, as well as gender and cultural differences in the perceptual evaluations. Each lighting condition included different luminances and correlated colour temperatures (CCT). Statistical analyses reduced the 71 employed scales into two fundamental factors: liveliness and cosiness. No gender differences were found, however factor analyses revealed that cosiness was more important for the female participants, and liveliness was more important for the male participants. Results found that the increase of luminance achieved a more lively room. The authors discussed further results relating cultural differences and compared them to the results found by Vogels et al. (2009), who worked with

Dutch observers. They pointed out that the relationship between light appearance and atmosphere perception showed some discrepancy between cultures, i.e. the Dutch participants felt more lively and cosier under lower CCT sources compared to the Chinese participants, who felt lively under higher CCT sources and were not affected by the CCT for the feeling of cosiness.

Finally, with few exceptions, it seems that most of the scientific studies previously mentioned are focused on artificial lighting. This leaves a thin body of knowledge about daylight and aesthetic judgements, making this field of research interesting and yet, in need of attention. In addition, architecture is a field more recognised with practice and experience-based knowledge than with research science and theoretical knowledge. Furthermore, and in the author's opinion, it seems architecture is more focused on designing good buildings than writing good scientific research articles. It is probably due to this preference that architecture is a field that does not produce as much research as other fields such as medicine, biology, and psychology. Architects design with daylight, but they do not conduct research about daylight and architecture. Thus, the need to perform research about daylight and architecture (represented by indoor environments) is spurred by the little attention that daylighting research seems to receive among practicing professional architects.

2.6 Summary

Four different bodies of knowledge have been discussed in this chapter: visual perception, environmental studies, daylight and colour (in relation to architecture), and daylighting design. The last two cannot, of course, be considered separately. For the purpose of pedagogically differentiating the basic concepts of daylighting and advanced daylighting design, they were separated in different sections.

In general knowledge, the literature shows that light is a crucial element in the human vision process. Without light, humans cannot see. Additionally, light provides health and well-being to humans (e.g. via the circadian system), and connects them with their environment. The general notion that humans spend most of their waking time indoors, has spurred research focusing on environmental studies from different disciplines such as architecture and psychology. Logically, the commitment to understand and improve human environments is a valid and necessary field of research.

The literature acknowledges that light has an effect on environmental evaluations. Moreover, aesthetic judgements are included not only as a part of environmental studies but also as a part of lighting quality. On the basis of the given knowledge, it is clear that this interdisciplinary topic (i.e. light + environmental aesthetics studies) is still not clearly understood. Furthermore, most studies have concentrated efforts on artificial light studies, whereas the topic of daylight shows little presence in environmental aesthetics literature.

The basic deliverer of daylight remains the window. However, the minimum fenestration criteria rely upon new sustainable recommendations. On one hand, windows are considered the source of heat loss in buildings, and their size reduction is recommended. On the other hand, windows are considered as an alternative solution to artificial lighting, and thus, capable of producing energy savings. One way or the other, new fenestration standards will affect lighting quality and thus the aesthetic of an environment. Establishing knowledge-based criteria for well-lit environments that are aesthetically pleasant can aid architects, lighting designers, psychologists and future users.

CHAPTER 3

EXPERIMENTAL METHOD

3.1 Simulation as experimental method

The simulation of environments is a sensorial representation of the real world, usually predominated by the visual experience. This method is widely used in different fields; e.g. entertainment industry, medicine, and vehicle and military training. Moreover, simulation research is considered as one of seven architectural research strategies (Groat and Wang, 2002).

In their discussion about simulation research, Groat and Wang (2002) argued that simulation allows humans to '*experience emotions stirred by the representation without undergoing the dangers of the real things they represent'*. Not every case presents a direct danger (in the literal meaning of the word), but complications and difficulties of architectural research are always a possibility (see further discussion of difficulties in conducting scientific research in Sections 3.2 – Paper I and 3.3 – Paper II). Additionally, simulation has been discussed as useful as '*an intermediate point of knowledge acquisition*': it can test theories and provide material with which to develop new theories (Crano and Brewer, 1973), as presented by Groat and Wang (2002).

Although simulation research presents itself as an alternative for solving real environment research problems, it suffers from (valid) criticism. The main critique is directed toward the reduction of information content and isolation of the real world in simplified versions of reality. Indeed, in a study about different simulated representations of the real world (i.e. mock-ups, reduced scale models, photographs and virtual renderings), disadvantages of each representation method were found (Cauwerts, 2013). However, when a simulation method can replicate the real world in a holistic manner, it can offer benefits able to overcome its disadvantages. For example, Groat and Wang (2002) claimed that significant variables in a simulation experiment can be observed and further actions can be hypothesised. In addition, de Kort et al. (2003) argued that simulation increases experiential realism and external validity and retains experimental rigor. Gaining experiential realism, via a well-designed simulation, means that a simulated environment can obtain similar responses to the stimuli from a real environment (de Kort et al., 2003).

As previously mentioned, many methods are used to simulate an environment: drawings, sketches, photographs, slides, virtual renderings, films, high dynamic range (HDR) images, and animated pictures are examples of two-dimensional (2D) representations. Similarly, mock-up rooms, and reduced scale models are examples of three-dimensional (3D) representations. Although all these methods are generally used by researchers, one can question whether these methods replicate real environment conditions in an acceptable manner. Naturally, a simulated environment will always act as a reduced environment; however, there is a need to know how closely simulated environments can recreate real environments. Studies focused on the comparison and validations of the simulation methods are, undeniably, needed.

Within 2D representations, slides are a well-known simulation method used for lighting research. To test their validity, a study performed by Hendrick et al. (1977) focused on the comparison of slides against mock-ups as research methods. Certainly, slides offer a cost and time efficiency advantage over mock-ups. Although their study yielded promising results, showing a degree of similarity between the results of both methods, the authors argued that further work was needed. Other simulation method that was evaluated against real spaces to test its validity is the HDR images. Newsham et al. (2010) compared six interior scenes presented to the experiment participants in three presentation modes: real spaces, conventional images, and HDR images. The HDR images accurately reproduced the range of luminance of the real space, contrary to the conventional images which maximum luminances were 10 times lower than the HDR images. Both types of images were visualised in a 17-inch computer monitor. The scenes were rated for brightness, uniformity, pleasantness, and glare. The HDR images were evaluated as more significantly realistic than the conventional images only in scenes containing areas of high luminance. Their results suggested that for scenes with large areas of high luminance, the HDR images can be used as an alternative to evaluate the visual appearance of real spaces for lighting quality research. To avoid repetition, other examples of 2D representation studies performed in recent years are discussed in Section 3.3 – Paper II.

If the goal of environmental simulation is to obtain experiential realism in a holistic manner, the experience of depth can raise the realism to 2D representations. As pointed out before, scale models and mock-up rooms are examples of 3D representation; i.e. the sense of depth can be experienced.

The validity of scale models was studied by Lau (1972), who found a degree of similarity to responses between scale models and a full-size mock-up room. Similar to the study by Hendrick et al. (1977), Lau (1972) recommended further research to confirm the findings. Additionally, Cowdroy (1972), presented by Dubois et al. (2007), found equal results for glare assessments made in large scale models (scale > 1:6) compared to ones performed in full-scale environments. Probably due to these validations, many research studies use scale models for lighting studies, e.g. daylighting in atrium buildings (Matusiak, 1998), performance of daylighting systems (Arnesen, 2002), impact of glazing type on visual perception (Dubois et al., 2007), glare from a translucent façade (Matusiak, 2013), and light level perception in interiors (Zaikina, 2013). Regarding the full-scale mock-up rooms, they have been discussed as acceptable environments for studying visual perception, as they allow an increased number of present stimuli from the real world compared to other simulation methods (Cauwerts, 2013). Many examples of lighting studies using mock-up rooms are found in lighting journals. Studies that have used mock-up rooms include, for example, subjective impressions of lit conference rooms (Flynn et al., 1973), sensor type of daylighting systems (Littlefair and Motin, 2001), impact of daylighting and reflectance on the size impression of a room (Matusiak, 2004), influence of window form in the size impression of a room (Matusiak, 2006), daylighting for vision impaired persons (Matusiak et al., 2009), appraisal of lighting and performance in open-plan offices (Veitch et al., 2008), and window size and reflectance on aesthetic judgements (Moscoso et al., 2015).

Both of the discussed 3D representations (i.e. reduced scale models and mock-up rooms) offer the experience of depth, and are broadly used in lighting research. However, within daylighting studies, assuming that natural light, rather than artificial overcast sky or artificial sun is used, uncontrollable variables emerge. The continuous fluctuations of daylight produce different luminous conditions impossible to control and replicate each time an experiment participant observes a selected environment. This is, clearly, not acceptable in experimental and lighting research.

Stereoscopic imaging is one attempt to increase realism compared to conventional 2D imaging. Whilst 2D imaging presents only one image for the left and the right eyes of the viewer, stereoscopic imaging (or 3D imaging) presents two different images: one for the left eye and another for the right eye of the viewer. 3D imaging can be categorised into two types of technologies: active and passive. The difference between these two types of technologies lies in the presentation of the two images to each eye. While passive technology presents both images simultaneously, active technology presents one image to each eye while blocking the other eye's view. This process is done rapidly, interchanging between the two eyes. These presentation/blocking actions are performed rapidly so the interruptions do not interfere with the visual perception of the image as three-dimensional. Different 3D visualisation technologies are currently available for artistic, recreation, education, training and/or scientific purposes; e.g. 3D projection systems (active or passive), 3D monitors (active or passive), and 3D headsets.

All the above mentioned technologies deliver two slightly different images, one for each eye. These two images seen together create the illusion of three-dimensional depth. Depth is, thus, included in the spatial information sent to an observer's brain and can increase the experiential realism. This increment in realism was studied by Cauwerts and Bodart (2011). Their study compared visual perception of daylit rooms using 2D and 3D photographic projections. The results showed that some scenes were judged more realistic with the 3D photographic projection.

Other studies that have used stereoscopic images for lighting research include the investigation conducted by Wienold et al. (1998). In their study, daylighting systems installed in virtual offices were simulated via RADIANCE software (Ward, 1994) and saved as high-resolution slides. The slides were presented via a stereo-projection using four projectors. The study focused on short- and long-term user acceptance of the daylighting systems. Fontoynont et al. (2007) used a stereographic and interactive large screen display to present a set of calibrated luminous scenes to observers. The focus of the study was to correlate photometric quantities, i.e. luminous distribution and quality impression of the scenes.

To the author's knowledge, there seems to be no available study regarding the validity of stereoscopic images as a simulation method for aesthetic judgements in daylit scenes. Logically, the present dissertation could not be based on results produced by an untested method; hence, it was decided to test the method.

The selection criteria for the type of stereoscopic image method to use in the present research were straightforward: the possibility of projecting images of environments in near-to-real scale, and the economic resources available. Between the available stereoscopic imaging technologies, 3D monitors are usually limited in size, and thus have a disadvantage in creating a full-scale environmental projection. 3D headsets imply the use of considerable amounts of economic resources, and their use was considered to be a time-consuming method for conducting experiment with several participants (i.e. each participant can use one headset at a time). Needless to say, this method was discarded. Thus, 3D projection systems were found to be the most suitable system for the scientific purposes of the present research. The stereoscopic imaging method reached a satisfactory full-scale projection, which was suited for achieving experiential realism. In addition, it allowed the participation of multiple observers at the same time, making experimental sessions more agile and efficient. Moreover, two of the most important pieces of equipment used in this type of stereoscopic image method (i.e. the photographic cameras and the projectors), are easily available at any business selling photographic and/or video equipment (see description of equipment in Paper II).

The following sub-sections present the results of the pilot study and main experimental study to validate stereoscopic images as a method for daylighting and aesthetic studies.

3.2 Experimental set-up and pilot study

PAPER I: Virtual environments to study daylight and colour. Towards a new approach of advanced research method. Published in Nordic Light and Colour 2012.

VIRTUAL ENVIRONMENTS TO STUDY DAYLIGHT AND COLOUR
Towards a new approach of advanced research method

Claudia Moscoso

ABSTRACT
The aim of this paper is to present the analysis of the usability of virtual environments (VE) as a research tool to investigate the interaction of daylight and colour on the perceived quality of small architectural rooms. Given the fact that daylight and colour research can be very broad fields to study, this paper examines whether 3D – HD imaging serves as VE tools to study the interaction of three different daylighting levels and achromatic colour wall surfaces on the perceived visual quality of a small room. The paper focuses on a full scale pilot experiment with observers. In order to be more precise, student rooms have been chosen as the small rooms to study. This paper also includes the description and preliminary results of the pilot study, designed to test the usability and validity of VEs as a research method.

Background

Different indoor daylighting environments seem to have a strong impact on people in different ways. These effects of daylight on humans seem to be divided in two fields: the non-visual and the visual effects. For the non-visual effects, considerable amount of research has found that daylight plays a critical role over human physiological and psychological state. One example of this is the discovery that photoreceptive retinal ganglion cells influence circadian rhythms to light and dark patterns (Lockley *et al.*, 2003, Brainard and Hanifin, 2005), which has direct influence in the human health and well-being (Commission Internationale de l'Eclairage, 2004). These findings have not only interested the medical and psychological research communities, but different disciplines have begun to study further daylight importance in human daily activities and try to develop methods to apply the findings.

The visual effects of daylight are another, equally important field of research. Research proves the general preference for windows and daylight (Farley and Veitch, 2001); where aesthetic judgements, by the appraisal of a space appearance, are visual effects that can also influence human comfort or discomfort (Aries *et al*., 2010). Butler and Biner (1990) made a preliminary study where skylights were desirable to increase the feelings of spaciousness of a room. Stamps and Krishnan (2006) found that rougher boundaries created by windows contribute to judge spaciousness, and at the same time, recognize the spaciousness as a desirable characteristic of an indoor environment. Veitch (2011) discusses that some might consider the aesthetic preferences as a not necessary criteria to consider when discussing shelter, but that inhabiting a place that is appraised as more attractive may be considered a psychological good in itself. Considering this, it could be argued that the indoor appearance can benefit both human physical and psychological state.

In order to appraise an indoor environment, one of the most important senses to use is sight. Our visual perception seems to have a larger capacity of recognition and information processing than any other of our senses. Having in consideration the visual effects of daylight, it can be sensible to think in terms of the daylight influence on the visual totality of a room. Through different research studies, Hårleman (2007) addresses the significant impact of different daylight qualities on the perceived colour experience in interiors. Colour becomes then, an indispensable aspect of the spatial experience and its relation with daylight should be studied deeper. Nonetheless, the interaction of daylight and colour receives scant attention in architectural research.

Fridell Anter and Klarén (2010) state that studies of the interaction of light and colour can encounter problems due the lack of a common terminology, theory and methods. Usually light is seen as an individual field of research than colour, and studies made for each field focus on different aspects and separate research methods. This is true irrespective of light source, which is for daylight as well as for artificial light.

Considering the visual aspect of both daylight and colour, how does daylight and colour interact in an indoor environment? And most importantly, how does this interaction have an impact on the perceived quality of a room? In order to study the visual effects of both daylight and colour on an indoor environment a common understanding and method seems to be needed.

The Problematic of Studying Daylight and Colour in Architecture

Daylight and lighting research have their own dynamics to study. To conduct experiments in real environments can carry possibilities of control problems. Pellegrino (1999) for example, had troubles in setting up different lighting systems and the experimental hours had to be carried out until daylight could be excluded from his settings. To keep the - hopefully - stable inside experimental conditions, the variable outside conditions must be controlled. This is, obviously, a great challenge even for the most experienced researcher.

The perceived colour in architectural spaces is influenced by a number of factors. Fridell Anter (2000) discusses three different types of factors that influence the perceived colour of facades. However, these factors could also be determinant in indoor spaces. The three elements in discussion are: (i) the qualities of the reflecting coloured surface, where the seen colour depends on the type of surface material which holds the colour; (ii) the viewing conditions, including the intertwined elements of illumination such as intensity, composition and angle influence also the perceived colour; and (iii) the observer's references, attitudes and intentions. How we perceive colour is then highly influenced by several factors in which a world of questions could arise. For example, when considering the viewing conditions and noticing that the light intensity, composition and angle affect the human perception of colour, it is clear that the variable daylight conditions can produce instability of the perceived colour surface. This exemplifies that daylight and colour should not be considered separately, but on the contrary, a shared study of these two fields can provide a clearer picture of their interaction and impact on an interior space.

The trans-disciplinary project SYN-TES (Fridell Anter and Klarén, 2010), investigated via the subproject OPTIMA (Fridell

Anter and Klarén, 2011) how both light and colour design influence the spatial experience, functionality and energy consumption. This has been a recent research project cared to have a scientific holistic approach to light and colour. Their pilot study was made in full scale rooms, and one of the conclusions argued that in a longer test series, with enough time for modification, that method could lead to more specific conclusions than the ones achieved in the pilot study. Considering the difficulties and time consuming process that can carry the modification of colour wall surfaces and lighting design, it may be suggested a new simulation research method that could achieve similar results as full scale studies.

The importance of conducting precise and rigorous scientific research about the interaction of daylight and colour and its impact on the visual quality of architecture can encounter diverse challenges for most researchers. Most of these challenges seem to appear when conducting experimental research in real rooms. These challenges have their origins in logistics issues, economic resources availability, consuming time to perform experiments, lack of space and different spatial characteristics to which one wishes to investigate. Many researchers are often not able to do research in the field due the demanding process of attaining control over these challenges. And if they do, their findings can be rather limited.

Previous Simulation Research
In order to perform varied architectural research within the daylighting and colour fields, without encountering the listed problems, simulation research methods have been used in the past. Photographs, slides, scaled models, rendered images and computer simulation software have been used for these purposes with promising results. Some of these studies are discussed in the subsequent paragraph.

In the 1970s, basic static simulation methods were developed and used to study lighting and architecture. Lau started with the use of scale models to evaluate lighting quality (Lau, 1972) and Hendrick and others studied the effect of light on visual impression, using slides (Hendrick *et al*., 1977). Lau (1972) found results that generally showed a considerable degree of similarity with former results of Real Environment (RE) experiments. According to lighting research using slides (Hendrick *et al*., 1977), the comparable results with RE indicated that slides were a useful simulation tool. If the results obtained using a simulation method (e.g. slides) were considered promising for the similarity from experiments in real settings, then we have reasons to believe that the newest simulation methods like Virtual Environment Experiments (VE) might be equivalent to the experiments made in RE.

Having this in consideration, latest technology, more advanced than slides or scale models, could have the potential to offer significant results when used as research tools. Virtual environments using 3D – High definition imaging may offer a better approximation to reality than any other simulation method. And at the same time, it may be possible to retain control over the different stimuli and variables of an experiment. Other advantages of simulation methods range from the reduction of cost for experimental settings construction to the possibility to reach bigger audiences.

Virtual Environments have been used to carry out lighting research. While Wienold *et al*. (1998) use virtual reality to study a method to predict user acceptance of daylighting systems; Fontoynont *et al*. (2007) used also stereographic images to find a correlation of lighting quality descriptors with semantic characterization of luminous scenes. VE have also been tested for validity in colour appearance research (Billger, 2003, 2004, Stahre, 2009). Nonetheless, very few research efforts is encountered using VEs as an only method to investigate daylight or colour; and even less so, in the interaction of daylight and colour on the visual evaluation of a room.

Preliminary discussion
In order to carry out these investigations, different conditions and experimental rigor should be retained. Taking in consideration the different challenges that both daylight studies and colour studies face, VE methods to study this interaction should be studied and developed.

The validity of VE as architectural research method has not been proven yet. Little research activity is encountered to compare assessments of real rooms versus virtual rooms. Most of this research is found in the discipline of environmental psychology (de Kort *et al*., 2003). Their study discusses a valid point when testing VE as research tool: A rigorous study of this kind should start with an unbiased researcher. This means, there are two premises a researcher should consider when conducting VE studies: (i) VEs are not substitute for REs, and (ii) a VE will always be a reduced environment.

Under these premises, it can be stated that in order to investigate a VE as a research method, this must be evaluated together with a RE. If the results obtained under VEs are not significantly different than the results obtained under REs, then the validity of VEs results may be trusted.

Taking in consideration the previous discussion about the importance of study the impact that the interaction of daylight and colour can have over the perceived quality of a room, the

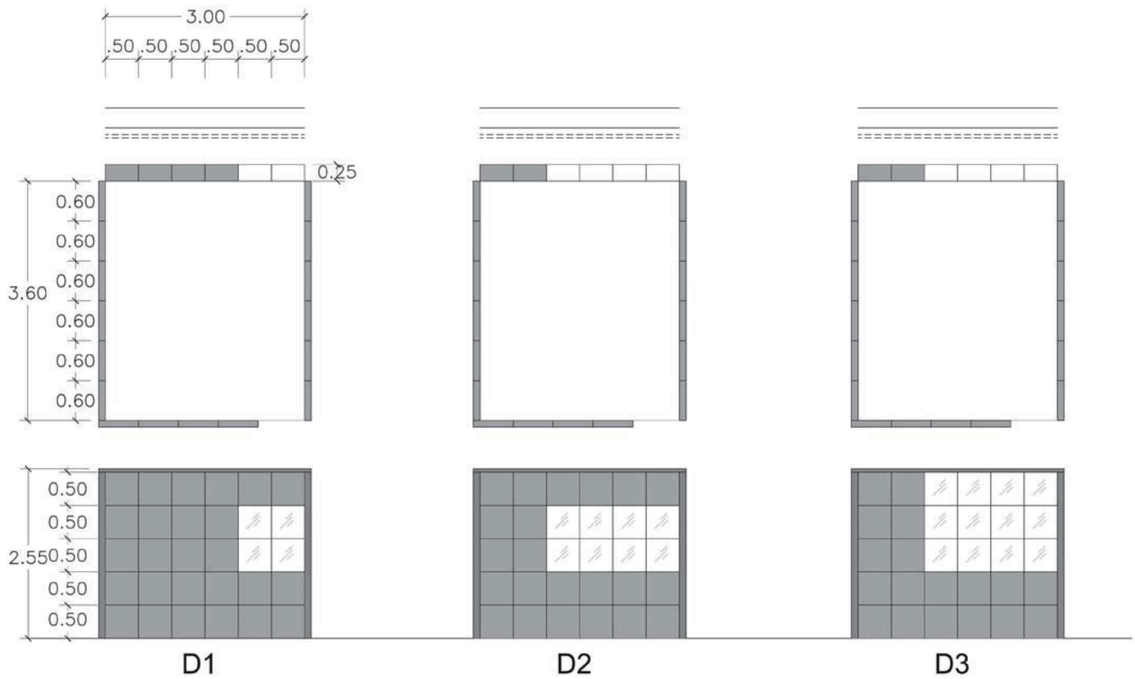
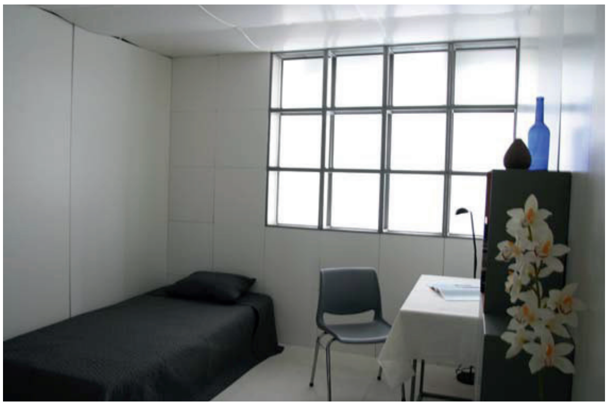


Figure 1: Floor Plan and Schematic Section of RE. Three different daylight openings



Figures 2 and 3: Similar furniture and furniture colour configuration in White and Black REs.

research question becomes: Are VEs a valid research method to study how the perceived quality of a room is affected by the interaction of daylight and colour? To start to test this, a pilot study has been design and executed.

Pilot Study

Aim and Scope

This project deals with the study of the comparability between the two research tools mentioned above: Real Environments (RE) and Virtual Environments (VE). The pilot study was designed to: (i) get a better approximation of knowledge of the different environments to study, (ii) test the different stimuli, and (iii)correct potential mistakes that could arise during the experimental session to try to avoid them in the main experiment. The results of the pilot study will then be a starting point that will help to maintain scientific rigor when fulfilling the core of the PhD project, the main experimental sessions.

Two real temporary full scale rooms, one black and one white, were constructed on the Room Laboratory (Romlab) located at the Norwegian University of Science and Technology (NTNU), Trondheim - Norway. The 3D pictures were taken directly from the real environments (RE) and shown on a 1:1 scale. The pictures were projected on a silver screen in the same laboratory. Both RE and VE were observed and evaluated by experimental participants.

It is expected to find some differences in scores between the VE and the RE, because interaction with the environment may not be possible with the VE. There is also expected difference in scores between different wall colour surfaces and different daylight openings. From the collected data from both methods VEs and REs, the limits of using a VE method can be drawn and the method can be narrowed down to study specific scopes within daylight and colour in architecture.

Methods, Hypothesis and Procedure

The pilot study had the following characteristics:

• *Real Environments:* Two rooms of equal dimensions (3.00 x 3.60 m) with similar openings and furniture configuration. One room had black wall surfaces and the other had white wall surfaces. These rooms were built with the aid of the "wall bricks" (boxes of 50x50x25cm) and pre-constructed wall panels (width = 60cm), both already present at the Romlab (See figure 1). To form windows, metal frames of equal dimensions to the "bricks" fulfilled this purpose. In order to have better control of the fluctuations of the Illuminance that natural light can present, translucent curtains were used. Due the position of the rooms inside the Romlab, the glazing areas to provide daylight to the room were placed on a North-East position, this way, unexpected direct sunlight, if any, was not possible after midday. However, the pilot experiment was carried out during overcast sky. The furniture was simplified by using boxes of 50x50x25 cm, presented at the laboratory. In addition, a chair, a lamp and bedding set was set in place to create the "student room". In both of the rooms, the furniture was situated in the same coordinates relating the position of the door entrance and the window (See Figures 2 and 3). Both have furniture of the same colour as the wall surfaces and in some cases (e.g. bed and bookshelf) were of a grey colour, in order to maintain achromatic colours and control over the variables (See Figures 2 and 3). The nominal colour of the wall elements and main furniture was registered with the Natural Colour System (NCS). When establishing the nominal colours of the room elements, it was seen that not all of the elements were completely achromatic, but they had a hint of chromatic attributes (hue towards yellow - See Table 1). Illuminance and Luminance values were measured using a lux meter (See Table 2) and luminance pictures taken with an EOS350D digital reflex camera (See figure 4). The participants were inside the RE when evaluating them.

	Name	Elements	Code
Black Room	Lateral walls	Wall Panels	S 8500 - N
	Window walls	Wall bricks	S 9000 - N
	Bedding set	Synthetic fabric	S 7000 - N
	Bookshelf	Wall bricks	S 4502 - Y

White Room	Lateral walls	Wall Panels	S 0502 - Y
	Window walls	Wall bricks	S 0500 - N
	Bedding set	Synthetic fabric	S 7000 - N
	Bookshelf	Wall bricks	S 4502 - Y

Table 1: NCS Codes – Nominal Colours of real environments elements.

Figure 4: Example - Luminance picture of the RE - White Room, D1. The different colours indicate the approximate value of luminance expressed in cd/m2.See graphic bar to the right.

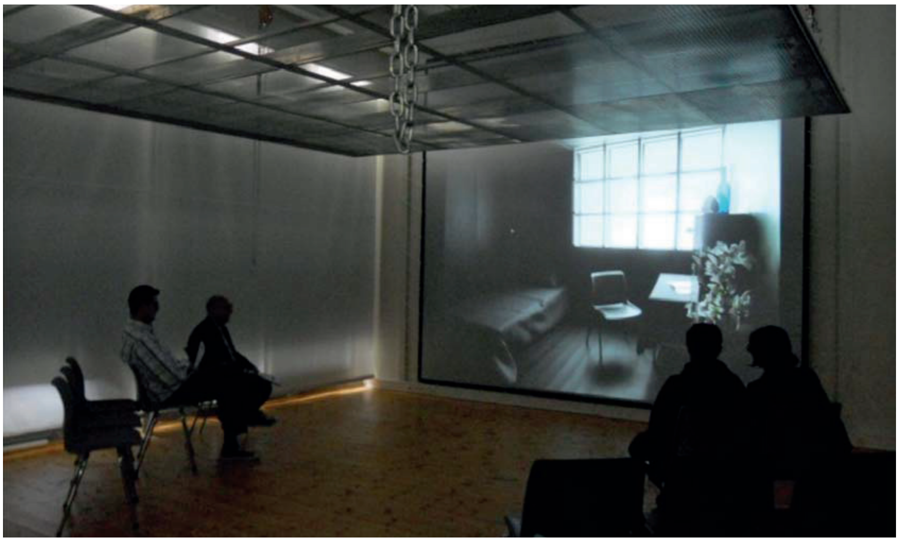


Figure 5: Stereoscopic images of the rooms, projected on an Antipolarized Silver Screen.

Room Colour	Daylight Level	Bed(lux)	Desk(lux)
Black Room	D1	1	69
	D2	22	110
	D3	34	138
White Room	D1	51	156
	D2	123	236
	D3	166	325

Table 2: Mean Illuminance values measured at two different points of the RE. All values measured each time before the participants evaluated the rooms.

• *Virtual Environments:* Tri-dimensional pictures (3D) taken with two photographic cameras OLYMPUS SP-800UZ with a lens 30xwide. The cameras were placed horizontally at an observer's height (1,65 m.) when taking the pictures. One camera captured a "left eye view" and the second camera captured the "right eye view". These pictures have a 4:3 format and 14 megapixels. The images were opened in a PC using the Stereoscopic Player software. They were then projected with the help of two High Definition Projectors of more than 5000 ANSI Lumen on an Antipolarized Silver Screen, especial to have a good performance of 3D imaging. Participants of the experiments made use of circular polarized glasses to assess the scenes from a distance not greater than 3 meters (See Figure 5).

• *Participants:* A total of 8 persons were participants of the pilot experiment. The participants were recruited via email and announcements at the Intranet side of NTNU. The sample consisted of participants with and without architecture training. They were from different nationalities and cultural background. The gender of the sample was 4 female and 4 male participants. The age of the participants ranged between 26 and 62 years old (M = 30). Every participant was tested for their vision prior the experiment to confirm that they did not have particular vision impairments which could compromise the collected data. The two vision tests conducted were: a. Luminance Contrast Test (Spatial Contrast Sensitivity), via computer software *VigraC* and using the Michelson Plot curve to test 5 different spatial frequencies and b. Stereoscopic Vision Test, making use of the *Random Dot 2 – Stereo Acuity Test*. All of the participants received a free movie ticket to see a movie of their choice for their cooperation to the experiment. Every participant read a "General Information Sheet for Participants" with full explanation of the experimental session. After having read the information sheet and heard the oral instruction, every participant signed an individual consent form where they freely consent to participate in the study.

• *Experimental Hypothesis:* In order to carry out an experiment able to throw results that can be compared between the RE and the VE, an *Experimental Hypothesis* was formulated. This way, the different variables (independent, dependent and extraneous) can be identified and controlled. By maintaining the same settings and variables in both VE and RE regarding daylight and colour, the scores from both environments can be easily compared.

The Experimental Hypothesis has been defined as:
H_1 = High daylighting level and white wall surfaces can produce a better visual evaluation of friendliness, complexity and spaciousness of a room than low daylighting level and black wall surfaces.

From this hypothesis, the independent and dependent variables were deduced. Independent variables: Daylight (3 different daylight levels) and Colour (White and Black wall surfaces). Dependent variables: Friendliness, Complexity and Spaciousness. Making use of a Within-Participant Experimental Design, where the participants evaluated both VE and RE, it was obtained a better control over the difference between participants, making it easier to compare difference between results.

• *Experimental Procedure:* The comparison between methods (RE and VE) was carried out making use of a mixed method approach. The Quantitative part used: Questionnaires with Semantic Differential Scaling, luminance pictures and Illuminance measurements of two points of the REs. The Qualitative part used: Open-ended and In-depth interviews after the questionnaires were answered by the participants. The objective was to complement the information gathered in the quantitative part of the experiment.

The pilot experiment was carried out at midday when the daylight level is at its highest point. The task introduction, along with written and verbal instruction was given by an assistant experimenter, who was not completely aware of the critical aspects of the experiment, in order to avoid giving the participants too much information that could bias their scores. After this part, the group of participants was divided in three subgroups; where the first group started evaluating the RE – White Room, the second group started evaluating the RE – Black Room and the third group started with the evaluation of the VEs – stereoscopic pictures. The groups then were rotating between the different stimuli presented until all the stimuli could be evaluated by all of the participants. By the randomization of stimuli presentation, bias connected to the Context effect or sequential contraction bias was controlled. The participants filled one written questionnaire for each presented stimulus. In total, there were 12 different stimuli (six in RE and six in VE).

The written questionnaires contained questions about the architectural visual qualities of the room. Nine of those questions were in a scale format (Semantic Differential Scale), where a group of 3 adjectives represented each dependent variable; these adjectives can be referred as *Architectural Quality Descriptors:*

Friendliness	Complexity	Spaciousness
Pleasant – Unpleasant	Simple – Complex	Spacious – Tight
Exciting – Dull	Legible – Illegible	Open – Closed
Ordered – Chaotic	Coherent – Incoherent	Spatially Defined-Undefined

Other nine questions were "comments" were they were free to write comments or not. The rest of the questions were about the overall evaluation of the room. At the end of the quantitative part of the experiment, participants were free to go and those who were voluntarily willing to stay and have a qualitative interview, remained to be interviewed. The goal with this interview was to gather extra information that could complement the answers given in the questionnaires. Four of the participants volunteered to get interviewed. The interviews were private, where the main experimenter sat alone with each of the participant to have a debriefing time and asked pre-established questions. The interviews last around 20 minutes with each person, and it was documented in writing by the experimenter.

Preliminary Results

At the delivery of this essay, the collected data from the pilot study needs more time to be statistically processed and for final conclusions to be drawn. However, some first results were found between VE and RE:

- The order, coherence and spatial definition show more similarity between VE and RE in the white room and D1.
- The order of a room was equally evaluated in both VE and RE in the black room. The scores did not only were the same in both environments, but also in three different daylight conditions.
- The legibility of a room also threw similar scores when evaluated in both VE and RE in the white room with the three different daylight stimuli.
- The complexity of the white room with D2 obtained very similar evaluations in both VE and RE.
- The white room with D3 obtained similar scores in both environments in more architectural quality descriptors than any other presented stimuli. Among them, the scores of the pleasantness, spaciousness, exciting level, legibility, openness, order, coherence and spatial definition showed similarity with very small variance between scores.

Considering this last discussed point, the first results seem to show that high daylight levels and white wall surfaces of a room are a better condition to evaluate a room in VE with these characteristics than a room with lower daylight levels and black wall surfaces. The assessment of a small room under this situation seems to be possible to perform equally well with VE as in RE.

During the qualitative interview, interesting answers from the participants were collected. All the participants that were interviewed mentioned that even when they could perceive a large difference between evaluating the VE than the RE, their scores were not significant different. They also mentioned that some architectural quality descriptors, like order, legibility and spatial definition, were easier to assess. The scores from the questionnaires corroborate this information (See list of preliminary results). All of the interviewed participants acknowledged the interaction of both daylight and colour as the room characteristics that were responsible for their overall perception of the room in both VE and RE.

Discussion of daylight level, wall colour and evaluation of room atmosphere

This study has been focused on the testing of the new method (VE); however some interesting observations have been made from the obtained scores of the pilot study. For example, by making a comparison between the white and the black room, considering the same size of windows, it seems that the colour of the wall surfaces becomes important in the evaluation of a room, i.e. the interaction between the white walls and the different daylight stimuli threw significant higher scores in the friendliness, complexity and spaciousness descriptors than the black walls and the same daylight stimuli. This means that it is important to notice that the interaction between the daylight level and the colour of the wall surfaces played an important role in the evaluation of the environments.

Concluding Remarks

The experience of the VE is obviously different from a RE in many ways. Despite these differences, the preliminary results of the pilot study show a positive approximation to the usability of virtual environments (3D pictures) as a research tool to study certain architectural quality descriptors in small rooms with white wall surfaces and high illuminances. However, the robustness of the results needs to be increased by corroborating this information with a statistical processing of the data and by conducting more experiments with a larger sample of participants.

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3.3 Validation of stereoscopic images as a research method

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CHAPTER 4

FINDINGS

4.1 Primary daylighting design: window size

PAPER III: Impact of window size and room reflectance on the perceived quality of a room. Accepted for publication in Journal of Architectural and Planning Research.

Is not included due to copyright

4.2 Advanced daylighting design: daylighting systems

PAPER IV: Aesthetic perception of a small room with different daylighting systems. Under review in scientific journal.

Is not included due to copyright

CHAPTER 5

GENERAL CONCLUSIONS

5.1 Summarised results and discussion

PAPER V: From windows to daylighting systems: How daylight affects the aesthetic perception of architecture. Published in the Proceedings of the 28th Session of the CIE, 2015.

FROM WINDOWS TO DAYLIGHTING SYSTEMS: HOW DAYLIGHT AFFECTS THE AESTHETIC PERCEPTION OF ARCHITECTURE

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Abstract

This paper argues that when evaluating the quality of a lit indoor environment, standard photometric measurements are not always sufficient. The aesthetic judgements of an indoor space are another parameter important to the users, but sadly, usually disregarded by lighting and environmental investigations. This paper presents the results and discussion of two different experimental procedures (covering 14 environments and 76 participants) designed to evaluate the influence of daylight on the aesthetic perception of small rooms. Empirical data and statistical analyses suggest that for immediate evaluations of a lit indoor environment, e.g. the size of a window or the design of a daylighting system are considered more significant than e.g. the light level in the room.

Keywords: Daylight, Environmental Aesthetics, Window Size, Daylighting System

1 Introduction

When designing a built environment, an architect considers several factors, e.g. the shape of the architectural space, the function of the space and the number of users who will inhabit the space. Either previously considered or not, light becomes another architectural element that contributes to create a visual environment by e.g. enhancing shape or accentuating colours and textures. Consequently, the perceived quality of architecture is influenced by all those elements, in particular by light.

Most lighting studies seem to be focusing at using lighting metrics to describe light in a space. Pellegrino (1999) argued that "*many methods are used to quantify lighting, whereas there is no comprehensive and widely accepted method for the evaluation of its quality. Designers are provided with a variety of numerical criteria for assessing the effectiveness of their projects: illuminances, illuminance uniformity, luminance ratios, glare indices, etc. Even when they are all considered, however, the lit environment, while functional, will not necessarily be pleasant.*"

One must wonder: are numerical parameters enough to describe or design a well-lit environment? Beyond the numerical principles, it seems to be also aesthetic parameters to consider when evaluating a lit environment. A well-lit environment is an environment that not only allows visual acuity and avoids visual discomfort. A well-lit environment has also the potential to relate a person with its surroundings in a satisfactory environmental experience. This is not a new information, already in the 1970s, studies showed that windows, for example, influenced the perceived quality of a room in an unrelated manner to view or sunshine (Collins, 1975). Furthermore, recent discussions have argued that light creates and enhances the quality of indoor atmospheres, and that the amount of light available is only *one* of the many parameters to define visual well-being and to give aesthetic value to scenes (Dubois, 2003, de Kort and Veitch, 2014).

Aesthetic judgements have been discussed to be relevant for the evaluations of lit environments in different studies (Pellegrino, 1999, McCloughan et al., 1999, Loe, 2009, Veitch, 2001). Yet, with so much discussion around the topic, it is surprising that knowledge that documents the effect of lighting on aesthetic judgements is limited and sparse. Indeed, few research efforts are found in studies that focus on the pleasantness of the lighting environment (Laurentin et al., 2000, Veitch et al., 2008), and the brightness of a room (Küller et al., 2006). Moreover, following the assumption that inhabiting a well-lit space can affect human's well-being and health, few other investigations have studied aesthetic judgements to understand the linkage between lighting and task performance, health, satisfaction, comfort and mood (Veitch and Newsham, 1998). Nevertheless, most of these studies focused on artificial lighting. To the authors' knowledge, very little to none research activity has been done in the last years to study daylight's impact on the aesthetic perception of architecture.

The Light and Colour Group at the Norwegian University of Science and Technology (NTNU) attempted to take a first step towards the understanding of how the aesthetic quality of a lit environment is affected by daylight deliverers. Two experiments were designed and carried out. The first experiment studied the daylight delivered by windows, and the second experiment studied the daylight delivered by windows equipped with daylighting systems. Thus, this paper reports empirical findings on how windows and daylighting systems affect the aesthetic perception of indoor environments. Establishing knowledge-based criteria for well-lit environments that are aesthetically pleasant can be of help for architects, lighting designers, psychologists and future users.

2 Selection of dependent variables

Various conceptual models indicating emotional and cognitive processes have been developed to understand the relation between man and the environment (Cold et al., 1998). In particular, the Kaplan's' preference model "Framework for Predictors of Preference" (Kaplan, 1987) explains the relevance of visual quality. This model explains that humans need a scene's available information at a first stage to recognize and understand the environment, and at a second stage to explore and act in the situation that can threaten or benefit their survival. Humans have the need to understand what they see and get involved with the environment, and the information available in the scene is crucial in their evaluations. This model proposes two dimensions in these two stages. *Coherence* and *Legibility* enable the understanding of the environment at an immediate and inferred perception respectively. Likewise, *Complexity* as an immediate perception and *Mystery* as an inferred perception enhance the desire to explore and act in the environment. Considering that light allows the information delivery of a scene, this theory can well be applied to lighting research.

Furthermore, environmental research has identified six main types of aesthetic attributes related to preferences: *Order*, *Complexity*, *Openness*, *Naturalness, Upkeep* and *Historical Significance* (Nasar, 2000). Since the present research directs attention to the perceived quality of an interior space, *Naturalness* and *Upkeep* (i.e. civilities) are excluded from the study. These two attributes can relate to both interior and exterior architecture, but they are not as strongly related to the interior space as the others. Needless to say, historical significance does not apply in the present study, considering that it refers to new environments. Other aesthetic attributes were selected from literature about environmental and lighting research. These include *Pleasantness* (Flynn et al., 1979, Laurentin et al., 2000), *Excitement* (Nasar, 2000), *Spaciousness* (Inui and Miyata, 1973, Flynn et al., 1979, Stamps, 2010), and *Spatial Definition* (Kaplan and Kaplan, 1989)presented in (Nasar, 2000). Consequent with the considered literature and theoretical background, the following variables were selected to study; they are given here with their dictionary and operational definitions:

- Pleasantness: The room gives pleasure, delight or satisfaction. Chiefly in a weakened sense: agreeable, nice, and enjoyable.
- Excitement: The room elicits, provokes active positive conditions.
- Order: The room is arranged methodically or suitably, is absent of chaos or uniform style.
- Complexity: The room is visually rich; all its elements are distinctive and well interconnected.
- Legibility: The room is legible; all its elements can be "read", and thus is easy to find the way around the environment.
- Coherence: The room has a logical connection or consistency with its function.
- Spaciousness: The room is considered spacious, wide, or commodious; it possesses extensiveness of area or dimensions.
- Openness: The room has open views; it allows access or view, view free from obstruction.
- Spatial Definition: The room can be seen with its bounds or physical limits (i.e. floor, walls, and ceiling.)

3 Empirical studies

Regarding energy consumption, windows have always elicited opposite opinions. On one hand, a window was considered a solution to reduce energy consumption of artificial lighting in buildings used most during daytime; on the other hand, it has always been subject of energy-loss during the heating or cooling periods. Indeed, windows have been identified as responsible for roughly 30 % of the heat loss of buildings in Norway (Grynning et al., 2011). Although advances in energy-efficient glazing technologies are giving hopes for keeping windows dimensions at the present level, not all energy-efficiency experts agree with this and turn their thumbs down to large window dimensions. Thus, the first experiment focused on window size as one of the independent variables for the study. An a priori experimental hypothesis was based on the idea that as the window size increased the positive aesthetic appraisal of the room increased.

Moreover, windows' daylight collection is limited as they alone cannot redistribute light deeper in the interiors. For daylight redirection purposes, additional daylighting systems need to be working together with the daylight openings of a building. Due to their common use, two types of venetian blinds and two types of light shelves were selected for the second study. Although blinds are usually considered a shading system, when the physical properties of their slats are altered to reflect light, these can be considered a daylighting system. The a priori hypothesis for the second study was based on the idea that the daylighting system redirecting light deeper in the interior and achieving higher light levels could obtain higher positive aesthetic evaluations of the studied room.

The evaluation of the aesthetic attributes in both experiments was set to be studied at an immediate response level (phasic arousal). This was due to the experimental design and methods used in the presented experiments (See sections 3.1.1 and 3.2.1).

3.1 Experiment 1: Window size and room reflectance

This full-scale laboratory experiment studied the impact of window size and room reflectance on the perception of the nine aesthetic attributes discussed in section 2.

3.1.1 Method

Twenty-six persons (14 male, 12 female) participated in the study. Their ages were between 24 and 62 years old (*M* =32,7; *SD* = 8,4). Two rooms of equal dimensions (3 m × 3,6 m, height 2,5 m) with similar openings and furniture conditions were constructed at the NTNU Room Laboratory (Romlab, 2013). The rooms simulated a student room. The ceilings, walls and floors differed between rooms: one room had white surfaces (WR), and the other room had black surfaces (BR). In this way, there were two reflectance values: black walls and ceiling – mean reflectance factor Y/*l*: 0,05; and white walls and ceiling – mean reflectance factor Y/*l*: 0,87. For both rooms, three different window sizes were used. The windows were: small (D1) – 1 m × 1 m, medium (D2) – 2 m × 1 m, and large (D3) – 2 m × 1,5 m. Thus, the experimental design was window size (3 levels) x room reflectance (2 levels). In total, there were six stimuli to be assessed (See Figure 1). Luminance measurements were taken of each stimulus seconds prior to participants' evaluations (see Figure 3). The experiment was divided in three experimental sessions. The sessions were carried at midday under overcast sky conditions. Additionally, white translucent curtains (transmittance 46 %) were used to control natural light fluctuations. The participants were divided in two groups to evaluate the white and the black room at different presentation orders. The groups were rotating between the presented stimuli, such as all the participants evaluated all the six stimuli for a repeated measures analysis. The participants evaluated their immediate perception of the stimuli filling out questionnaires containing 7-step semantic differential scales. There were nine scales, one for each assessed attribute.

3.1.2 Results

Statistical results from nine separate factorial univariate analyses indicated that window size has an effect on the aesthetical perception of eight of the studied attributes, with just one exception, the attribute *Order* $F(1,97; 49,28) = 2,63$; $p = 0,08$. The room reflectance had also an effect on the evaluation of all the nine aesthetic attributes. The interaction of window size and room reflectance was statistically significant in only two attributes: *Pleasantness* F(1,76; 44) = 3,44; *p* = 0,047 and *Legibility* F(1,91; 47,69) = 12,94; *p* = 0,00.

Additionally, scatterplots containing the mean ratings of the attributes and the mean luminance values of each stimulus were analysed (see Figure 2). Due to the amount of studied variables, we are not presenting the complete representation of the nine attributes in this paper, and are only presenting four as example means. For the complete group of all nine attributes and for a complete overview of the results, please refer to (Moscoso et al., 2015a). The rooms with larger windows obtained higher ratings for all the nine attributes. The rooms with high reflectance (WR) were ranked higher in all nine attributes than the rooms with low reflectance (BR). However, the results were unexpectedly interesting for the evaluation of the attributes *Excitement*, *Spaciousness* and *Openness*. For only these three attributes, the black room with the large window obtained higher scores than the white room with the small window. These results suggest that the window size has larger impact on the evaluation of these three attributes than the surface reflectance.

Figure 1 – Experimental stimuli for experiment 1

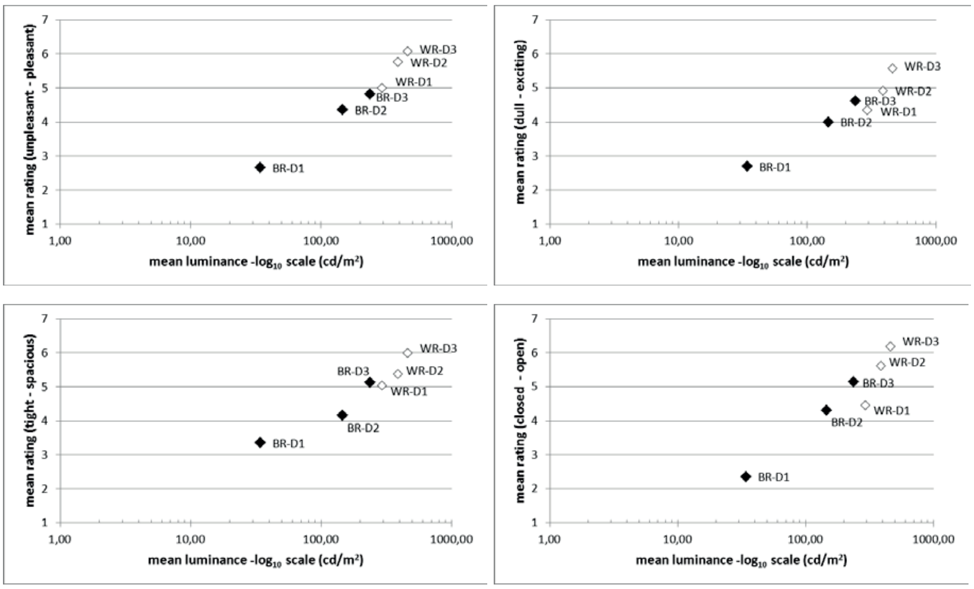

Figure 2 – Relationship between the mean ratings of the attributes Pleasantness, Excitement, Spaciousness and Openness and the mean value luminance of each scene

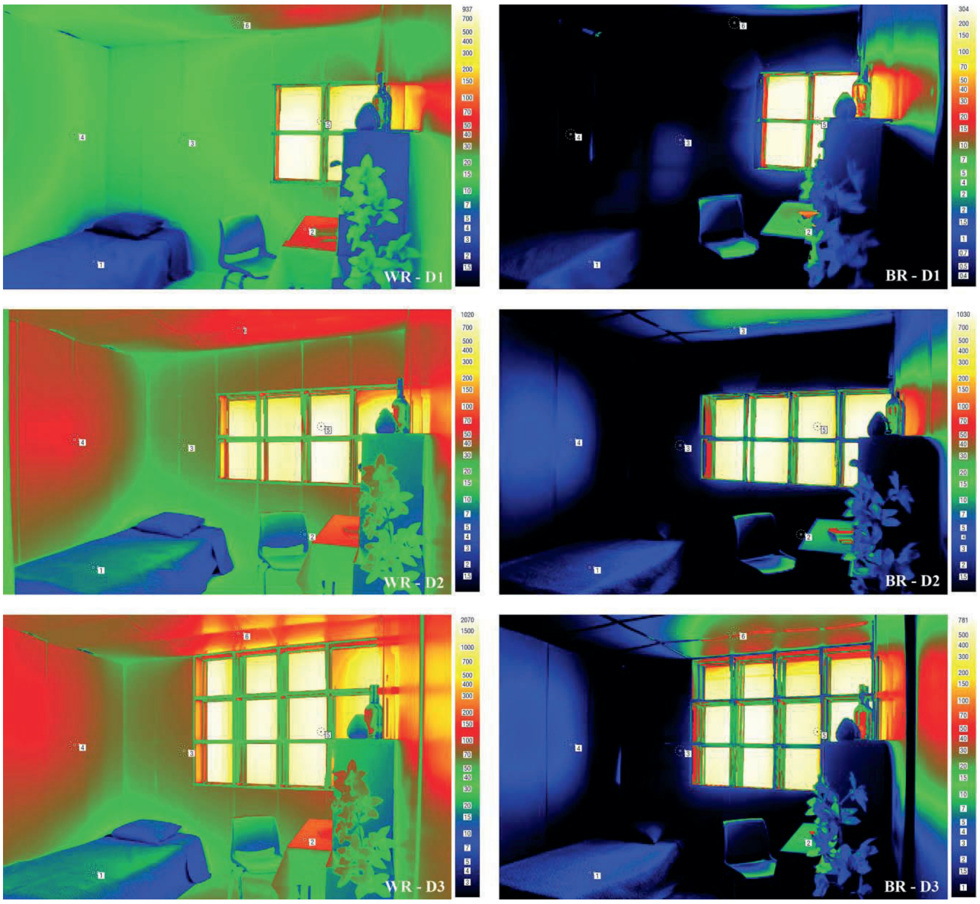

Figure 3 –Luminance pictures of each stimulus in experiment 1

3.2 Experiment 2: Daylighting systems and sky type

This experiment studied the influence of four different daylighting systems and sky type on the aesthetic perception of the same nine attributes studied in experiment 1 and discussed in section 2. The experiment made use of the stereoscopic pictures method, previously validated by (Moscoso et al., 2015b) .

3.2.1 Method

The total sample for the second experiment was of fifty participants, of whom 28 were female and 22 were male. Their ages ranged between 21 and 58 years old (*M* =32, *SD* = 8,7). A single office room facing south located at the 4th floor of the Central Building 1 at NTNU campus in Trondheim, Norway, was chosen for the study. The dimensions of the office were 2,67 m × 3,38 m, with a height of 2,82 m. The office room had two windows of 0,87 m × 1,56 m, with clear double-glazing. The reflectance of the walls and ceiling were of 0,87. The chosen daylighting systems were:

- White Venetian Blinds (WB) used as base case, as it is considered a shading system. Slat overlapping fraction of 20 %. Both slat sides had a diffuse reflectance of 0,7.
- High Reflecting Blinds (HRB) with a slat overlapping fraction of 20 %. These blinds were divided in two sections: the upper part of 0,45 m had the concave side of the slats oriented upwards and a specular reflectance of 0,9. The lower part had the concave part of the slats oriented downwards.

- Hybrid Light Shelf (HLS), with dimensions of 0,40 m × 1,14 m, just used for its daylight redirection properties. The interior had a semi-specular interior surface with a reflectance of 0,85.
- Mirror Light Shelf (MLS), of dimensions 0,30 m × 1,15 m. These MLS were tilted 5° towards the interior of the office. The reflectance of the mirrors was of 0,94.

Beneath the light shelves, white blinds similar to the WB were installed for having better control over the stimuli. The tilt angles for the slats calculated for achieving cut-off angles (i.e. the minimum tilt angle that assures that no direct sunlight passes between the blind slats) (Kolås, 2013). Each daylighting system was tested under two sky conditions: overcast sky (OS) and clear sky (CS). Stereoscopic pictures were taken of each stimulus. Luminance values were measured right after the stereoscopic pictures were taken (see Table 1). In total, there were 8 different stimuli for aesthetic evaluation (See Figure 4). Hence, the experimental design was daylighting system (4 levels) x sky type (2 levels).

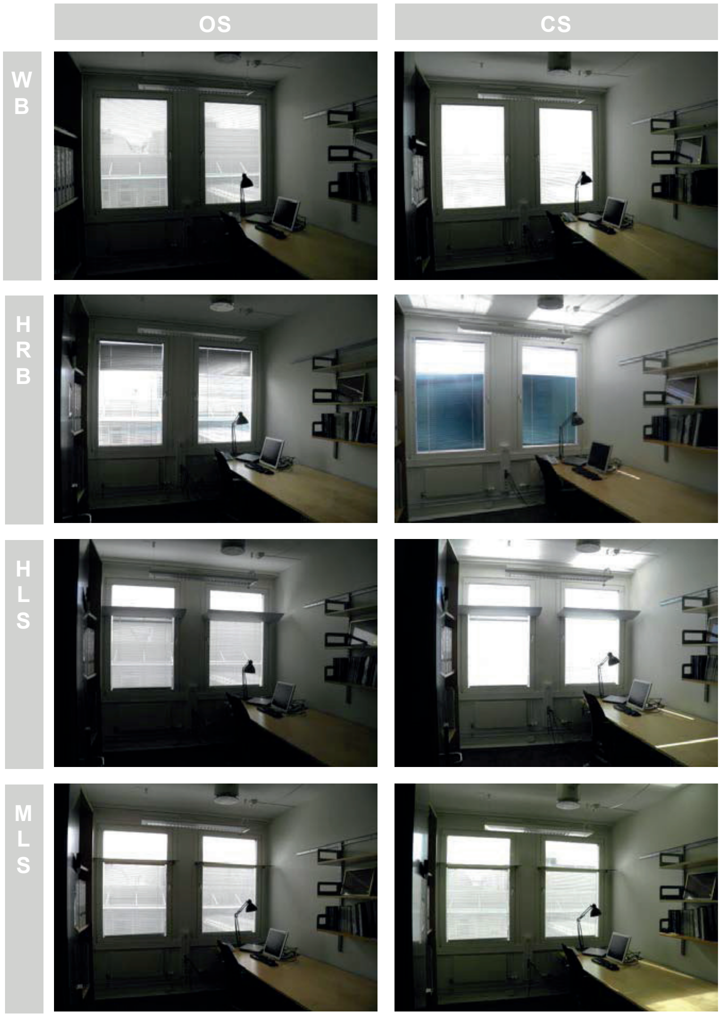

Figure 4 – Pictures of the eight different stimuli for experiment 2

Table 1 – Luminance values taken at nine different points of the room in experiment 2 (u=cd/m^2)

D. SYSTEM	SKY TYPE	1	2	3	4	5	6	7	8	9	MEAN
WB	OS	34	30	123	317	25	44	11	11	17	68,00
	CS	101	168	653	854	148	64	98	21	75	242,44
HRB	OS	58	145	492	2600	42	199	34	44	95	412,11
	CS	1109	474	174	362	1897	278	431	33	357	568,33
HLS	OS	393	168	721	640	359	146	58	40	96	291,22
	CS	1641	890	4787	6017	6894	596	409	35	645	2434,89
MLS	OS	203	107	374	669	95	191	43	37	74	199,22
	CS	958	792	4482	5883	684	461	359	38	109	1559,56

The stimuli were presented in 12 sessions. The experimental sessions were carried at the room laboratory of NTNU campus, during daytime. The stereoscopic pictures were projected on a silver screen in a randomized order for each session. The participants evaluated all the eight stimuli for a repeated measures analysis. Similarly to experiment 1, all the evaluations were done using a 7-step semantic differential scale for each assessed attribute. Thus, each participant received 8 different questionnaires (one for each stimulus), each containing nine scales, where they evaluated their immediate perception of the room. After each session, some participants willingly volunteered to have a debriefing qualitative interview with the researcher.

3.2.2 Results

Results from a two-way repeated measures MANOVA analysis suggested that both the daylighting system $F(27,23)=9{,}88$; $p<0{,}05$; Wilk's $\lambda = 0{,}079$; partial $\eta^2 = 0{,}92$ and the sky type $F(9,41)=22{,}73$; $p<0{,}05$; Wilk's $\lambda = 0{,}167$; partial $\eta^2 = 0{,}83$ had an effect on the evaluation of the aesthetic attributes. Additionally, the interaction was also significant $F(27,23)=3{,}04$; $p<0{,}05$; Wilk's $\lambda = 0{,}219$; partial $\eta^2 = 0{,}78$, suggesting that the effect of the sky type depended on the daylighting system or vice versa.

Further statistical results using univariate analyses were performed; for the complete overview of the numerical results please refer to (Moscoso and Matusiak, 2015). An experiment-wise alpha rate of 0,05 was used. Hence, the new alpha level considered was $p < 0{,}006$. The statistical results suggested that the daylighting system and the sky type separately had an effect on most of the nine studied attributes. The two remaining attributes, i.e. Order $F(3,147) = 0{,}93$; $p = 0{,}43$ for daylighting system and $F(1,49) = 0{,}16$; $p = 0{,}70$ for sky type, and Openness $F(3,147) = 1{,}62$; $p = 0{,}19$ for daylighting system and $F(1,49) = 1{,}00$; $p = 0{,}32$ for sky type, were not affected by any of the independent variables. The interaction between the daylighting systems and the sky types was statistically significant for six of the studied attributes. The attributes Order $F(3,147) = 1{,}23$; $p = 0{,}30$; Complexity $F(2{,}67;130{,}44) = 4{,}35$; $p = 0{,}008$ and Spaciousness $F(3,147) = 3{,}40$; $p = 0{,}02$ found not statistical support to claim that they were affected by the interaction of the daylighting system and the sky type. In addition, the estimated marginal means of each variable were analysed. In order to simplify the interpretation of the results, a classification over which daylighting system was preferred under the different sky types is presented in Table 2.

Moreover, extra information was gathered from the qualitative interviews. The participants' comments and responses indicated two possible causes of the preference of the HRB over the other daylighting systems under clear sky. It was indicated that *i.* The presence of light patches on the desk was not a favoured characteristic for a working environment. These desk light patches are present in the HLS-CS and MLS-CS. Although there is a light patch in HRB-CS, its area does not seem to be of unpleasant proportions; and *ii.* The physical characteristics of the light shelves (i.e. the large dimensions) were considered "heavy" and aesthetically uncomfortable, especially for the HLS. Similarly, two main causes were orally given by the participants for the preference of HRB under overcast sky conditions. It was indicated that *i.* The distribution of the light on the working area of the desk was considered best in comparison to the other daylighting systems, and *ii.* The possibility of having view out, rated most available with the HRB.

Table 2 – Preferred daylighting systems for the positive evaluations of the nine aesthetic attributes in experiment 2

ATTRIBUTE	CS	OS
Pleasantness	HRB	HRB
Excitement	HRB	HRB
Order *	HRB	WB
Complexity **	HLS	HRB
Legibility	HRB	MLS
Coherence	HRB	HRB
Spaciousness **	HRB	HRB
Openness ***	MLS	HRB
Spatial Definition	HRB	HRB

NOTES * Order was affected by neither the factors nor the interaction. ** Complexity and Spaciousness were not affected by the interaction of the factors. *** Openness had an effect only from the interaction of the factors.

4 General discussion

The collective findings of this paper seem to illustrate that different parameters not connected with photometric measurements, influence the aesthetic perception of a small room.

In experiment 1, the window size played an important role in the perception and aesthetic evaluation of the studied room. Moreover, it had a bigger effect than the room reflectance. The experimenter made an a priori assumption that the black room would achieve lower ratings than the white room. Although this was generally the case (the WR was rated higher than the BR), and as discussed in section 3.1.2, for the attributes, Excitement, Spaciousness and Openness, the BR with the large window obtained higher scores than the WR with small window. This reinforces the notion that the window size is preferred over the room reflectance. Whether due to the availability of view out or due to the daylight flux entering through the windows, the results show that large window sizes (i.e in the scope of the study, around 40 % of the window wall) are a preferred parameter for a positive aesthetic perception. Previous studies about large window preferences are supported by these new findings (Inui and Miyata, 1973, Keighley, 1973).

In experiment 2, and similar to experiment 1, the experimenter made an a priori assumption that, since the solar glare was controlled by blinds in the lower part of the windows, high daylight levels would obtain the highest positive ratings for each attribute. Luminance measurements showed that both light shelves were the daylighting systems that produced high daylight levels (i.e. HLS – CS M_{lum}: 2434 cd/m^2 and MLS-CS M_{lum}: 1559 cd/m^2). However, it was the HRB and not the light shelves that ranked higher in the majority of the attributes. As discussed in section 3.2.2, some possible reasons were given by the participants in the following interview after the experiment. Most of their comments were not directly related to photometric measurements, e.g. the physical characteristics of the daylighting systems, the presence of disturbing light patches and the possibility of the view outside.

Moreover, it becomes necessary to comment further about the aesthetic attributes. For the majority of the attributes, interesting results are found in experiment 1. There were no significant interaction effects. Despite of the well-known strong relation between the amount of daylight entering through a window and the reflectance of a room, it appears as luminance as such is not always an accurate predictor of the visual evaluations of certain aesthetic attributes.

The attribute Order was only affected by the factor room reflectance in experiment 1. Neither the factor window size nor the interaction between the factors had an effect on Order. In experiment 2, neither one factor nor the interaction of factors affected this attribute. The definition given to the participants (see section 2) for this particular attribute was related to the fixed stimuli in all the scenes. The furniture configuration in both experiments was not varied and thus, the arrangements for a student room in experiment 1 and an office in experiment 2 were kept constant. This could explain why neither of the independent factors affected the ratings of Order. The rooms were always suitably arranged for a student room and an office.

Finally, it becomes clear that windows and daylighting systems affect the Pleasantness and Legibility of a room and that in addition, those two factors depend on the room reflectance and sky type respectively. This is important in terms of people’s acceptance about the quality of the room they are judging. Following the notion of Kaplan’s theory (Kaplan, 1987), the legibility of an environment is crucial for humans to understand and make sense of a situation that can benefit their survival. Additionally, the pleasantness of an environment has been identified as preferred by people in general independently of education or emotional experiences (Cold et al., 1998). Thus, it can be argued that these two quality attributes are necessary for a satisfactory environmental experience. Living in an environment judged as having high quality can affect humans’ mental and socioemotional health (Evans et al., 2000, Evans et al., 2001, Gifford and Lacombe, 2006). Hence, one must wonder: is it not important to include aesthetic judgements in the evaluation of a lit environment? The results of both experiments seem to answer this question in a positive manner.

5 Conclusion

Two concluding remarks can be made. First, results from both experiments indicate that daylight (delivered by windows and/or daylighting systems) affects the aesthetic perception of a built environment. Second, lighting measurements alone cannot necessarily predict the aesthetic qualities of a room. The results of both experiments analysed together open a new discussion about the influence of non-photometric factors in the quality evaluation of lit environments. Although lighting metrics are necessary, other factors, such as the ones discussed in section 4, should be studied deeper when evaluating the aesthetic quality of a lit architectural space. This new information hopes to serve as guideline and shed a new light about the importance of the aesthetic quality of a built environment in relation to lighting.

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5.2 Main conclusions

The main purpose of the present research was focused on shedding new light on aesthetics judgements related to daylighting research.

On one hand, environmental aesthetics is a field of research closely linked to environmental psychology. In Section 2.2.2, the importance of aesthetic judgements for environmental evaluations was addressed. Aesthetic impressions are intrinsic to the visual totality of a space. Researchers, usually within the environmental psychology field, acknowledge environmental aesthetics as generators of feelings of health and well-being (Cold et al., 1998, Nasar, 2000, Evans et al., 2000, Evans et al., 2001, Noschis, 2001). Many factors can alter the aesthetic judgement of a room, such as the lighting conditions present in the room.

On the other hand, daylighting research is another field of research closely linked to, but not limited to, architecture and building physics. In Sections 2.3 and 2.4, discussions about daylight and its crucial role in built environments have been given. Furthermore, the main focus of photometric outcomes in lighting and daylighting studies, and on building performance indicators in building physics studies has also been discussed.

In the author's opinion, there is no doubt that both fields are equally relevant for the understanding of the indoor environment and its effect on humans. However, the literature reveals a limited area of knowledge in interdisciplinary studies considering both aesthetic judgements and daylighting studies (see Section 2.5). There is still little that we know about how daylight affects the aesthetic impression of a room.

Thus, the main goal was to investigate the effect that basic and advanced daylighting design (i.e. windows and selected daylighting systems) have on the aesthetic judgements of a small indoor environment. As given in Section 1.2.2, the main research question was:

How does daylighting design affect the aesthetic impression of a built environment?

Three sub-questions were derived from the main research question:

1. *To what extent does window size affect the aesthetic judgements of a small room?*
2. *To what extent do different daylighting systems affect the aesthetic judgements of a small room?*

3. *Within the scope of research, which daylighting system is preferred for eliciting positive aesthetic judgements of a small room?*

Two experiments were performed to answer these questions. From the main findings presented in this dissertation, the overall conclusions related to these research questions are given below.

Moreover, an additional question arose as the result of a methodological concern (see Sections 1.2.2 and 3.1):

Can stereoscopic imaging be considered an accurate experimental method in comparison to experiments in real environments when used in aesthetic and daylighting studies?

A pilot study and a main experiment were conducted to answer the question with a methodological aim. From the work presented in Chapter 3, the answer to the methodological question and the conclusions below are drawn.

5.2.1 Experimental method – conclusions

The results of the experimental method evaluation presented in Chapter 3 lead to the following main general conclusion:

- Stereoscopic images are suggested to be an accurate experimental method, which may be used as an alternative to full-size real environments experiments for selected aesthetic attributes under particular daylighting conditions.

Consequently, detailed conclusions can be classified into two analyses: *measurement validity* (i.e. which attributes are suitable to be studied with stereoscopic images), and *measurement accuracy* (i.e. how different numerical outcomes from stereoscopic imaging are from real environments experiments). The following conclusions are drawn in relation to the set of attributes studied in the present PhD project. Therefore:

On *measurement validity*:

- From the nine studied attributes, the aesthetic attributes suitable to be studied in rooms with high reflectance surfaces are: Pleasantness, Excitement, Order, Complexity, Legibility, Coherence, Spaciousness, Openness, and Spatial Definition.

- From the nine studied attributes, the aesthetic attributes suitable to be studied in rooms with low reflectance surfaces are: Pleasantness, Excitement, Order, Complexity, Legibility, Coherence, and Openness.

- The attributes Spaciousness and Openness did not get enough statistical support to claim that they deliver similar results in both experimental methods; therefore, they cannot be studied with the stereoscopic images method in rooms with low reflectance surfaces.

On *measurement accuracy*:

- From the nine studied attributes, the attributes that measure slightly higher scores in the stereoscopic images than in the real environments are: Pleasantness, Excitement, Legibility, Coherence, Spaciousness, and Openness in rooms with high reflectance surfaces; and Pleasantness, Excitement, and Legibility in rooms with low reflectance surfaces.

- From the nine studied attributes, the only attribute that measures slightly lower scores in the stereoscopic images than in the real environments is Order in rooms with high reflectance surfaces. The attributes that measure slightly lower scores in the stereoscopic images than in the real environments in rooms with low reflectance surfaces are: Order, Complexity, and Coherence.

- The attributes Complexity and Spatial Definition seem to give equal results with the stereoscopic images method as with real environments experiments.

5.2.2 Daylighting design and aesthetic judgements - conclusions

The findings, outcomes of the two experimental procedures presented in Chapter 4, lead to the following main general conclusion:

- Daylighting (within the scope of the present research, i.e. daylight delivered by windows and/or daylighting systems) has a significant impact on the aesthetic impression of a small room.

The results are in accordance with Veitch (1998, 2001) and Veitch and Galasiu (2012), in which the aesthetic judgements are integrated with lighting quality, and are considered more than theoretical interest. This means that the experimental testing of the effect of light on aesthetic judgements grants a deeper understanding of their relation, and can allow us to identify human preferences and to test new hypotheses about information processing in lit environments (Veitch, 2001).

More detailed conclusions are drawn based on both the quantitative and qualitative methods used, which are explained in Section 1.3.2. The following conclusions answer at a profound level the first main research question and the three specific sub-questions previously postulated (see Sections 1.3.2 and 5.2). The conclusions are structured according to the daylight deliverer; i.e. windows and daylighting systems.

On *window size*:

- Window size has an effect on the judgement of the attributes: Pleasantness, Excitement, Complexity, Legibility, Coherence, Spaciousness, Openness, and Spatial Definition.

- Only the attribute Order was not affected by the window size.

- The aesthetic attributes were ranked higher as the window size increased. This means that e.g. the level of pleasantness was highest with the large window and decreased with the size of the window.

- For the evaluation of the attributes Excitement, Spaciousness, and Openness, window size appears to be a more important parameter than the room reflectance. In the scope of the study, black walls were expected to be rated lower than white walls; yet, for the three mentioned attributes, the window size appears to overcome the expected negative effect that black walls could provide. This means that e.g. despite the common conception that light coloured walls increase the perception of spaciousness of a room, the result suggests that a large window size (in the scope of the research: width = 2.00 m, height = 1.50 m) is more important than reflectance as a criterion for evaluating spaciousness. As stated in paper III, this interpretation would be similar to the results obtained by Inui and Miyata (1973, 1977) , whose findings revealed that window size is one of the most important predictors to judge spaciousness. Likewise, the results seem to be in accordance with Keighley (1973b), who discussed that the window height preference lies between 1,8 and 2,4m; and with other similar research conducted also by Keighley (1973a), in which was discussed that although this preference is less decisive in windows with obstructed views, windows should be nevertheless, of a basic horizontal shape. Additionally, the preference over the larger windows of the experiment appear to be in accordance with Cuttle (1983), who noted that *'the larger the windows are, the more desirable they are perceived to be'*.

On *daylighting systems*:

- Within the scope of research (i.e. among the four studied daylighting systems), the most preferred daylighting system that provoked high positive rankings in the majority of the aesthetic attributes in a small office is the High Reflecting Blinds System. This was the case for the attributes: Pleasantness, Excitement, Coherence, Spaciousness and Spatial Definition in both sky types.

- The High Reflecting Blinds were also preferred for the attributes Complexity and Openness under overcast sky conditions and for the attribute Legibility under clear sky conditions.

- The Hybrid Light Shelf was the preferred daylighting system for the evaluation of the attribute Complexity under clear sky conditions.

- The Mirror Light Shelf was the preferred daylighting system for the evaluation of the attribute Legibility in overcast sky conditions and Openness under clear sky conditions.

- In general, the studied daylighting systems have an impact on the judgements of the aesthetic attributes: Pleasantness, Excitement, Complexity, Legibility, Coherence, Spaciousness, and Spatial Definition.

- Conversely, daylighting systems do not have an effect on the evaluation of the attributes: Order and Openness.

- Openness, however, is influenced by the interaction of daylighting systems and sky type. This means that the performance of a certain daylighting system under a specific sky type does have an effect on the evaluation of Openness. According to the graphical plots (see Section 4.2 - Paper IV: Figure 6), both studied blinds (i.e. white blinds and high reflecting blinds) were preferred under overcast sky conditions, and both studied light shelves (i.e. mirror light shelf and hybrid light shelf) were preferred under clear sky conditions.

Moreover, the summarised results of both experimental studies performed under the present PhD period, suggest that photometric measurements are not always the perfect predictors to judge certain aesthetic attributes. These results agree with Fontoynont (2002), who discussed the difficulty in evaluating the performance of daylighting systems based only on lighting numerical performance and glare control. He claimed that performance evaluations of daylighting systems should not dismiss subjective criteria, such as: *how aesthetically are the physical components of a system (e.g. blind, glass material)?, how pleasant is the quality of the view?*, and *how agreeable are the light patterns indoor (e.g. light distribution, reflections)?*. Similarly, the results agree with Wang and Boubekri (2011), who discussed that daylight guidelines need to change, and not only emphasise indoor daylight by means of illuminances or daylight factors, but also include human factors as important design criteria together with photometrical variables.

For example, despite the strong relation between window size and room reflectance in the first study (see Section 4.1), the statistical results did not show any significant interaction effect on the evaluations of the majority of the attributes. This means that for the aesthetic judgements, window size and room reflectance acted as independent factors and their interaction (light being emitted from a surface, i.e. luminance) was not considered by the study observers. This interpretation is confirmed by analysing the attributes Excitement, Spaciousness, and Openness, in which rooms with lower luminance levels obtained higher scores than rooms with higher luminance levels. Further statistical analyses in the study of these three specific attributes (i.e. Excitement, Spaciousness, and Openness) can help the interpretation of these results. Moreover, the results regarding the impact of window size on spaciousness and openness, agree with the statement that windows make an environment appear more spacious and reduce the feeling of enclosure (Veitch and Galasiu, 2012). Furthermore, the preference over the large windows could be explained by the '*prospect and refuge theory*' and the '*permeability theory*' (see Section 2.2.1). The large windows contributed to the feeling of spaciousness of the environment, this at the same time, provides a safe distance between an observer and any possible danger. Likewise, the openness relates to the permeable boundaries of an environment, in which the large windows grant the possibility of visual evaluation of the world.

Results from the second study confirm the need to see beyond photometric guidelines only. The analyses between the preferred scenes and the photometric monitoring of each scene indicate that a higher light level is not always the preferred condition for a positive aesthetic evaluation (see Section 4.2 – Paper IV: Discussion). This could be related to the psychological link to glare and overheating suggested by Roche et al. (2001), which research indicated a lower preference of high levels of daylighting compared to low levels of daylighting. The light distribution in the working area, light patches, physical and geometrical characteristics of the systems and the availability of view to the outside were criteria highly used by the observers of the second experiment to carry out their aesthetic evaluations.

Finally, the author as an architect herself understands the architectural profession, in which opposing design criteria usually appears in architectural design. On one hand, architects are aware of the power that architecture has on the stimulation of the human's senses and feelings (Pallasmaa, 2005, Zumthor, 2006). On the other hand, the architectural design is often based on previous experiences and/or national design requirements for designing with daylight, in order to achieve a minimum daylight factor or a minimum glazing area. However, as it has been discussed throughout the present dissertation, the aesthetics of a lit environment is influenced by factors beyond photometric guidelines, making necessary to include a more human oriented approach to the quantitative focus.

These results shed new light on different areas of focus of daylighting studies, such as the aesthetics of a lit environment. A better understanding of daylighting design and its effect on environmental aesthetics has the potential to help architects to develop new measures to be implemented in successful architectural design solutions using daylighting. Yet, in the author's opinion, daylighting in relation to environmental aesthetics is still a thin body of knowledge; and although the presented results seek to contribute to a discussion on aesthetic perception of lit environments, they should not be understood as a final and complete set of guidelines, as there is still much that we do not know. The presented results sought to provide new knowledge that can serve as a departure point for the development of new theories and assumptions in order to understand more of this interdisciplinary topic.

5.3 Recommendations for future research

The presented work has been based on experimental and simulation research. Although stereoscopic imaging as a simulation method was tested and validated, it is clearly not the only simulation method available for experimental studies. However, there is not enough research on the validation of simulation research. Other types of technologies, e.g. passive and active stereoscopic viewer technologies can be tested to prove their validity as research methods. Furthermore, new technologies such as 3D scanners, which seem to provide versatility in changes of visual conditions of environments (e.g. a scanned image of a built environment can be modified by changing the colour of the wall surfaces), can also be of interest to researchers eager to facilitate experimental studies.

In relation to daylighting research, it is important to note that the proposed stereoscopic image method presents limitations. For example, in terms of photometric measurements, the stereoscopic images do not match the luminances measured in the real rooms. Thus, a logic continuation is to conduct further studies by matching the luminances of a real room with the stereoscopic images. A natural research inquiry would be whether the accuracy of the stereoscopic images increases by matching the real luminances with the represented luminances in the images.

The stereoscopic images were tested using environments presenting two achromatic colours: white and black. Although chromatic colours displaying similar reflectance properties (i.e. equiluminant colours) as the ones used in the first study could be used, it would be interesting to test the validity of stereoscopic images in studies with a range of other chromatic colours commonly used on wall surfaces (e.g. blue, green, red, yellow).

Regarding the aesthetic and daylighting studies, it would be interesting to study how important aesthetics judgements are in the evaluation of the visual totality of a room. Specifically, it would be interesting to perform a comparison study where the aesthetic judgements can be measured in relation to other lighting quality indicators to see what proportion of satisfaction of the overall environment they represent. Moreover, in the author's opinion, aesthetic judgements should be incorporated in daylighting studies aimed at providing recommendations for lighting quality.

Both studies have dealt with a limited sample group of independent factors (i.e. three different window sizes and two types of daylighting systems). Naturally, other daylighting systems should also be studied. In addition, a wider range of window sizes should be considered for future studies. Although the presented results show that, for example, larger windows produce a higher level of pleasantness, it is logical to assume that there must be a threshold for the feeling of pleasantness related to window size. Considering that humans also tend to seek privacy in certain environments, one could argue that larger window areas (i.e. larger than the ones studied in the presented work) could diminish the privacy level and thus reduce the aesthetic satisfaction of an indoor environment.

Finally, although the results with overcast sky conditions can be extendable to other parts of the world, the results with clear sky conditions should be compared to other latitudes, seasons and climate conditions where there is a significant difference in solar elevation angles from northern Europe, where this work has been carried out.

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GLOSSARY

Achromatic colours Colours with no chroma, e.g. black, white, and gradations of grey.

Aesthetics Different definitions of aesthetics are available according to the background of each researcher. Yet, within environmental psychology studies, the definition that prevails in research is the one simplified as: *'the knowledge which derives through the senses of things perceivable'* (Cold et. al., 1998).

Brightness Describes the perceived light reflected from an object.

Chroma Defines the purity of a hue and describes a colour hue's strength.

Circadian Rhythm Biological process that operates in a 24 hour cycle, and is affected by light via the intrinsically photoreceptive retinal ganglion cells (ipRGCs) located in the human retina. The circadian rhythm dominates e.g. light and dark patterns, sleep and wake cycle, body temperature, and hormone production.

Clear sky The standard clear sky present variations of luminance over altitude and azimuth. The area around the sun holds the highest luminance, whereas the opposite area (about 90° from the sun, at the other side of zenith) appears dimmest. The horizon luminance is higher than the luminance of the zenith (Aschehoug & Arnesen, 1998)

Coherence* Refers to an aesthetic attribute characterised as present in a scene that is perceived as having a logical connection or a structured consistency with its function.

Complexity* Aesthetic attribute referring to a scene that is visually rich with a large amount of distinctive different elements.

Daylight Factor According to the CIE definition, the daylight factor (D) is the *'ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed* *hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded.'*

Dependent variable In an experiment that uses statistics to analyse the results, the dependent variable refers to the variable used to observe an effect, or to prove if it is the effect.

Excitement* Aesthetic attribute referring to a scene that elicits or provokes active and positive emotional conditions.

Glare Visual conditions in which there is excessive contrast or an inappropriate distribution of light sources that disturbs the observer or limits the ability to distinguish details and object (CIE, 2002).

Illuminance Describes the amount of light falling on a surface, it relates to the luminous flux incident on a specific area.

Independent variable In an experiment that uses statistics to analyse the results, the independent variable refers to an altered input to test if it is the cause. It indicates what it is changed by the experimenter.

Legibility* Aesthetic attribute referring to a scene that is legible, where all its elements can be 'read', and thus is easy to find the way around the scene.

Light In the present dissertation, light refers to the part of the electromagnetic spectrum that elicits a human visual response (i.e. it is visible to the human eye). The visible range of the electromagnetic spectrum stretches from 380 nm to 760 nm; thus, wavelengths below the 380 nm are refer as ultraviolet rays, and wavelengths above the 760 nm are refer as infrared rays. Despite differences encountered in research among disciplines, the present work does not make use of the concept *invisible light* to refer ultraviolet and infrared rays.

Luminance Describes the amount of light emitted from a particular surface area. It relates to the luminous intensity falling on a projected square metre.

Mesopic vision	Vision in which both rods and cones are active; between scotopic and photopic vision. The mesopic luminance range is from 0.001 to 3 cd/m^2 (Valberg, 2005).
Openness*	Aesthetic attribute referring to a scene presenting open views; allowing access or view free from obstruction.
Order*	Aesthetic attribute referring to a scene arranged methodically or suitably, absent of chaos or uniform style.
Overcast sky	Sky with altitudinal asymmetry, covered by clouds with no visible sun. According to the definition of the CIE overcast sky model, the luminance of the zenith is three times greater than the luminance of the horizon.
Perceived light	Describes the brightness appearance of a surface, i.e. how bright or dark a surface is judged to be.
Photopic vision	Referred as vision where cones are active, and rods do not contribute to vision. The photopic vision operates with luminances above 3 cd/m^2 (Valberg, 2005).
Pleasantness*	Aesthetic attribute that relates to a scene that gives pleasure, delight or satisfaction; e.g. an agreeable, nice, and/or enjoyable scene.
Quality	Subjective term which definition varies depending on a person's background and the field where it is used, i.e. the concept of quality differs if it is used in the business or the physics field. Due to the nature of this dissertation, the term quality is described from a philosophical point of view. Quality is not limited to the common description of a general excellent standard of something, but in a broader term, it refers to a *distinctive attribute or characteristic possessed by something* (OED, 2015). This means that both positive and negative connotations are possible when using the term quality, e.g. 'an obsessive quality'. Thus, quality is related to how things are perceived by humans, whether the perception is positive or negative. Due to its intangible nature, quality in the social science is considered a construct; which can be better understood by establishing measurement rules (Veitch & Newsham, 1998).

Reflectance Describes the ratio of incident luminous flux that is reflected from a surface.

Scotopic vision Vision occurring in dark conditions, where just rods are active. Scotopic vision operates in luminances below 0.001 cd/m^2 (Valberg, 2005).

Silver Screen Type of projection screen with a highly reflective surface. The screens are embedded of silver or reflective aluminium, making them suitable for polarised 3D projection. This happens because, unlike other types of projection screens, silver screens reflect more light back avoiding the attenuation of brightness when using polarised glasses.

Spaciousness* Aesthetic attribute referring to a room that is considered spacious, wide, or commodious; or that it possesses extensiveness of area or dimensions.

Spatial Definition* Aesthetic attribute which refers to a room that can be seen with its bounds or physical limits (i.e. floor, walls, and ceiling.)

Stereoscopic vision Refers to the perception of depth or 3-dimensional perception, based on binocular vision (i.e. a person who uses two eyes to see).

Transmission According to the CIE, it refers to the radiation that passes through a medium without changing its frequency or its monochromatic components.

Well-being In environmental aesthetics research, well-being refers to the people's preferences for places, to the healing effect of natural elements in stressful situations, and to the preferences for a stimulation balance in a built environment (Cold et. al., 1998).

** Note: The aesthetic attributes used in the present dissertation are presented with their operational definitions. Such definitions were based on the research analysed, i.e. the understanding of the concepts provided by (Kaplan, 1987, Nasar, 2000, Stamps, 2004).*

APPENDIX A

NTNU - Norwegian University of Science and Technology

Faculty of Architecture and Fine Art

Department of Architectural Design, Form and Colour Studies

Visual Evaluation of Daylighting Systems in an Office

Method: Semantic Differential Scale + Questions and Descriptions

Date and Time: ____/____/____ Start: ____:____ End: ____:____

Daylighting System: OS - WB

Participant Information

Name or Initials: ______________________________

Gender: Male____ Female____

Age: ________

Profession / Occupation: ______________________________

** Remember that the participant is not going to be evaluated, the quality of the room is. Answer the questions in the order they are given. Please put only one tick on the scale.

1 THE ROOM IN GENERAL

Describe in your own words your spontaneous perception of the room's character and atmosphere:

Mark your impression at the diagram:

Stimulating ——————|—————— Relaxing

Negative ——————|—————— Positive

Page 1 of 3

1 Pleasantness: The quality of being pleasant. Pleasant: That gives pleasure, delight, or satisfaction. Now chiefly in weakened sense: agreeable, nice; quite enjoyable. (E.g. you think that the room is enjoyable).

Unpleasant Pleasant

2 Excitement: To induce, elicit, provoke (actions, manifestations); to bring about, occasion (active conditions). (E.g. The room feels exciting and provokes in you a good and active state of mind).

Dull Exciting

3 Order: To place in order, give order to; to arrange in a particular order; to arrange methodically or suitably. (E.g. you think that the room is well organized).

Chaotic Ordered

4 Complexity: The quality or condition of being complex. Complex: A whole comprehending in its compass a ***number of parts***, ***of interconnected parts*** or involved particulars; a complex whole. (E.g. you think that the room is visually rich with a large amount of distinctive different elements)

Simple Complex

5 Legibility: The quality of being legible. Legible: That can be "read". (E.g. It is easy for you to see the corners, room details, etc.)

Illegible Legible

6 Coherence: Logical connection or relation; congruity, consistency. (E.g. you think the room feels as an office or has a connection with its function of an office).

Incoherent Coherent

7 Spaciousness: The state or quality of being spacious, wide, or commodious; extensiveness of area or dimensions; roominess. (E.g. you think that the room is spacious).

Tight Spacious

8 Openness: The quality or condition of being open. Open: Not closed or blocked up: allowing access or view, free from obstruction. (E.g. you seem that the room has enough openings)

Closed Open

9 Spatial Definition: The setting of bounds or limits; limitation, restriction. (E.g. you think that the room is well spatially defined, you can see where the walls start and end, etc).

Undefined Defined

Comments:

APPENDIX B

NTNU - Norwegian University of Science and Technology

Faculty of Architecture and Fine Art

Department of Architectural Design, Form and Colour Studies

Visual Evaluation of Daylighting Systems in an Office

Following Interview

Method: In-depth & Open-Ended Questions (To be answered orally)

Date and Time: ____/____/____ ____:____

Participant Information

Name or Symbol: ________________________________

Gender: Male____ Female____

Age: ________

Profession / Occupation: ________________________________

INTERACTION BETWEEN MAN, OBJECT AND ROOM

1. Did you feel any discomfort when evaluating the 3D pictures? Were you comfortable during the session?

2. What was your overall perception of the room(s)?

3. Which characteristic of the room would you say it was responsible for your general perception? Define/describe different scenarios if possible.

4. What would you change in the room to make it:
    a. More pleasant? Less pleasant?
    b. More legible? Less legible?
    c. More open? Less open?
    d. More exciting? Less exciting?
    e. More spacious? Less spacious?
    f. ...

5. Do you want to add something more about the rooms? Something that you haven't been asked?

1