Perceptual effects of daylight patterns in architecture

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Abstract

The profound impact of daylight on occupants is broadly recognized in the fields of architecture and lighting. In particular, the façade and its interplay with light is a central design element, while the diversity of daylight in space is widely acknowledged as a source of interest and stimulation that enriches our spatial experience. However, little is known about how the façade geometry and the resulting daylight patterns affect occupants. Moreover, we have limited knowledge on the impact of space function and of regional differences on human perception.

This thesis investigates the effect of façade and daylight patterns on human responses, while simultaneously examining the impact of space function and regional differences on these responses. The literature suggests two important challenges in current experimental methods in lighting research that might be contributing to the aforementioned knowledge gaps: the changing daylight conditions, which create an unstable variable, and the use of rating scales as the sole method of data collection. To address these challenges, this work introduces two main methodological contributions: the use of immersive virtual reality (VR) as an experimental tool, and the collection of physiological data as a complementary measure to rating scales. Specifically, a novel experimental method that combines VR with physically-based scenes was developed and tested against real environments in experiments that examined its adequacy regarding the perception, presence, and physical symptoms of participants.

Following the positive findings for the adequacy of this method, VR was employed in a series of experimental studies that investigated human responses to façade and daylight patterns, and laid the foundation for a wider study that was replicated in Switzerland and Greece. In all studies, each participant was immersed in a daylit interior space with varying façade configurations of a constant aperture ratio, and the impact of façade geometry, sky type, and spatial context on participant responses was examined in different experimental designs.

The outcomes of this work revealed that the façade and daylight patterns impacted both the subjective and physiological responses of participants. In particular, façade and daylight patterns consistently influenced the spatial experience, such as how pleasant, interesting, exciting, calming, and complex the space was perceived. The façade geometry also impacted spatial attributes that are traditionally considered objective, such as the perceived brightness, spaciousness, and satisfaction with the amount of view in the space. Moreover, the presented façade and daylight patterns significantly affected the participants‘ heart rate, demonstrating in a VR setting that façade elements and their interaction with light can have quantifiable effects on occupants.

The perceptual effects of façade geometry were shown to be robust to changes in the sky type, as well as the function, type, and window size of the space. In addition, no differences were found between the responses of participants in Switzerland and Greece, revealing the generalizability of these design-driven perceptual effects across latitudes in Europe. The findings of this thesis demonstrate the importance of façade design as a powerful driver of the spatial experience, outlining new directions in the design of buildings that are not only comfortable and energy efficient, but also delightful for their occupants.

Keywords: daylight, façade, patterns, architecture, perception, physiological responses, virtual reality, visual interest, complexity.

Résumé

L'impact important de la lumière du jour sur les occupants est largement reconnu dans les domaines de l'architecture et de l'éclairage. La façade et son interaction avec la lumière sont des éléments centraux de la conception d'un bâtiment, et la diversité de la lumière du jour est reconnue comme une source d'intérêt qui enrichit notre expérience spatiale. Cependant, l'effet de la géométrie de façade et des motifs de lumière qui en résultent sur les occupants est peu connu. De plus, nous avons peu de connaissances sur l'impact de la fonction de l'espace et des différences entre régions géographiques sur la perception humaine.

Cette thèse s'intéresse à l'effet des motifs de façade et de lumière du jour sur la perception par l'human, tout en examinant l'impact de la fonction de l'espace et des différences entre régions sur ces réponses. La littérature suggère deux défis importants concernant les méthodes expérimentales actuelles qui pourraient contribuer aux lacunes des connaissances susmentionnées : les conditions changeantes de lumière du jour, qui créent une variable instable, et l'utilisation d'échelles d'évaluation comme unique méthode de collecte de données. Pour relever ces défis, ce travail introduit deux contributions méthodologiques : l'utilisation de la réalité virtuelle (RV) en tant qu'outil expérimental, et la collecte de données physiologiques en tant que mesure complémentaire aux échelles d'évaluation. Plus précisément, une nouvelle méthode expérimentale combinant la réalité virtuelle avec des rendus physiquement réalistes a été développée et testée en comparaison à des environnements réels.

Suite à ce travail, la RV a été utilisée dans une série d'expériences qui ont permis d'établir les bases d'une étude plus approfondie menée en Suisse et en Grèce. Dans ces études, chaque participant a été plongé dans un espace éclairé par la lumière du jour avec différentes configurations de façade à taux d'ouverture constant, et l'impact de la géométrie de façade, du type de ciel et du contexte spatial sur les réponses des participants a été examiné.

Les résultats de ces études ont révélé que les motifs de façade et de lumière du jour ont un impact significatif sur les réponses subjectives et physiologiques des participants. En particulier, ces motifs ont influencé systématiquement l'expérience spatiale, telle que la perception d'un espace comme agréable, intéressant, stimulant, apaisant et complexe, ainsi que la perception de la luminosité et la satisfaction avec la quantité de vue. De plus, les motifs de façade et de lumière du jour ont affecté la fréquence cardiaque des participants, ce qui démontre dans un environnement de réalité virtuelle que les éléments de façade et leur interaction avec la lumière peuvent avoir des effets quantifiables sur les occupants.

Les effets sur la perception induits par la façade se sont avérés robustes aux modifications du type de ciel, de la fonction et du type d'espace, ainsi que de la taille de fenêtre. En outre, aucune différence n'a été constatée entre les réponses des participants en Suisse et en Grèce, ce qui suggère la possibilité de généraliser ces résultats à différentes latitudes en Europe. Les résultats de cette thèse démontrent l'importance de la géométrie des façades comme facteur de l'expérience spatiale, offrant de nouvelles directions pour la conception de bâtiments non seulement confortables et économes en énergie, mais également agréables pour leurs occupants.

Mots clès : lumière du jour, façade, motifs, architecture, perception, rèponses physiologiques, rèalitè virtuelle, intérêt visuel, complexité.

Contents

Chapter 1

Introduction

Daylight has a profound impact on our experience of space. In the field of architecture, the interplay between light and space is often quoted as the driving force behind the conception of a building. Illustrating the central role of light in architecture, Corrodi and Spechtenhauser [2008] state that "the identity of a space is thus determined by its scale, the nature of its openings and the flow of light, and by the rhythm of light and shadow".

However, in the complex and multidisciplinary design process from the concept to the construction of a building, these sensory aspects of light and space are often overshadowed by current —and essential— concerns regarding energy performance and occupant comfort. In the subject of daylight, these concerns translate to task- and energy-based performance indicators which aim to create adequately illuminated spaces and reduce the use of electric lighting. This approach neglects the importance of creating spaces which do not only limit energy consumption and user discomfort, but also bring visual delight to their occupants.

Lighting research has repeatedly acknowledged the dichotomy between the appreciation of the interplay of space and daylight in architecture, and the lack of recommendations or guidelines regarding these design qualities [Pellegrino, 1999; Fontoynont, 2002; Steemers and Steane, 2012; Veitch and Galasiu, 2012]. This dichotomy is also criticized in the field of architecture, as it has a direct influence on the design priorities and the resulting experiential quality of built environments. On this subject, McCarter and Pallasmaa [2012] emphasize that "in today's architectural practice, light is regrettably often treated as a quantitative phenomenon".

As long as we have limited concrete evidence of how the space and light jointly influence occupant perception, the sensory aspects of light remain an abstract quality that cannot be quantified and thus become secondary in today's performance-driven design process. The present thesis aims to bridge this gap by broadening our understanding of how the architectural features in a space and their interplay with daylight can systematically affect its occupants. Drawing from the fields of architecture, lighting, environmental psychology, psychophysiology, and statistics, this thesis seeks to uncover the joint impact of façade and daylight characteristics on the way occupants experience space.

1.1 Context and background

1.1.1 Human-centric architecture

The importance of daylight is widely acknowledged in current design practices, as demonstrated in building standards and regulations, but this has not always been the case. While daylight was the primary building illumination strategy until the middle of the twentieth century, the development of electric incandescent and fluorescent lamps, and the subsequent emphasis on the utility and efficiency of electric light led to the questioning of the role of daylighting in architecture, a trend that was not abated until the oil crisis of 1973 [Boubekri, 2008].

The dismissive view of architecture towards natural lighting in the 1960s is reflected in this quote by Phillips [1964], in his book *Lighting in Architectural Design*: "It is inevitable that artificial light must become the primary light source where efficiency of vision is combined with an economic analysis of building function. Natural lighting is becoming a luxury". Phillips wonderfully criticizes his own words, showcasing the current shift of perspective in architectural design, in his book *Daylighting: Natural Light in Architecture* [2004], stating that "the fact that this was not deemed stupid at the time is a measure of how far down the road of the controlled environment life had become".

This narrow understanding of human needs is not without consequences for occupants. A well-known example of the negative effects of controlled indoor environments is the Sick Building Syndrome (SBS), where exposure to the indoor environment, particularly in office buildings, is related to symptoms of lethargy, headache, dry skin, and irritation of the eyes, nose, or throat [World Health Organization, 1983]. The World Health Organization estimated that SBS affected up to 30% of occupants in new, remodeled or renovated buildings in the 1980s. While psycho-social factors are suggested to play a role in SBS, indoor environmental factors, including lighting quality, are consistently reported to be contributing considerably to the symptoms of occupants [Redlich et al., 1997].

Another conflict between controlled indoor environments and humans, which will be discussed again in Section 7.2.2, is often manifested in the interaction between occupants and automated control systems. Building occupants have been shown to manually override up to 88% of automatic control actions that close the blinds [Reinhart and Voss, 2003] or even intentionally sabotage lighting control systems [Cunill et al., 2007].

These examples of severe misalignment between the intentions and the outcomes of building design in the present and not-so-distant past are important reminders of the responsibility that lies in the hands of researchers and professionals in the building sector.

Considering that wrong design choices in architecture and the built environment —such as restricting the access of occupants to fresh air and natural light— are directly affecting human well-being [Salingaros, 2014a], it is essential to learn from these examples and adopt a perspective that puts the occupant in the forefront. In the field of daylighting, this perspective encompasses not only energy- and comfort-driven targets, but also the emotional and physical well-being of building occupants [Andersen, 2015].

This approach is even more critical in the face of current environmental concerns. Today's threat of climate change and resource depletion, in which the building sector is an important contributor [Intergovernmental Panel on Climate Change (IPCC), 2019], necessitates the design and construction of buildings with a maximum lifespan that are both sustainable and satisfactory for their occupants. Lam and Ripman [1977], already several decades ago, bluntly asserted that "we can no longer afford to waste space and energy so lavishly to produce such pitiful, pitiless environments", a statement that is even more pertinent today.

The challenge, which is far from solved, lies in better understanding the needs of occupants and establishing what constitutes a satisfactory environment. While a multi-sensory approach, which addresses several indoor environmental parameters, is argued to be central for a deeper understanding of human responses to their surrounding environment [Chinazzo, 2019], crucial gaps in scientific knowledge exist even when considering a single human sense, such as vision.

1.1.2 Façade and daylight patterns in architecture

The needs of occupants for variation in the intensity and composition of light in a space is one such knowledge gap. In particular, the treatment of light in current architecture has been repeatedly criticized for a lack of diversity. Practices and regulations that limit access to direct sunlight in favor of illuminance uniformity are claimed to lead to a "monotone light landscape" [Köster, 2004], and have been argued to be unnecessarily strict for many spaces where occupants could benefit from the sensory stimulation offered by variation in the lighting conditions [Steemers and Steane, 2012]. In the same vein, architects advocate not only the presence of sunlight, but also the presence of shadows, and the creation of light patterns in a space: "our buildings tend to permit too much light and distribute it too evenly, weakening thus the sense of place and intimacy" [McCarter and Pallasmaa, 2012].

Similarly, Salingaros [1999] emphasizes the importance for visual diversity and the absence of these qualities in modernist architecture: "looking around at twentieth century buildings, one is hard-pressed to discover visual patterns". Contemporary architecture, however, shows an important change of perspective in the last decades, through what Corrodi and Spechtenhauser [2008] name the "new aesthetic of veiling". This aesthetic embraces the use of decorative patterns, semitransparent surfaces, multilayered façades, and permeated walls, which mediate the light that enters the space [Corrodi and Spechtenhauser, 2008].

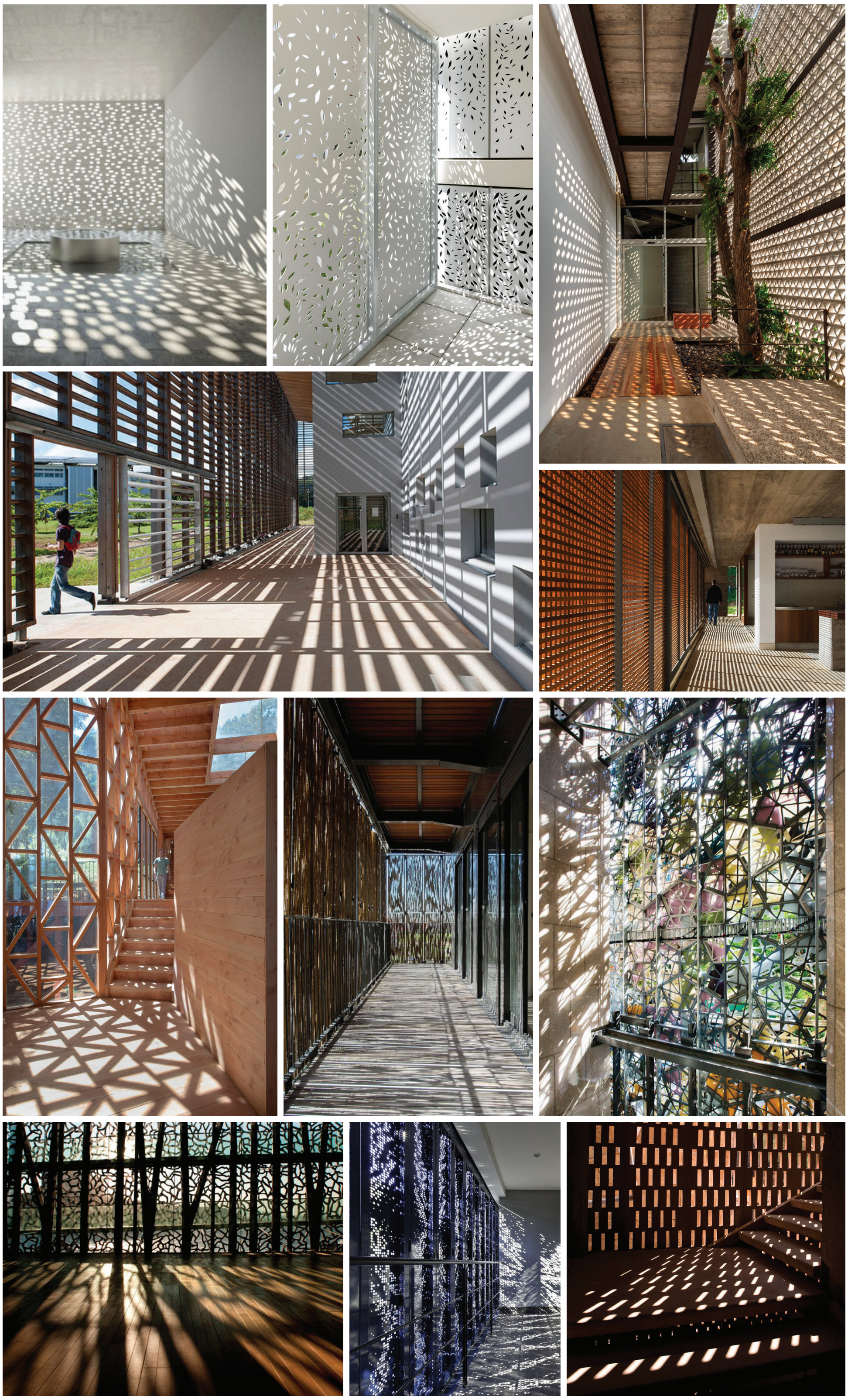

Figure 1.1 – Photographs of contemporary architectural works from the website *ArchDaily*, with common feature their emphasis on the use of light through patterned façade elements. Further details about these works can be found in the Appendix B.

These architectural elements and their interaction with light are a central part of the design, as reflected in the descriptions and photographs that are chosen to represent the buildings in printed and online publications. An example of these photographs, depicting contemporary works of architecture that are featured in the popular architecture website *ArchDaily*, can be found in Figure 1.1. A notable feature of these photographs is that the point of interest is not simply the façade design, but the interplay between the façade and the sunlight, which creates a variety of light patterns in the interior of the buildings. While one of the primary functions of the façade design, particularly from a clients' perspective, relates to how the building is perceived from the outside [Pastore and Andersen, 2019c], these photographs illustrate an occupants' point-of-view. Given the prominence and variety of these decorative façade elements in contemporary buildings, the emerging question is how these elements, and the resulting light patterns, are perceived by occupants.

The diversity of light in an interior space is inextricably linked to architectural elements that shape the way daylight enters the space. However, we are lacking systematic knowledge about the impact of the façade openings and of the resulting light distribution on occupants. Pallasmaa [2011] talks about "our shared pleasure in being in the shadow of large trees", arguing that specific visual features of the built environment can induce emotional responses linked to human evolution, in line with the biophilia hypothesis and theories in environmental psychology that will be discussed in Section 2.2.2. Can different geometric characteristics of the façade and the light patterns in a space alter an occupant's spatial experience? Can they affect an occupants' physiological responses? To answer these questions, it is necessary to establish a "science of architecture", as advocated by Salingaros [2016], and examine the joint effect of architecture and daylight on humans.

1.2 Research scope

This section will outline the present thesis through an overview of the research problem, objectives, and approach in this work.

1.2.1 Problem statement

In the field of architecture, the diversity of daylight has been widely recognized to have a profound impact on the way occupants experience space. In the same vein, lighting research has repeatedly linked luminance variation with the creation of visual interest. While most lighting design recommendations and metrics tend to restrict direct sunlight penetration in order to avoid glare or overheating, this trend has been criticized, and recent regulations acknowledge the occupants' need for sunlight access. In parallel, contemporary architecture shows a shift towards the use of permeated façade elements that mediate the incoming light, creating diverse daylight patterns.

However, little is known about the influence of the spatial distribution of daylight on human perception. In particular, we have limited knowledge regarding the impact of the characteristics of façade openings and of the corresponding daylight patterns on occupants. Considering the prevalence of architectural façade elements that filter the light that enters a space, it is essential to broaden our understanding about the perception and preference of occupants towards these elements.

Moreover, although considerable research in lighting has been devoted to investigations in working environments, less attention has been paid to different uses of a space, and to how the spatial context might influence the occupant's expectations and perception of a daylit space. In addition, current methodological recommendations in lighting research underline the importance of regional differences in occupant perception, and emphasize the need for empirical studies with different populations to establish the generalizability of research findings.

This thesis aims to provide substantial evidence on how the façade openings and the resulting daylight patterns can jointly affect the experience of a space. To conduct this investigation, this thesis introduces and uses experimental tools that address two important limitations of experiments in lighting research: the changing lighting conditions in real environments, and the use of rating scales as the sole method of data collection. These experimental tools are employed in a series of studies that systematically investigate the effect of façade and daylight patterns on human responses, broadening our knowledge on the joint impact of space and light on occupants. Furthermore, the present work aims to address the aforementioned knowledge gaps by examining the impact of space function and of regional differences on human perception. To this end, this thesis employs different scenarios of space use and replicates experiments in Switzerland and Greece, seeking to test the generalizability of research findings across space configurations and across latitudes in Europe.

1.2.2 Thesis objectives

The present thesis seeks to address the following research question:

Do the spatial characteristics of the façade geometry and the resulting daylight patterns influence human responses?

In the process of answering this question, this investigation extends to a number of additional research objectives that support the present work and were identified as essential through the state of the art in Chapter 2. Specifically, the review of the literature regarding human factors in lighting research reveals the necessity for highly controlled visual stimuli and motivates the development of an experimental tool that combines physically-based images with immersive virtual reality. An additional methodological consideration is the coupling of subjective assessments with physiological indicators to examine the effect of façade and daylight patterns on humans through multiple experimental procedures. Moreover, considering the importance of placing people in a specific context for the validity of research outcomes, the present thesis examines the subject of different space functions and their impact on the perception of daylit spaces. As discussed in Section 1.2.1, another important research question concerns the existence of regional differences in the appraisal of daylit scenes, which is investigated through the replication of experiments across latitudes in Europe. Finally, the last part of the thesis explores the extension of the main research findings towards the prediction of human responses to façade and daylight patterns, and the application of those findings in a real-word setting.

These critical points for the validity and generalizability of the present work lead to the following primary and secondary research objectives, which are addressed in different chapters:

1. To investigate the influence of façade and daylight patterns on subjective responses (Chapters 5 and 6)

Methodological foundations:

1.1. To demonstrate the adequacy of virtual reality as an experimental tool for investigating the perception of daylit spaces (Chapter 4)

Secondary objectives:

1.2. To investigate the influence of the expected function of a space on the perception of façade and daylight patterns (Chapters 5 and 6)

1.3. To examine the influence of regional differences on the perception of façade and daylight patterns (Chapter 6)

1.4. To identify the potential of existing image-based metrics as predictors of subjective responses to façade and daylight patterns (Chapter 7)

2. To examine the influence of façade and daylight patterns on physiological responses (Chapter 5)

The next subsection presents an overview of how the individual chapters of this thesis address the aforementioned objectives, and introduces the relation between these chapters and their outcomes.

1.2.3 Thesis outline

This chapter introduced the context of the present thesis, and specified the motivation and objectives of this research. To orient the reader, this section presents an outline of the chapters to follow, elaborating on the information from Section 1.2.2.

Chapter 2 begins with a review of the current knowledge regarding the positive effects of access to daylight, sunlight, and view out, as well as the use of contrast and complexity as drivers of visual interest in architecture. Moving to methodological concerns, Chapter 2 examines factors that relate to the generalizability of findings in lighting research, namely the effect of the function of the space and of regional differences on perception. Lastly, it explores relevant research methods for determining the effects of light and space on occupants, identifying the use of immersive virtual reality and physiological indicators as promising research tools. In addition to identifying current knowledge gaps that are directly related to the main research question, this literature review brings forth multiple additional elements of importance for the present thesis and for the field of lighting research, which are examined in the empirical studies described in the next chapters.

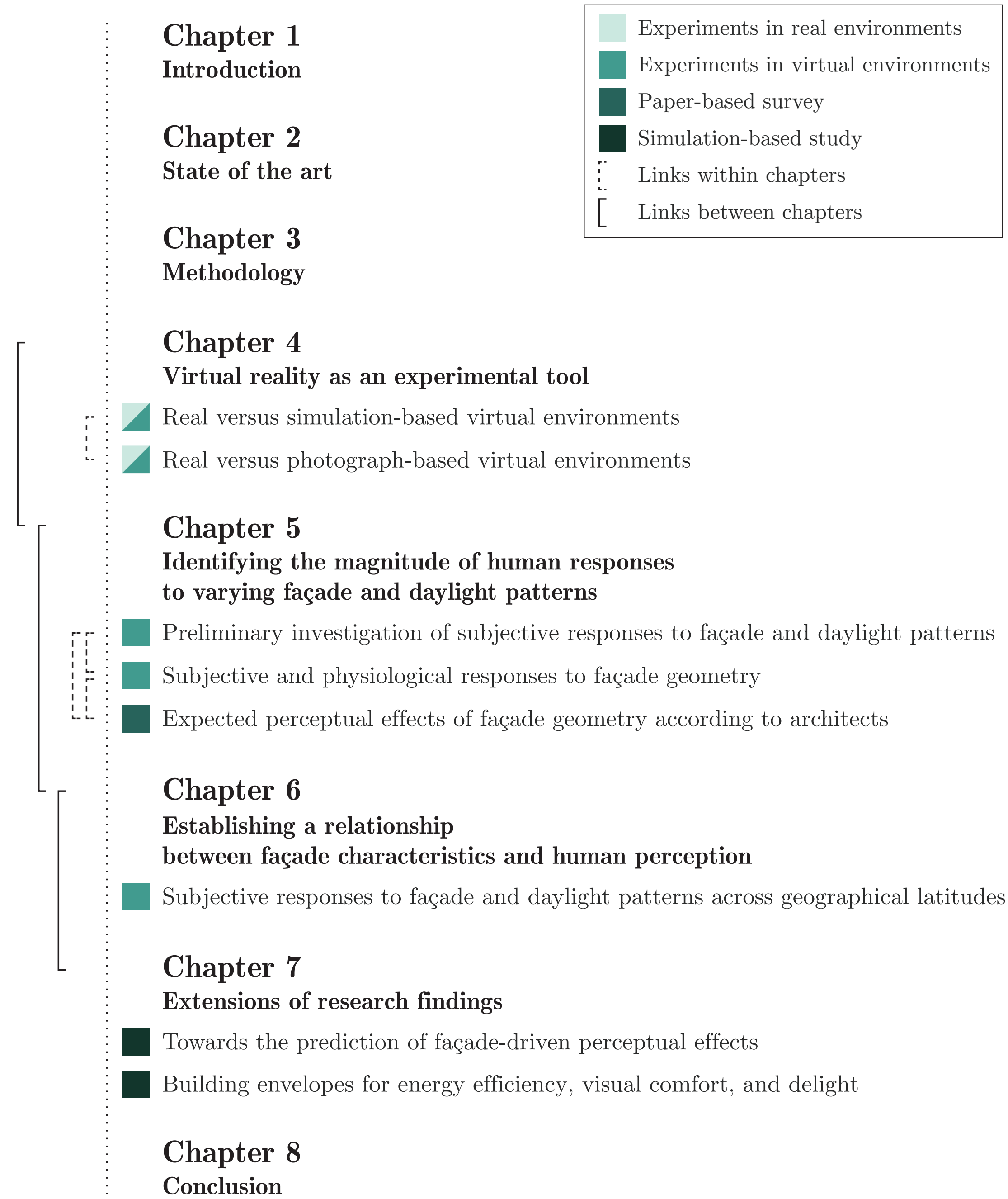

Figure 1.2 – Outline of the thesis structure and the links between and within chapters.

Next, Chapter 3 presents the methodological approach, research methods, and expected outcomes of the present thesis. Chapters 4, 5, and 6 form the core of this thesis, and describe seven studies, each of which builds upon the findings of the previous one, that aimed to provide evidence regarding the methodological approach and the research objectives of this work. In addition, Chapter 7 presents two additional studies, primarily based on simulations, that illustrate the application potential of the findings of the present thesis. Figure 1.2 outlines the layout of the thesis and the links between the different chapters, which will be briefly introduced below. Each chapter is self-contained and can be read both independently and in conjunction with the rest of the thesis.

Following the identification of the changing lighting conditions as an important stumbling block in daylighting research and the necessity for fully controlled and portable visual stimuli for the purposes of this work, this thesis sought to develop a novel experimental method, combining physically-based renderings with immersive virtual reality. Chapter 4 introduces this method and examines its adequacy as a surrogate to real environments for empirical research on the perception of daylit scenes. The findings of this chapter build the methodological foundations for the remainder of this thesis and support the use of the developed experimental method in the subsequent empirical studies. The work in this chapter has been published in part in the journal LEUKOS [Chamilothori et al., 2019c], and the resulting insights on the use virtual reality for empirical studies in lighting research have been presented at the CIE Expert Tutorial and Workshops on Research Methods for Human Factors in Lighting [Chamilothori et al., 2018c].

In continuation of these findings, Chapter 5 uses this virtual reality-based experimental method to assess the extent of human responses to variations in façade and daylight patterns and demonstrate the potential and relevance of the central research question of the present thesis. The outcomes of this chapter reveal the magnitude of human responses to the geometric composition of façade and daylight patterns, and motivate further investigation with a wider range of façade geometry variations. To this end, Chapter 5 continues with the selection of contemporary façade designs from existing buildings that are deemed as promising regarding their expected perceptual effects, according to architects. The work in this chapter has has been published in the journal Building and Environment [Chamilothori et al., 2019a] and presented at the 3rd International Congress on Ambiances [Chamilothori et al., 2016] and the 2018 Conference of the Academy of Neuroscience for Architecture [Chamilothori et al., 2018a].

Building on these positive outcomes, Chapter 6 employs the most promising façade variations according to architects to investigate the effect of façade geometry, lighting conditions, and scenario of space use on participant responses in extensive experimental studies conducted in virtual reality. In addition, this chapter examines the regional differences in the perception of daylit scenes between Switzerland and Greece, aiming to assess the generalizability of these findings across latitudes in Europe. This chapter concludes the experimental investigations in the present thesis, building on the outcomes of Chapters 4 and 5 to address the core research question of this work. Part of the research introduced in this chapter has been presented at the Light Symposium 2018 [Chamilothori et al., 2018b].

Chapter 7 builds upon the results of Chapter 6, and presents extensions of these findings in different research areas through two studies which are primarily based on simulation. The first study concerns the potential of existing image-based measures of contrast and complexity for predicting the occupant responses to façade and daylight pattern variations, with the ultimate aim to support design decisions regarding the façade geometry. In addition, the second study demonstrates the application of the thesis findings into the design of a kinetic shading system that shifts states to alter the occupants' experience of space.

Lastly, Chapter 8 concludes this thesis with an overview of the achievements and impact of the present work, and discusses promising future research directions.

Chapter 2

State of the art

This chapter provides an overview of the state of the art in several scientific areas of relevance that lie in the intersection between architecture, lighting, and human perception. Specifically, this chapter addresses questions pertaining to the effect of daylight access on perception, the creation of visual interest in the space, the impact of the space function and the existence of cultural differences on the appraisal of daylit spaces, and lastly, how existing research has attempted to quantify the effect of light and space on human perception.

Starting from the positive effects of daylight and view out on occupants, this literature review will present experimental evidence on the importance of access to direct sunlight for human perception and discuss this aspect in juxtaposition with visual discomfort. As a natural extension of this topic, we will address the current knowledge on the use of contrast and complexity as a source of visual interest in architecture. Specifically, this state of the art will cover research efforts in assessing and predicting visual interest across the field-of-view of an occupant, as well as the use of the façade design as an element of interest, drawing from the fields of lighting, environmental psychology, and architecture. Next, we will cover two additional areas of importance: the effect of the function of the space on the occupants' appraisal of a daylit scene, and the evidence for regional differences in this appraisal. Moving to relevant research methods for investigating the perception of daylit spaces, this chapter will present a review of the use of virtual environments in empirical lighting research, and outline different approaches for quantifying the perceptual effects of light and space. This literature review draws from different disciplines to bring forward the need for further knowledge on the joint influence of light and space on occupants and to identify promising research methods that will be used in the present thesis to advance this knowledge.

2.1 Positive perceptual effects of daylight

Daylight has an undeniable value in various aspects of architectural design, ranging from energy efficiency and user comfort to the perception of architectural space. This is reflected in the stance of researchers and practitioners in the building sector, as shown through a survey by Galasiu and Reinhart [2008] which found that energy savings, avoidance of glare, and aesthetics were the three most often selected criteria for evaluating of the quality and performance of a daylighting design.

However, current scientific knowledge on the joint impact of daylight and space features on human perception is fragmented. Boyce [2003] argues that "perception is much more sophisticated than just producing a feeling of visual discomfort", while underlining the difficulty of establishing generalizable knowledge regarding the high-order perceptions of lighting conditions, such as interest. To help situate the present thesis, this section begins by examining the current knowledge on the positive perceptual effects of access to daylight and outside view, and proceeds with a review of these effects in the context of direct sunlight.

2.1.1 Access to daylight and view out

The preference of occupants for access to daylight and view out has been long established. In one of the first surveys investigating the preference of office workers towards daylight and view out, Wells [1965] found that 90% of the respondents evaluated the view to the outside as important, even if there was enough artificial lighting for working. At the same time, 81% of the respondents preferred daylight over electric lighting [Wells, 1965]. The preference towards natural over artificial lighting is consistent across multiple studies over the last five decades [Markus and Hopkinson, 1967; Heerwagen and Heerwagen, 1986; Veitch et al., 1993; Roche et al., 2000; Cuttle, 2002; Osterhaus, 2005; Borisuit et al., 2015], indicating that this preference is not a result of technological limitations of artificial lighting systems at the time of each study, but rather a result of the visual and temporal qualities of daylight.

The amount and quality of light is considered as one of the most important factors in the physical attributes of a work environment [Ne'eman et al., 1984]. Veitch et al. [2007] conducted an extensive field study with 779 occupants of nine open-plan offices in Canada and the US, investigating how job satisfaction is affected by the satisfaction with environmental features of the workplace. Subsequent factor analysis revealed three aspects of the environment that affected job satisfaction: the satisfaction with lighting, satisfaction with privacy and acoustics, and satisfaction with ventilation and temperature. These factors emerge consistently as important for the occupants' satisfaction with the environment in a wide range of space uses, including office environments [Veitch and Newsham, 1998; Wong et al., 2008; Bluyssen et al., 2011], schools [Astolfi and Pellerey, 2008], as well as residential buildings [Lai et al., 2009]. Such findings demonstrate the importance of achieving satisfactory luminous conditions, which can in turn significantly contribute to the occupants' overall satisfaction with the indoor environment.

There is growing evidence that daylight exposure influences the mood, alertness, stress levels, and sense of well-being of occupants [Edwards and Torcellini, 2002; Boyce et al., 2003; Veitch and Galasiu, 2012]. These findings relate to the overwhelming preference of occupants towards having access to a window, the two main functions of which are the provision of daylight and view [Collins, 1975; Farley and Veitch, 2001]. Regarding the amount of view, several studies have demonstrated that occupants prefer large windows [Chauvel et al., 1982; Cuttle, 1983; Keighley, 1973; Moscoso et al., 2015a], with the width, rather than the height, being the most critical dimension of the window [Ne'eman and Hopkinson, 1970].

While the preference for large windows could be regarded as a universal tendency, Butler and Biner [1989] argued that preference towards window size is affected by the function of the space. In a survey, 59 undergraduate students were asked to select their preferred window configuration in terms of number, size, and transparency of windows for a variety of spaces, ranging from offices to bathrooms, and to identify the most important factors influencing their choice from a total of 18 predefined options. Findings showed that for specific uses, such as a bathroom, a small window was preferred over a large one. The choice of access to sunlight as a factor of preference towards a window configuration was not shown to be influenced by the type of space. However, other factors, such as privacy, were shown to be the dominant ones for specific uses of space, highlighting the importance of context in the appraisal of space, which will be further discussed in Section 2.3.

The view content and the depth of the view have also been identified as important factors in the satisfaction with the view access [Ne'eman and Hopkinson, 1970]. The presence of multiple visual layers, greenery, and water are highly preferred [Markus and Hopkinson, 1967; Kaplan, 2001; Aries et al., 2010; Hellinga and Hordijk, 2014; Matusiak and Klöckner, 2015]. In the seminal study by Ulrich [1984], access to view towards nature —rather than towards a wall— was shown to reduce recovery time and use of analgesics. While at the time this effect was attributed to the view content, current knowledge on the non-visual ocular processes of light suggest the positive influence of higher light exposure on circadian regulation and overall health as an alternative explanation [Veitch and Galasiu, 2012].

Occupants' impressions of a space have been shown to be significantly affected by the presence of daylight and windows. In particular, the presence of daylight has shown to render a space more pleasant [Heerwagen and Heerwagen, 1986; Edwards and Torcellini, 2002; Laurentin et al., 2000] and less tense [Stokkermans et al., 2015]. Manipulation of view access and view content has also been shown to lead higher evaluations of pleasantness [Kaye and Murray, 1982; Chauvel et al., 1982; Aries et al., 2010; Veitch et al., 2013] as well as spaciousness [Kaye and Murray, 1982; Ozdemir, 2010; Stamps, 2010; Veitch et al., 2013].

While the presence of daylight and view are confounding factors in many studies, the positive effects of windows appear to hold true also in studies that separate the access to daylight and view out. In such an experiment, Moscoso et al. [2015a] investigated the effect of window size and room reflectance on the impressions of a space. To avoid an influence of view, experiments were conducted at midday with an overcast sky, using white translucent curtains to cover the windows. Two identical rooms with white and black surfaces, were used in combination with three window sizes. Each participant was exposed to one level of room reflectance and to all three window sizes, in random order of presentation. Results showed that both the room reflectance and the window size significantly influenced the impressions of the space. While in this experimental study the window size was decoupled from the view out, the larger window led to more positive ratings of how pleasant, exciting, complex, or spacious the space was perceived.

Yet, although view and daylight access have been shown to be dominant factors in the satisfaction of occupants with the lighting conditions [Veitch et al., 2005], these same factors can lead to thermal and visual discomfort [Roche et al., 2000; Veitch et al., 2005; Aries et al., 2010]. This contradiction has also been found in a series of experimental studies with scale models that investigated the effect of glazing type on occupant perceptual impressions and visual comfort. Specifically, glazings with higher visual transmittance were rated as more pleasant, natural, and beautiful, and simultaneously led to higher evaluations of visual discomfort [Dubois et al., 2007b; Dubois, 2009]. This important paradox between conditions that are perceived as both positive and uncomfortable will be discussed further in the next section.

2.1.2 Access to direct sunlight

One of the central issues in lighting design is the creation of environments that are both visually stimulating and comfortable [Boyce, 2003; Reinhart et al., 2006; Inanici and Wymelenberg, 2009; Wymelenberg et al., 2010]. Current lighting design practices tend to restrict sunlight penetration in favor of visual comfort and energy savings, to avoid glare risk and overheating from the sun, respectively [Mardaljevic and Nabil, 2005; Wienold and Christoffersen, 2006; Illuminating Engineering Society of North America (IESNA), 2012]. This restriction of direct sunlight access has been criticized as a trend that produces monotonous and dull luminous environments [Köster, 2004; Corrodi and Spechtenhauser, 2008]. Contrary to this tendency, the new European standard "Daylight in buildings" requires a minimum number of hours during which a space receives direct sunlight [European Committee for Standardization (CEN), 2019]. Moreover, recent advances in lighting research underline the importance of sunlight access through performance indicators that aim to predict the effects of luminous conditions on the well-being and perceptual impressions of occupants [Amundadottir et al., 2017].

One important motivation in uncovering the relationship between physical characteristics of the visual scene and the occupants' appraisal is that perceptual impressions — such as how pleasant, interesting, spacious, or attractive is a space— have been shown to significantly decrease physical and psychological discomfort in field studies [Aries et al., 2010; Pastore and Andersen, 2017]. While glare is an important source of dissatisfaction and one of the main drivers of occupant interaction with shading systems [Christoffersen et al., 2000; Dubois, 2003; Galasiu and Veitch, 2006], the view to the outside has been consistently reported as a mediating factor in glare perception [Hopkinson, 1972; Chauvel et al., 1982; Osterhaus, 2001]. Specifically, the preference for view access can be translated into glare tolerance, as demonstrated in post occupancy evaluation studies of an open-plan office conducted by Konis [2013] where occupants were shown to prefer setting the shading system partially open, despite frequent reporting of visual discomfort. Moreover, the resulting partially screened view did not seem to impact negatively the occupants' satisfaction with the visual connection to the outside view.

Using the view content as an independent variable, experiments using projections [Tuaycharoen and Tregenza, 2005] and real environments [Tuaycharoen and Tregenza, 2007] have demonstrated that perception of glare discomfort decreases as the level of interest towards the view to the outside increases. Similarly, experimental studies using a simulated window have shown that glare sensation was affected by the participants' subjective impressions of the view, even under the same lighting conditions [Kim et al., 2012]. In another study that used projected scenes, Tuaycharoen [2011] found that the perceived complexity of the view out was a significant factor influencing glare perception, with scenes of high complexity being evaluated as significantly less glaring than those of low complexity. This further step in identifying a specific characteristic of the visual stimulus —complexity— that has these mediating effects is of particular importance, and will be discussed further in Section 2.2.

It appears thus that these mediating effects on occupant discomfort can be induced not only by one specific element in the scene —view—, but rather by different features in the scene that increase visual interest and attention. In this vein, Van den Wymelenberg et al. [2010] investigated the acceptance of occupants towards luminance patterns in their field-of-view through an experimental study in an office environment with 18 participants. Following a repeated measures design, participants were instructed to manually adjust the blinds to a position that they deemed to be "just disturbing" and "most preferable" regarding discomfort glare, and the resulting conditions were recorded using high dynamic range photography. Contrary to expectations, 11 out of 12 participants that took part in the study under sunny or partly sunny sky chose to allow direct sunlight into the room when asked to create their preferred condition. While the sample size in this study is limited, these findings demonstrate the potential of luminance distributions in the scene as drivers for a satisfying daylit environment. The authors note that "adequate luminance variations create a stimulating and interesting environment" and raise the issue of identifying what constitutes an adequate variation in luminances.

These findings are in agreement with Boubekri and Boyer [1992], who found that glare in a sunlit office room was evaluated as more tolerable than the level predicted by the daylight glare index (DGI), and attributed this finding to the positive effects of sunlight. In addition to the preference towards daylight that was addressed in Section 2.1.1, occupants have been shown to strongly prefer the presence of direct sunlight. In a field study assessing the lighting preferences of 400 employees in an office building, 86% of respondents reported that they "liked some sunshine in the office" during the whole year [Markus, 1967].

Dubois et al. [2007a] conducted an observational study in a student cafeteria to examine the seating preference of students performing various activities under different daylighting conditions. Behavior mapping and photographs were used to note the lighting conditions, as well as the position and type of activity of users every 15 minutes. Results showed that the majority (61%) of the users chose to occupy the brightest area close to the window for all types of activities, while lighting was reported by the participants as the most important factor in their seating choice. Moreover, the authors note that activities that required high visual acuity, such as reading or righting, were often performed in locations that would not meet IES recommendations, suggesting that a diverse range of luminous conditions can be accepted or even preferred by occupants, a finding that has been confirmed in several studies [Veitch and Newsham, 2000; Küller et al., 2006; Pastore and Andersen, 2019a].

A number of studies have assessed directly the impact of the extent of sunlight penetration on occupants. In a survey of 100 employees doing a variety of tasks — from manual to administrative tasks—, Leather et al. [1998] investigated the effects of sunlight penetration on participants' self-reported well-being, job satisfaction, and intention to quit. As a measure of sunlight penetration, participants were asked to report the maximum possible sunlight penetration in their work area as a percentage of the total floor area. Results revealed a significant main effect of the maximum possible sunlight penetration in the space on evaluations of well-being, job satisfaction, and intention to quit, with the area of sunlight penetration relating positively to well-being and job satisfaction, and negatively to turnover intention.

In another study that investigated the impact of sunlight penetration on occupants in an experimental setting, Boubekri et al. [1991] examined the impact of different window sizes and equivalent areas of direct sunlight on the self-reported mood of office workers. Four window size variations were created in an office room, creating four levels of sunlight penetration and experiments were conducted in days with intermediate sky. A between-subject design was followed, with one participant being exposed to one window size variation, placed either laterally or facing the window. A total of 40 participants conducted a proofreading task before responding to a questionnaire assessing their mood. The authors report a significant effect of sunlight penetration on reported relaxation when the participant was sitting sideways in relation to the window, with the sunlit area covering 10% and 45% of the floor area leading to an increased sense of relaxation. While this finding is questionable due to the window size being a confounding factor and the high number of multiple comparisons in the statistical analysis, it highlights the potential for further research on the effects of direct sunlight penetration on occupant perception.

Further work by Wang and Boubekri [2010a] on this topic examined the effect of seating position in a sunlit office on cognitive performance, mood, and preference of 100 participants. Ten different seating positions were set in an seminar room with an east-facing floor-to-ceiling window, placed at different levels of distance from the window and the sunlit area. Due to changing lighting conditions, both the light intensity and the size of the sunlit area in the room patch varied significantly, the latter being between 20% and 25% of the total floor area. Participants were randomly assigned to one of the ten seating positions in each experimental session, and were asked to perform two cognitive tasks and report their mood before and after the task. In addition, they were asked to place different types of furniture (a work desk, a meeting table, and a pair of relaxing chairs) on floor plans of the space to indicate their preferred seating positions for the related activities, and explain the motivation for their choice. Results showed that the seating position had a significant effect on cognitive performance for both tasks, but no clear relationship was found between participants' performance and their position compared to either the window or the sunlit area. In addition, seating position significantly influenced the reported mood of participants. While the participants' mood generally decreased after the cognitive tasks, the authors report that the participants in positions that were close to the sunlit area and had a better view access were less affected, having a smaller average decrease on reported mood. Regarding preferred seating positions, the majority of the participants chose positions close to or within the sunlit area for all types of activity, with 19% of participants placing the work desk in the sunlit area. Participants were asked to specify not only the position, but also the direction of the furniture, which, in combination with the reported motivation for this choice, provides interesting insights on seating preference. Specifically, the three most often stated reasons for seating preference were visual comfort, outdoor view, and control, the latter referring to an overview of the room and the door. These findings show that while physical proximity to the sunlit area was strongly preferred, the view direction in the preferred seating positions was partly driven by a sense of control, leading to choices that allowed an overview of the room.

In a second publication concerning the same experiment, Wang and Boubekri [2010b] examined further the subject of declared seating preference. The analysis of the preferred seating positions for each of the three activity scenarios —isolated work, team work, and relaxing— revealed that proximity to sunlight was preferred for both isolated work and relaxing, but not for teamwork. These results underline the importance of considering the impact of the function of the space on occupants' expectations and preferences, a subject that will be discussed further in the Section 2.3.

The way we perceive daylight in a space is inextricably linked to its architectural features, its openings, volume, and surfaces. To investigate the joint impact of space and daylight —and the resulting contrast in the scene— on occupant impressions, Rockcastle et al. [2015; 2017a; 2017b; 2017] conducted a series of experimental studies in virtual environments. In a preliminary study [Rockcastle and Andersen, 2015] and later an extensive online survey with 175 participants [Rockcastle et al., 2017a], Rockcastle et al. investigated subjective responses to rendered images of daylit architectural spaces with varying contrast. A total of three variations of sky and nine variations of space were assessed through a Latin square design experiment. Participants were asked to evaluate their impressions of the daylight composition in the space using bipolar rating scales such as low contrast-high contrast, simple-complex, calming-exciting, and sedating-stimulating. All sky types corresponded to clear sky conditions, with varying sun position. The sun positions were different for every space, as they were selected to represent instances of lowest, mean, and highest contrast in that particular space across a year according to the contrast metric RAMMG [Rizzi et al., 2004]. However, the sun positions corresponding to the lowest contrast instances resulted in minimal sunlight penetration in the space, while those corresponding to the highest contrast instances resulted in higher levels of sunlight penetration. Results from both the preliminary study and the online survey showed a significant effect of sky on ratings of contrast, complexity, stimulation, and excitement. Further pairwise analyses in [Rockcastle et al., 2017a] revealed that the sun position corresponding to high contrast (high level of sunlight penetration for that space) led to significantly higher evaluations of contrast, complexity, stimulation, and excitement compared to the sun position corresponding to low contrast.

Similarly, the space depicted in the image was shown to have a significant effect on the same attributes, demonstrating that the architectural features of a scene influence the occupants' impressions.

Further work by Rockcastle et al. [2017b; 2017] examined the impressions of daylit interiors of architectural spaces in an immersive virtual reality environment, extending the investigation from a two-dimensional to a three-dimensional stimulus. A total of 109 participants were shown either 180° or 360° virtual reality scenes in a mixed design experiment, with the space being the within-subject factor and the sky being the between-subject factor. Using a similar procedure as in [Rockcastle and Andersen, 2015], the contrast metric mSC [Rockcastle et al., 2017a] was used to select the instance of lowest and higher contrast in each space for an overcast and clear sky, respectively, resulting to two sky conditions of overcast sky with low contrast and clear sky with high contrast. Eight different spaces were used in this study, five of which were common with the previous experiments. Participants were asked to evaluate their impressions of how pleasant, interesting, exciting, calming, diffuse, and contrasted was the space using a unipolar scale. While no overall effects are reported for the effect of space, pairwise analyses reveal significant differences between pairs of spaces for all attributes in both 180° and 360° scenes. However, significant differences were found between the overcast-low contrast and clear sky-high contrast conditions only for ratings of how pleasant, diffuse, and contrasted the space was perceived for the 180° scenes, and how calming, diffuse, and contrasted for the 360° scenes. These differences between the perceptual effects of space and of sky type motivates further work to investigate the interplay between architectural design and daylight. When is a space perceived as interesting, and how does the daylight in the space contribute to this perception? To this end, the next section presents research that aimed to relate physical attributes of the visual environment with perceptual impressions.

2.2 Contrast and complexity as a source of visual interest in architecture

A substantial amount of research has been devoted to determining which attributes of an environment matter most in the perception of occupants, and how these attributes relate to physical characteristics of that environment. A particularly important —and elusive— aspect in this topic is the prediction of visual interest in a scene. To this end, we first introduce relevant work in the field of lighting, which mainly focuses on an occupants' field-of-view, and continue with studies from the fields of environmental psychology and architecture to gain further insights about the role of the building envelope on perceptual impressions of occupants.

2.2.1 Assessing visual interest across the field-of-view

In the seminal study by Flynn et al. [1973], 40 participants evaluated their impressions of a conference room across six different configurations of artificial lighting in a within-subject experimental design. Factor analysis indicated three factors that represented the participants' impressions of the lighting conditions: brightness, uniformity, and the presence of peripheral lighting. Moreover, their findings showed that lighting configurations that were evaluated as the most pleasant contained non-uniform and peripheral lighting, regardless of the level of perceived brightness.

Using a similar procedure, Hawkes et al. [1979] investigated the appearance of an office environment across 18 artificial lighting configurations with in a Latin square experimental design with 28 participants. Their findings demonstrated that the perception of light in the space could be represented by the dimensions of brightness and interest, which related to the perceived intensity and uniformity of the lighting conditions, respectively. Moreover, lighting conditions that were evaluated positively in the dimensions of brightness and interest were often rated as more attractive. While perceived brightness was found to correlate strongly with the logarithm of the vertical illuminance measured at the eye of the observer, no promising physical attribute was found for perceived interest. However, the authors noted that the lighting conditions evaluated as the most interesting had more sharp boundaries between areas of light and shade, indicating that contrast might play an important role in the perception of visual interest.

In another study with 28 participants and 18 artificial lighting configurations, Loe et al. [1994] examined the appearance of a conference room, using a very similar procedure to that of Flynn et al. [1973]. Findings showed that the participants' impressions of the studied configurations could be represented with the factors visual lightness, visual interest, and a third factor relating to the scale "tense-relaxed". As the third factor corresponded to solely a single scale and accounted for 10% of the variance in participants' responses, it was not considered further in the analysis. Correlation analyses between perceptual impressions and physical attributes of the scenes showed that the average luminance and the standard deviation of luminance in a 40° horizontal band centered at the eye height of the observer were good predictors of brightness (visual lightness) and interest, respectively. Here also the authors state that both brightness and interest are necessary to create satisfactory lighting conditions.

The studies of Flynn et al. [1973], Hawkes et al. [1979], and Loe et al. [1994] were conducted with a limited sample size, especially considering the use of factor analyses. However, in a later study by Veitch and Newsham [1998] that examined the appearance of an open-plan office with 292 participants and nine artificial lighting conditions, the findings are quite similar, with three emerging factors: brightness, visual attraction, and complexity.

Lastly, in a recent study by Stokkermans et al. [2018], 24 participants were exposed to rendered scenes with a total 105 variations of artificial lighting conditions. The authors related the participants' impressions of brightness and uniformity of the scenes with the evaluations of the atmosphere attributes cosiness, liveliness, tenseness, and detachment, stemming from the work of Vogels [2008]. Their results showed that these atmosphere impressions can be described as a function of perceived brightness and uniformity. In addition, the authors investigated the correlation between physical attributes of the images and the ratings of brightness and uniformity. While the average luminance in the 40° horizontal band, proposed by Loe et al. [1994], correlated strongly with ratings of brightness, no promising indicator was found for perceived non-uniformity.

Non-uniformity in the lighting conditions can even allow for energy savings, as demonstrated by the results of a study conducted by Tiller and Veitch [1995] that investigated the effects of luminance distribution on the perceived room brightness in office spaces. In this study, the subjects were asked to match the brightness of two artificially lit mock offices. The authors note that rooms with non-uniform luminance distribution required five to ten percent less working plane illuminance compared to the brightness of the rooms with uniform luminance distribution. These findings demonstrate the importance of understanding further the impact of luminance distribution on perception, with potential implications for building energy use.

While most research on this topic employed artificial lighting, presumably for possible commercial applications, a limited number of studies have investigated the perception of occupants in daylit environments. In order to examine the non-uniformity in an occupants' field-of-view, Parpairi et al. [2002] developed the luminance difference (LD) index, which measures the difference in luminances over a set acceptance angle across a selected view position. This method was then applied in a field study in three university libraries with 26 participants in each location, where it was concluded that luminance variability is highly appreciated by the participants. The results showed that the more variable the luminance in the user's field of view, the more pleasant the space was perceived. Specifically, diversity rather than intensity in the luminance levels was more satisfying to the subjects, within a certain range. Of course, as discussed above, a central —and, to date, unresolved— issue is the definition of the acceptable range of luminance diversity, and the subsequent robust distinction between stimulating and uncomfortable lighting conditions. While this distinction is a challenging topic for the field of lighting, the solution is not to restrict all access to direct sunlight; as noted by Parpairi et al. [2002], "subjects do not enjoy working in bland, monotonous environments, [...] they enjoy the stimulation of variable luminances in the field of view".

To examine the relation between visual interest and the luminance diversity, Rockcastle et al. [2013a] developed the image-based metric Spatial Contrast (SC), which takes into account the differences in the luminance of neighboring pixels across an image. Using the participant impressions of rendered scenes from the online survey described in Section 2.1.2, Rockcastle et al. [2017a] demonstrated that a modified version of that metric, referred to as mSC, is successful at predicting occupants' impressions of excitement across a range of rendered grayscale scenes depicting architectural spaces under different lighting conditions. Further application of this metric in 180° and 360° rendered images of daylit architectural spaces that were shown in virtual reality in a second study by Rockcastle et al. [2017], showed a marginally better fit with a composite indicator of the median ratings of excitement, interest, and pleasantness, than solely with ratings of excitement. This small discrepancy might be due to the methodological differences between the two studies, and motivates further research to test the predictive potential of this metric under different settings. Nevertheless, this work underlines the potential and necessity of established indicators for the perceptual effects of daylight, which, as the authors state, could predict the occupants' impressions along different dimensions, such as pleasantness, interest, and excitement. Furthermore, the combination of mSC with current computational capabilities allows the assessment of contrast not only across a scene in a specific point-in-time, but also across the year, as it can be applied over daily and annual instances to evaluate the effect of the dynamic behavior of daylight on predictions of visual interest over time [Rockcastle and Andersen, 2014; Amundadottir et al., 2017]. While this metric is the first to successfully predict the positive perceptual effects of contrast across a range of spaces, the question remains on when contrast and luminance diversity in the field-of-view shifts from being a source of discomfort —as assessed in current glare indices [Hopkinson, 1971; Wienold and Christoffersen, 2006]— to a source of visual interest. One important research direction is the conduction of experiments in conditions with realistic luminance ranges to specifically examine this gray area between stimulation and discomfort. Another equally important direction is the investigation of human responses to different characteristics of luminance distribution, which has been argued to be a "missing variable" in current lighting research [Boyce, 2014]. Specifically, the size, distribution, and visual dominance of luminance patterns have been identified as potential factors of preference [Veitch and Newsham, 2000].

While the research presented in this section demonstrates the importance of both spatially and temporally diverse luminances in a scene, little is known about the spatial composition of these luminance patterns. Moreover, we have limited knowledge on how the façade openings and the characteristics of the resulting sunlight patterns affect occupants' perception and preference. The next section will examine the role of the façade in creating visual interest and mediating the daylight that enters a space.

2.2.2 Façade geometry and visual interest

In the field of environmental psychology, Evans and McCoy [1998] argued that a intermediate level of sensory stimulation is necessary for building occupants, with a lack of stimulation leading to boredom or even sensory deprivation. Particularly, they suggest intensity, variety, and complexity as design qualities that are pertinent to stimulation. This perspective is also in line with Berlyne's [1971] theory on stimulation, which argues that preference is a function of complexity, which in turn induces arousal (stimulation). A medium level of complexity is suggested as optimal, with both low and high levels of complexity being undesirable.

The notion of complexity is also important for theories of environmental appraisal, which aim to explain how humans evaluate their environment. The Attention Restoration Theory by Kaplan [1989; 1995] argues that natural environments have features that induce involuntary —rather than directed— attention, which contributes to restoration from mental fatigue, resulting from prolonged and effortful attention. In a similar vein, the Stress Recovery Theory [Ulrich, 1983] asserts that contact with natural elements reduces psychophysiological stress, but is rather an immediate and unconscious emotional response. Ulrich [1983] argues that involuntary attention can also be induced by stressful stimuli, and observes that these beneficial effects necessitate a stimulus which is perceived as both pleasant and moderately to highly interesting.

These theories are particularly relevant for the fields of architecture and lighting design, as they place the focus on the features of visual environment and their role as drivers of human psychological and physiological responses. Specifically, these features are suggested to also be present in the built environment [Kaplan et al., 1993]. According to the ART theory, one of the key features of elements that induces involuntary attention is fascination. While the novelty and complexity of a stimulus are deemed to be central to the creation of fascination [Silvia, 2008], currently very little is known about the specific visual attributes that make a stimulus fascinating [Joye and Dewitte, 2018].

To investigate the potential of building exteriors for perceived restoration, a recent study by Van den Berg et al. [2016] employed photographs of natural environments and buildings shown at different magnification levels. In this study, 40 participants were shown 40 photographs of natural scenes and buildings in their original size, and at 400% and 1600% magnification levels. The photographs of natural scenes depicted grassy areas, bushes, or trees, while the photographs of built scenes were divided into two groups of images depicting the exterior of buildings with either a low or a high degree of ornamentation and detail. Ratings of fascination, relaxation, beauty, and positive affect (emotion) were averaged to represent an index of restoration. While the natural scenes were evaluated as more restorative than built scenes, the unmagnified scenes of buildings with high ornamentation and detail were rated as significantly more restorative and were viewed for a longer time than the equivalent scenes of buildings with low ornamentation and detail. These findings demonstrate that the detail and ornamentation on a building façade are important factors for visual attention, fascination, and restoration.

Modernist architecture has been heavily criticized for a lack of ornamentation, details, and patterns [Salingaros, 1999, 2014a,b, 2017]. Particular emphasis is placed on patterns which schematically imitate natural elements, as they are suggested to retain beneficial visual similarities with nature [Joye, 2007]. Salingaros [1999] also emphasizes the importance of placing such patterns were they are visible —such as the building façade—, rather than in the building plan where they are not easily perceived by the occupants. Contemporary architecture, contrary to modernism, shows a shift toward the use of multilayered building envelopes, perforated walls, and decorative openings [Corrodi and Spechtenhauser, 2008]. According to Corrodi and Spechtenhauser [2008], this shift is characterized by ornamentation and the use of decorative patterns to filter the light that enters the space. However, even though the energy and daylighting performance of such patterned perforated façades has been widely investigated [Sherif et al., 2010, 2011; Sabry et al., 2011; Sherif et al., 2012b,a; Sabry et al., 2014; Karamata et al., 2014; Emami and Giles, 2016; Omidfar Sawyer, 2017], little is known about the occupants' perception and preference towards them.

Rockcastle et al. [2013b; 2017a; 2017] demonstrated that architectural design —the volume, form, openings, and floor plan— can dramatically alter the lighting conditions in a space, with equivalent effects in the occupants' impressions of visual interest. A further step in this investigation is the analysis of the perceptual effects of specific architectural elements within the same space. In the context of the building envelope, how does the variation of the geometry and spatial distribution of façade openings, and the resulting daylight patterns, influence the perception of occupants?

Omidfar et al. [2015] investigated this subject in an online survey where 130 participants were shown rendered time-lapse videos of an office space with six façade configurations of variable geometry and perforation of openings. The preference ranking of the façade variations, according to the participants' impressions —such as how appealing and comfortable they judged the lighting to be—, was compared with the façade performance in terms of Daylight Autonomy [Reinhart and Walkenhorst, 2001]. While no statistical analysis is reported, findings show differences in participants' judgments across façades. Moreover, the authors highlight the existence of considerable discrepancies between the daylight performance of the different façade variations, and the preference judgments of participants for the same façades, demonstrating a conflict between building performance and occupant perception. This study was the first to examine the perception of façade and daylight patterns as seen from the viewpoint of an occupant and highlight the potential of this research direction. However, since the studied façades differ both in the geometry of their openings and their perforation ratio, it is not possible to draw conclusions regarding the effects of specific façade features on occupant perception.

In a series of studies investigating the potential of fractal geometry as a source of visual interest, Abboushi et al. [2018a; 2018b; 2019] examined the impressions of participants towards façade variations with horizontal stripes and fractal patterns of a constant perforation ratio. Abboushi and Elzeyadi [2018b] investigated the potential of fractal patterns as mediators for the perception of discomfort glare. In a within-subject experimental study conducted in an office space, 22 participants were shown three variations of a window partially covered with a uniform surface, horizontal stripes, or a fractal pattern. The lighting conditions during the experimental sessions are not reported. Results showed that both ratings of visual comfort and satisfaction with view were significantly higher for the clear glazing compared to the pattern variations. Moreover, ratings of visual interest differed between the clear glazing and the horizontal stripes, with the former leading to significantly higher ratings. The authors contribute this finding to the uninterrupted access to the view out offered by the clear glazing.

In a second within-subject study by Abboushi and Elzeyadi [2018a], 33 participants reported their impressions of visual interest, visual comfort, and satisfaction with view in an office space with three façade conditions: a window that was clear, fully covered by horizontal stripes, or fully covered by a fractal pattern. Experiments were conducted during working hours over multiple weeks in the early summer season, resulting to vertical illuminance differences of 9'500 lux and to a total of 40% of responses collected in the presence of direct sunlight. Participants were seated either perpendicular or parallel to the window. No significant differences were found in the evaluations of visual comfort between the three façade variations in the presence of direct sunlight. Moreover, findings showed that in conditions of direct sunlight, the ratings of visual interest for the horizontal stripes and fractal pattern façade variations depended significantly on the participants' view direction in relation to the window. Specifically, the fractal pattern was rated as significantly more visually interesting compared to the horizontal stripes for a view direction perpendicular to the window, while the opposite effect was found for a view direction parallel to the window. Lastly, the clear glazing led to an increase of satisfaction with the view access compared to the two patterns —an expected outcome, since the view out was fully unobstructed—, while the fractal pattern was more negatively evaluated compared to the horizontal stripes for participants seating parallel to the window.

In another experiment by Abboushi et al. [2019], 92 participants were shown square black and white visualizations of patterns, projected on the wall of a lecture hall, and were asked to rate their mood and visual interest. These visualizations consisted of horizontal stripes and fractal patterns with varying degrees of complexity, as measured with the fractal dimension D [Mandelbrot and Wheeler, 1983]. The perforation ratio of the façade patterns (reported solely for the stimuli of this study) was 50%. Fractal patterns were evaluated as significantly more visually interesting and led to higher self-reported ratings of excitement compared to horizontal blinds. In a second experiment within the same study, where 68 participants were shown on a computer screen simulated scenes with the same patterns applied to the façade of a daylit office space, this result was replicated solely with fractal patterns of a specific fractal dimension D, underlining the need for additional studies to uncover the effects of façade characteristics on occupant perception.

While the studies by Abboushi et al. [2018a; 2018b; 2019] outline a very promising research area, findings are not consistent between the different experimental settings. Moreover, the studied stimuli are limited to variations of a specific façade geometry (horizontal stripes and fractals, the latter being an atypical choice for façade design), and thus motivate further research on the perceptual effects induced by façade configurations present in contemporary architecture. In addition, none of the existing studies examine the impact of daylight conditions as an independent variable affecting the perception of occupants, leaving a gap of knowledge regarding the relative effect of façade geometry and of the resulting daylight composition on the appraisal of space.

The next sections will address two additional factors of importance which have been suggested to influence the occupants' perception of a daylit space: the function of the space, and the potential cultural differences across geographical regions.

2.3 Space function and occupant expectations in a daylit space

Although researchers acknowledge the importance of luminance variation for a stimulating luminous environment, they note equally the difficulty of differentiating between satisfactory and unsatisfactory conditions, especially in cases of high luminance [Wymelenberg et al., 2010]. This difficulty of distinguishing the positive and negative perceptual effects of direct sunlight brings forth the subject of the space function and its influence on occupants' appraisal of daylit environments. In particular, both the activity of occupants in a space [Osterhaus, 1993] and their attention to the task when conducting a particular activity [Osterhaus and Bailey, 1992] are suggested as important variables that affect the perception and preference towards lighting conditions.

In a survey of preferred lighting preferences for different uses of the space, Butler and Biner [1987] asked 197 respondents to report how bright or dark they would prefer the lighting to be across different rooms and different scenarios of activities in that room (for example, eating in the dining room alone, with a partner, or with a group). Results showed that preferred light levels differed not only between different rooms, but also between different scenarios of use for the same room. Specifically, lighting preferences for a particular scenario were similar across different rooms where that activity can take place (for example, eating with a partner in the kitchen or the dining room). In the same vein, a wide variation in reported preferences for light levels were found for different activities performed in the same room, such as studying or listening to music.

In another survey by Biner and Butler [1989], 105 respondents were asked to indicate their lighting preferences for 48 hypothetical activities, consisting of 16 activities that were used in the previous survey, combined with three social scenarios (performing the activity with a platonic friend, with a group of friends, or a romantic partner). Results showed a significant effect of social scenario on preferred light levels, with mean brightness preferences being lower for the scenario with the romantic partner compared to either of the other two scenarios. These findings, along with the results of Butler and Biner [1987], underline the importance of defining a specific context when investigating occupants' perception and preference towards lighting conditions.

The appraisal of the lighting conditions in a scene relates to the assumed (or conducted) activity in a space, and the corresponding required visual acuity. More broadly, the visual size and contrast characteristics of the particular task, along with the properties of the background lighting, are crucial for the evaluation of daylight as conducive or not to that activity. The signal-to-noise ratio between the task and its background can provoke under-stimulation or over-stimulation [Boyce, 2003], which is a matter of necessary directed attention towards the task; thus, a matter of context. In the same vein, as discussed in Section 2.1.2, Wang and Boubekri [2010b] found an influence of activity scenario on the declared seating preference in a sunlit space. Surveyed participants were asked to place three types of furniture —a work desk, a meeting table, and a pair of relaxing chairs— on a floor plan to indicate their preferred seating position. While the authors do not report statistical analyses on this data, results showed that sunlight access was not welcome in the context of teamwork, but it was preferred in the context of both isolated work and relaxation.

In alignment with these findings, the use of a specific context, rather than an abstract experimental setting, is argued as a necessary methodological step in order to investigate high-order perceptions such as interest [Boyce, 2003]. Moreover, as current knowledge about the influence of space function on occupants' perception and preference towards lighting conditions relies solely on surveys, without the use of a corresponding visual stimulus or the actual conduction of an activity, further studies are needed to verify these results in a more realistic setting.

2.4 Regional differences in the perception of daylit spaces

In an extensive review on occupant preferences and satisfaction with lighting conditions and control systems, Galasiu and Veitch [2006] underline the lack of knowledge regarding the generalizability of research findings across different settings, and advocate systematic comparisons between latitudes and cultures. Similarly, current methodological practices in lighting research assert that it is necessary to test for potential cultural influences before assuming the generalizability of research findings across cultures [Veitch et al., 2019].

Pierson et al. [2018] investigated the cultural differences in the perception of discomfort glare between 73 Belgian and 80 Chilean participants in a field study. Results showed that while most of the studied glare indices successfully predicted the responses from the Belgian participants, this was not the case for the Chilean participants. These findings suggest a different perception or acceptance level of discomfort glare between the two groups, in line with previous research on regional differences in glare perception [Subova et al., 1991; Lee and Kim, 2007]. In the same vein, Yoshizawa et al. [2015] employed scale models with 8 artificial lighting configurations to compare the brightness perception of 24 Japanese and 24 French participants. A preliminary analysis indicated significant differences in the perception of brightness between the two populations for specific conditions.

In a study with 49 Caucasian-American and 49 Korean participants, Park and Farr [2007] examined regional differences on the perception of four artificial lighting configurations with varying correlated color temperature (CCT) and color rendering index (CRI) in a retail setting. Findings demonstrated that American participants evaluated the lighting as significantly more arousing compared to Korean participants. In addition, a two-way interaction was found between culture and CRI, with American participants rating the higher CRI as more pleasurable than the lower CRI, and Korean participants showed the opposite response.

Okamura et al. [2016] used projected slides of photographs of seven lampshades with two light sources to compare the evaluations of 75 Japanese and 27 Danish participants, using bipolar rating scales relating to perceptual impressions such as preference, pleasantness, brightness, comfort, and naturalness. Factor analysis indicated different dimensions representing the impressions of the two cultural groups, suggesting equivalent differences in their perception of the stimuli.

Lastly, Liu et al. [2015] conducted an experimental study with Chinese participants that closely replicated the studies of Vogels et al. [2008] on atmosphere perception. A pilot study was used to collect terms which are commonly used by participants to describe the lighting atmosphere, resulting to a total of 71 bipolar scales. These rating scales were used in an experiment where 29 observers were exposed to eight different artificial lighting conditions, with varying the CCT, luminance levels, and lamp types in a living room setting. Factor analysis was revealed the factors *cosiness* and *liveliness*, which were also found in the original experiment by Vogels [2008]. In subsequent experimental studies, Vogels [2008] identified two additional factors, *tenseness* and *detachment*, which were not replicated in Liu et al. [2015]. Moreover, further analyses by Liu et al. [2015] showed differences in the effect of CCT levels on atmosphere impressions between Chinese and Dutch participants.

These findings indicate both that questionnaire instruments —such as the atmosphere dimensions proposed by Vogels— should not be applied blindly to different populations, and that the replication of experiments across latitudes is necessary to verify the robustness of research findings. Moreover, while the aforementioned studies indicate the presence of regional differences in the perceptual impressions of artificial lighting, no studies, to the author's knowledge, examine such differences in the context of daylight.

2.5 Experimental approaches to investigate environmental appraisal

Although daylighting research has produced established metrics regarding human comfort and the energy performance of daylight, we are left with an inadequate understanding of how luminous conditions influence the occupants' perception and experience. A significant barrier in the acceleration of knowledge in this field is the difficulty of controlling the variation of luminous conditions in experimental studies. Although daylight is identified as one of the driving factors in architectural design [Zumthor, 2006; Holl et al., 2011], there are currently no methods that allow us to visualize and evaluate the dynamics and complexity of daylight in space, truly reproducing a user's experience, except when this space is finished and built.

However, using real environments to investigate human perception is complex in parameters and resources, while daylighting research faces the particular problem of conditions that change over time, such as weather and sky [Bülow-Hübe, 1995; Newsham et al., 2010]. This is an acknowledged issue in research investigating the effects of luminance distribution on occupant perception within the same space, as previous studies have invariably used visual stimuli which varied in both size and intensity, due to the changing daylight conditions [Boubekri et al., 1991; Wang and Boubekri, 2010a,b; Abboushi and Elzeyadi, 2018a,b]. To this end, virtual environments are suggested as an alternative method that can facilitate the exploration of the perceptual effects of light distribution [Boyce, 2014].

Indeed, there has been a growing trend towards the use of virtual representations in lighting research. Several studies have suggested that both photographs [Hendrick et al., 1977; Newsham et al., 2010; Cauwerts, 2013] and renderings [Mahdavi and Eissa, 2002; de Kort et al., 2003a; Newsham et al., 2005; Cauwerts, 2013] are a promising medium for investigating subjective responses to space and light. In addition, current rendering simulation tools can produce physically-based renderings, which provide accurate photometric data and allow researchers to relate these objective measurements with subjective assessments, a necessary process to uncover the existence of links between stimulus and response.

The challenge lies of course in obtaining research findings that are valid, reproducible and generalizable from virtual to real environments. A key factor in this is the creation of virtual environments that are perceptually realistic and provide an experience that is "indistinguishable from normal reality" [Loomis et al., 1999]. The user interaction and immersion have been identified as crucial parameters in creating virtual environments that can adequately substitute the human experience in the real space [Bishop and Rohrmann, 2003; de Kort et al., 2003b; Newsham et al., 2010; Cauwerts, 2013]. Moreover, current technological advancements have rendered head-mounted displays readily accessible and greatly improved in terms of usability [Parsons, 2015], and have led to their growing use in architectural research, such for investigating occupants navigation [Banaei et al., 2017] and sense of embodiment [Pasqualini et al., 2013] in architecture. Although there are few studies investigating the user's experience of a daylit environment in virtual reality [Franz et al., 2005; Heydarian et al., 2017], little evidence exists on the adequacy of such an environment compared to an equivalent real daylit space, rendering the applicability of this procedure questionable.

To this end, the present section explores the potential of virtual environments for experimental lighting research, with a particular focus on immersive virtual reality, and identifies the key features that are necessary to produce virtual scenes that can be used as surrogates to real spaces. Next, it examines relevant methodological approaches for quantifying the impact of luminous environments on human perception.

2.5.1 Virtual environments in empirical lighting research

Although simulated two-dimensional virtual scenes have been repeatedly identified as an adequate medium for investigating subjective impressions of space and light [Mahdavi and Eissa, 2002; Newsham et al., 2005; Cauwerts, 2013], the immersion of the user in the virtual environment has been a recurring subject in various studies comparing virtual and real environments. This attribute regards not only the field of view provided by the device, an important factor when comparing real and virtual environments [Newsham et al., 2010], but also the user interaction with the presented scene. Across a number of studies, the dynamic experience of a virtual environment is suggested as a feature that could greatly improve the realism and thus the potential of virtual environments for empirical research [Charton, 2002; Bishop and Rohrmann, 2003; de Kort et al., 2003b; Newsham et al., 2010].

However, a central debate in the use of virtual environments in lighting research is the luminance range of the display device, and the consequent tone-mapping of the dynamic range present in the real environment to the compressed dynamic range of the device. Is the immersion or interactivity in the virtual scene more important than the luminance range of the device to accurately represent an occupants' perception of the scene?

In a study comparing the perceptual accuracy of high dynamic range (HDR) and low dynamic range (LDR) images, Newsham et al. [2010] tested the hypothesis that photographs of interior environments would be perceived as more realistic and would be more perceptually accurate when shown in the high dynamic range ($\leq$4000 cd/m^2) rather than the low dynamic range ($\leq$200 cd/m^2) of an HDR display. To test this hypothesis, 39 participants evaluated six interior spaces with mixed daylight and artificial light sources, as well as the LDR and HDR photographs of these scenes using four scales:

dim–bright, non uniform-uniform, unpleasant-pleasant, and glaring-not glaring. In addition, they were asked to rate which of the two display modes were the most realistic in a side-by-side comparison. While the HDR images were indeed rated as more realistic for four out of six scenes, the side-by-side comparison of the two modes possibly biased this outcome. Indeed, the analysis of the participant responses between the real, LDR, and HDR scenes showed that the HDR display mode resulted in ratings with both an absence of difference with the real scene and a difference with the LDR —showing both the perceptual accuracy of the HDR mode and its advantage over LDR— solely for two out of six scenes, notably those with higher luminances. Lastly, the comparison between the LDR images and the real environment is not reported, while the experimental design of the study has been criticized for potential biases stemming from the successive presentation and evaluation of HDR and LDR images [Rockcastle, 2017].

These limitations are not present in the study by Murdoch et al. [2015], where LDR and HDR images were evaluated by different participants. In addition, both static stereoscopic (3D) and interactive monoscopic (2D) LDR display modes were examined, allowing the direct comparison of the effects of stereoscopy, interactivity, and increased luminance range on perceptual accuracy. Specifically, this study investigated the perceptual accuracy of artificially lit rendered scenes shown in various display modes, including variations in the luminance range of the display, the field of view area, the interactivity in the scene, the tone-mapping operator, and the renderer used to generate the scene. Photographs of the artificially lit scenes, projected in a low dynamic range display, were also used in the comparison. Due to limitations in the available technology and the number of experimental factors, the experimental study did not follow a full factorial design, but was rather an iterative process with multiple experiments combining different promising factors. Regarding luminance range, the devices that were employed offered either stereoscopy (3D stereo view) with a maximum luminance of 397 cd/m^2, no stereoscopy and maximum luminance of 180 to 280 cd/m^2, depending on the device, or no stereoscopy and a maximum luminance range of 1800 cd/m^2 (HDR display). In total, 127 participants rated different combinations of display parameters, and their responses were compared with the baseline evaluations of 28 participants that were exposed to the equivalent real-world artificially lit environments. Dependent variables consisted of impressions of pleasantness, brightness, diffuseness, contrast, uniformity, shadow visibility, as well as the atmosphere factors cosiness, liveliness, tenseness, and detachment. Their findings showed that photographs were the best performing medium, while the most perceptually accurate simulated representation was achieved with a 360° interactive panorama, tone-mapped with the Reinhard [2002] tone-mapping operator and shown in a 2D low dynamic range display. Moreover, the 360° interactive panorama, along with the 3D display mode, both of which had a comparable low dynamic range displays, were the best simulated representations in terms of the number of significant differences from the real environment. Both of these modes were shown to be considerably more perceptually accurate than the HDR display, with 3 times fewer significant differences from the real experiment compared to the HDR display. These findings show that both interactivity and stereoscopy are important factors, more so than high dynamic range, to accurately replicate an occupants' experience of a real space for the aforementioned perceptual impressions.

Although binocular disparity in stereoscopic projections is primarily recognized due to its contribution in providing depth information [Loomis et al., 1999], recent studies have also highlighted its importance for the naturalness of the resulting virtual environment [Lambooij et al., 2011]. In the subject of subjective evaluations of daylit scenes, while stereoscopic projections have been found to be an adequate representation method of real environments [Charton, 2002; Moscoso et al., 2015b], studies that compare the subjective assessment of scenes in 2D and stereoscopic 3D projections suggest that there is little difference in how they are perceived.

In order to compare the effect of 2D and 3D projection modes, Cauwerts and Bodart [2011] conducted a within-subject experiment where 38 participants were exposed to a real space, and then to 2D and 3D projections of HDR photographs with a maximum displayed luminance of 300 cd/m^2, for a total of eight interior daylit scenes. As the photographs were captured during each experimental session, the real space was always presented first, introducing a possible stimulus order bias. Participants were asked to rate their impressions of how bright, pleasant, glaring, stimulating, tense, spacious, friendly, usual, realistic, and warm was the presented space, and to rate their satisfaction with the space, the quantity, and the quality of the light. Lastly, for each projected scene, participants were asked to rate which one seemed more realistic. Although the 3D projection was rated as more realistic than the equivalent 2D projection, stereoscopy did not have a significant effect when directly comparing the subjective evaluations in the two projection modes.

Few technologies allow the combination of both stereoscopy and high dynamic range. The Stationary Virtual Reality (SVR) tool by Wienold et al. [1998] is a notable exception, employing multiple slide projectors to project a stereoscopic scene with a maximum luminance of 9'000 cd/m^2 as close as possible to the eyes of the user. Using a conceptually similar setup with a much lower maximum luminance, close to 1'400 cd/m^2, Moscoso et al. [2015b] investigated the perceptual accuracy of a stereoscopic projection on a silver screen. In this experiment, 26 participants were shown six variations of a daylit space representing a student room setting, with two levels of surface reflectances (black and white surfaces) and three levels of window size, both in a real environment and in a stereoscopic projection of the photograph of the equivalent real condition. The photographs of the scenes were captured using conventional cameras in an automatic mode, resulting to low dynamic range images corresponding to the left and right eye view of a user which were superimposed in the silver screen projection and combined with polarized glasses to create a stereoscopic scene. Results showed that the stereoscopic projection is an adequate representation method of real environments, particularly for the space with the white surface, where it was shown to be sufficiently accurate in representing the dimensions of pleasantness, excitement, order, complexity, legibility, coherence, spaciousness, openness, and spatial definition.

The impact of interactivity, stereoscopy, dynamic range, and image type on perceptual accuracy of virtual environments is also examined in a series of experiments by Cauwerts [2013]. In a mixed experimental design, 239 participants, in groups of roughly 40, were exposed to a total of four daylit scenes, seen either in reality, or in the following virtual representations: monoscopic static LDR and HDR scenes from photographs, stereoscopic static LDR scenes from photographs, monoscopic interactive LDR scenes from photographs, and monoscopic interactive LDR scenes from renderings. Participants were asked to evaluate the presented scenes across a number of perceptual attributes relating to pleasantness, enclosedness, brightness, coloration, contrast, light distribution, light directivity, and glare. No display mode was capable of reproducing the perception of enclosedness in the real space, a finding which suggests that immersion is necessary to accurately convey this spatial attribute. Moreover, the monoscopic interactive LDR photograph-based scenes were shown to be the most perceptually accurate, resulting to the lowest number of significant differences compared to the evaluations of the real scenes. In addition, this display mode was shown to be the only one able to replicate the dimensions of perceived pleasantness and the distribution of light in the real space. These findings, along with the outcomes of Murdoch et al. [2015], underline the potential of immersive virtual reality as a promising tool for daylighting research. Additionally, in the context of this thesis, the failure of all display modes that were studied by Cauwerts [2013] in accurately representing the sense of boundaries in the real environment necessitates further work for the development of an experimental tool that can address this limitation through increased immersion in the virtual scene.

Heydarian et al. [2015] compared the task performance in dark and bright conditions between a real environment and its virtual representation in virtual reality. An initial set of participants performed three tasks (reading speed, text comprehension, object identification) in a single occupancy office under four lighting conditions —two dark and two bright– with mixed artificial and natural lighting. In a second study, 120 participants performed similar tasks in the equivalent four simulated variations of the office room, shown in virtual reality. Results showed that the differences between the bright and dark conditions were consistent across the real and virtual environments, with the dark conditions leading to significantly lower performance in reading speed and text comprehension. Moreover, the authors used the difference in task performance between the bright and dark conditions as a measure of relative performance in each environment. No significant differences were found in relative performance between the real and the virtual environment, leading the authors to conclude that the participants' performance was sufficiently similar in the two environments.

Another relevant study allowed the users of a VR headset to adjust the blinds and artificial light in a virtual office space, aiming to investigate the participant's lighting preferences for office related tasks [Heydarian et al., 2017]. The participants were invited to adjust the light condition in the room to their preference and their preferred settings were later compared with light maps that represented the chosen lighting setup of the user. Although this study is an important step in exploring the potential of immersive virtual environments, it presents two significant limitations: the rendering of the virtual space was not physically-based and the researchers had no control over the specific properties of the virtual space projection. The final projected scenes were rendered through a game engine with a photo-realistic real time renderer. As a result, there is no indication of the actual light measurement values of the scenes that the participants were shown and acted upon. The participant's preferences and behavior in the virtual environment were identified in light maps produced separately with physically-based calculations, corresponding to high dynamic range values of real world luminous conditions and not to those of the scene that was projected with the limited luminance range of the headset.

Along with the simulation accuracy of the virtual scene, the subject of presence is an emergent factor in creating a virtual environment that can adequately replicate our experience of a real space [de Kort et al., 2003b; Diemer et al., 2015]. Presence is defined as the sense of "being there" in the virtual environment [Slater and Wilbur, 1997]. Schubert et al. [2001] identified three dimensions of self-reported presence through factor analysis: spatial presence, involvement and realness. These factors correspond to the user's sense of being in the virtual space, their lack of awareness of the real world, and the perceived realism of the virtual scene in comparison with the real environment.

Chen et al. [2019] examined the perceptual accuracy, satisfaction with the representational ability of the medium —such as sense of presence, realism, or depth of field—, and overall satisfaction with the environment across four presentation modes. In a within-subjects design, 40 participants first rated a reference physical room under three levels of CCT —an approach that introduces possible order effects— and then evaluated the same scenes shown through a 360° video projected on a smartphone-based VR headset, as well as an LDR video and an LDR photograph projected on a screen. Results show that the VR video had the highest levels of perceptual accuracy, as well as the highest ratings regarding the representational ability of the medium and the overall satisfaction with the environment. However, when comparing the number of significant differences between the virtual and real environments, the VR video and the LDR photograph showed an equally unsatisfactory level of perceptual accuracy, with only four out of twelve studied attributes resulting to an absence of a significant effect of medium. The authors suggest the limitations of the smartphone-based VR equipment as a possible explanation, indicating that the presentation of the VR video was not smooth and that the participants' movement in the virtual scene was restricted.

Similarly, Abd-Alhamid et al. [2019] compared a real and a virtual artificially lit office space, using photograph-based 360° scenes shown in a VR head-mounted display to create the latter. In a within-subject design, the task performance of 20 participants were tested in both environments using a characters contrast test and a Stroop color naming task. In addition, participants were asked to evaluate the visual quality (such as the level of detail, contrast, and colorfulness), the appearance of the lighting (such as the brightness and uniformity), the perceptual impressions of the room (how pleasant, interesting, calm, complex, or spacious the room was perceived), and lastly their reported presence and physical symptoms in the scene. Task speed was significantly lower in the virtual environment compared to the real environment, a finding which was attributed to the low resolution of current VR headsets. Accuracy was lower in the virtual environment for the color naming task but not for the character contrast task. Moreover, while significant differences were found between the two environments for all three aforementioned attributes of visual quality, no differences were found for any of the attributes regarding the appearance of the lighting or the perceptual impressions of the scene. Lastly, results showed a high level of perceived presence. Regarding physical symptoms, significant differences with a small-to-moderate effect size were found before and after the use of the headset in questions relating to eye strain, blurred vision, and dizziness. These findings indicate that current VR devices might be lacking in terms of visual quality —with subsequent effects on eye strain or task speed and performance—, but are promising for recreating the visual appearance and perceptual impressions of an interior scene, at least in the context of artificial lighting.

In another study, Higuera-Trujillo et al. [2017] compared the participant responses in an artificially lit real space and three different virtual environments that were shown in a VR headset: a low dynamic range photograph, a 360° static immersive scene based on this photograph, and a fully interactive simulated scene with photograph-based textures. A total of 100 participants were exposed to an artificially lit mock-up of a retail store and the equivalent virtual representations of that space in the three different formats using a within-subject design. Both subjective —perceptual impressions, emotional state, and sense of presence— and physiological —heart rate and skin conductance— responses were recorded for each condition. Results showed that the 360° photograph-based static scene was the most accurate method for the perceptual impressions, emotional state, and sense of presence of participants, followed by the interactive simulated scene, and lastly the photograph. In particular, the 360° static immersive environment was shown to accurately reproduce impressions of both pleasantness and enclosedness, the latter being a spatial attribute that was not successfully replicated in the interactive but non-immersive virtual scenes in the work of Cauwerts et al. [2013]. In addition, no significant differences in physiological responses were found between either the 360° photograph-based panorama or the interactive scene and the real environment. However, skin conductance responses differed significantly between the real environment and the photograph shown in VR, which was limited both in terms of immersion and interactivity in the virtual environment. These findings show that 360° immersive scenes shown in VR are particularly promising for experimental research, and suggest that immersion and realism are more important features than interactivity to sufficiently recreate the experience of a real environment. Nevertheless, there is a lack of knowledge regarding the adequacy of immersive virtual reality for the representation of daylit scenes, which is a stumbling block for the adoption of this technology in daylighting research.

In addition to a sense of immersion, the subject of adverse physiological reactions (cybersickness) has been identified as a possible factor of the perceived presence in virtual environments [Schubert et al., 2001; Lessiter et al., 2001]. To this end, a study by Van der Spek and Houtkamp [2008] examined the effect of cybersickness on impressions of a cityscape. Specifically, simulator sickness was induced to 30 participants watching a non-interactive city tour projected on a screen. Participants were asked to evaluate the environment using four bipolar scales: pleasant-unpleasant, arousing-sleepy, distressing-relaxing, and exciting-gloomy. Results showed that the reported adverse physical symptoms significantly influenced the participants' perceptual impressions. Specifically, participants experiencing cybersickness evaluated the environment as less pleasant and less arousing. This outcome is particularly relevant for the use of virtual reality as an empirical research tool, emphasizing the need for a multi-criteria analysis for the adequacy of virtual reality as a substitute for real environments.

2.5.2 Quantifying the effect of luminous conditions on occupants

In the context of lighting research, the subjective appraisal of the studied environment —such as judgments that a space appears exciting— has been argued to be intertwined with emotion processes [Veitch, 2001]. In this context, the work of Russell et al. [Russell, 1980; Russell et al., 1981] is particularly relevant, showing through factor analysis that emotional responses to environments can be reliably represented with two dimensions, pleasure (valence) and arousal (activation), illustrated in Figure 2.1. Although it has been argued that additional dimensions, such as potency, are required to adequately represent the domain of emotions [Fontaine et al., 2007], the dimensions of pleasure and arousal have been identified as especially pertinent for use in lighting research [Boubekri et al., 1991]. Moreover, these dimensions are suggested to be comparable to the atmosphere factors of *cosiness* and *liveliness*, derived from experiments in artificial lighting conditions [Vogels, 2008].

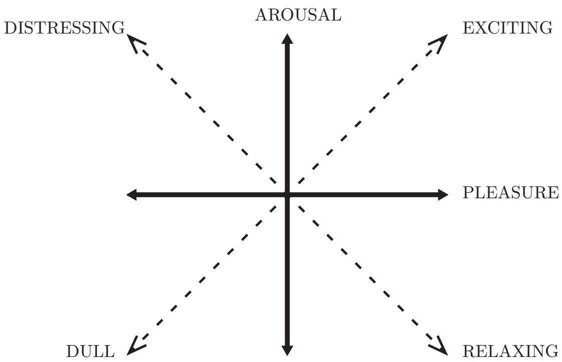

Figure 2.1 – Russel's circumplex model of affect (adapted from Boubekri, 1991).

A notable difficulty in understanding the impact of luminous conditions on subjective responses such as user mood and emotion is their dependence on the initial state of the observer [Vogels, 2008]. In contrast, a quality that is projected onto the environment, rather than the observer, is considered to be a more stable variable for the assessment of subjective experience [Küller, 1991]. In particular, impressions of the surrounding environment are suggested to be both independent of the initial emotional state of the observer and stable over time, although they can be influenced by other factors, such as the age or cultural background of the observer [Vogels, 2008].

The majority of existing research investigating the impact of light and space on perception has used rating scales as the sole instrument in assessing the effects of studied stimuli on participants, as seen in Sections 2.1 and 2.2 (for an extensive review of rating scales used in lighting research, the reader is referred to the work of Hyvärinen [2015]). However, the validity of rating scales in quantifying the perception of a luminous environment has been questioned [Houser and Tiller, 2003; Stokkermans et al., 2017]. An approach where subjective evaluations are coupled with an objective measure has been suggested instead as a more robust research instrument [Tiller and Rea, 1992]. This approach can greatly increase the robustness of research outcomes if the conclusions drawn from both subjective evaluations and physiological measures converge [Veitch et al., 2019].

Physiological responses such as heart rate and skin conductance have been widely used as measures of arousal of the autonomic nervous system. Skin conductance has been shown to be sensitive to a wide range of phenomena, such as attention, activation, novelty and significance of a stimulus [Dawson et al., 2007]. Heart rate, on the other hand, has been suggested to react in opposite directions when mental processing is required, where heart rate was shown to accelerate, or when attentional deployment is involved, where heart rate decelerates [Lacey and Lacey, 1958], and has thus been proposed as a more specific index of attention [Izso et al., 2009]. Similarly, low-arousal positive emotions, such as pleasure, have been associated with decelerated or unchanged heart rate, and unchanged skin conductance response [Kreibig, 2010]. The associations between these two physiological measures and responses of attention or pleasure render them particularly pertinent for research that examines the appraisal of luminous environments.

Visual stimuli have been broadly used to elicit different emotional responses [Lang et al., 1993; Lang, 1995]. The content of the visual stimulus, and particularly its valence —whether it is perceived as pleasant or unpleasant—, has been shown to affect the magnitude of both heart rate and skin conductance reactions [Bernat et al., 2006]. Compared to the range of valence of visual stimuli used in the literature, inanimate objects —including scenes of interior spaces, which are commonly used in lighting research— would be considered neutral [Dan-Glauser and Scherer, 2011], and are thus expected to elicit physiological reactions of small magnitude.

Studies employing measures of heart rate and skin conductance to investigate the effect of virtual representations of the built environment show mixed results regarding their sensitivity [Laumann et al., 2003; Geiser and Walla, 2011; Felnhofer et al., 2015] and suggest heart rate indices as more responsive for applications of environmental perception. However, in lighting research, where both measures have been used to study the physiological effects of different artificial lighting conditions, only skin conductance was significantly affected by the lighting conditions [Izso et al., 2009]. Following these findings, both heart rate and skin conductance indices seem promising for experimental studies that investigate the combined effect of building elements and lighting on occupants.

2.6 Summary of the current state of the art

The occupants' satisfaction with the lighting has been shown to be a central factor in their overall satisfaction with the indoor environment. At the same time, satisfaction with the lighting conditions strongly depends on access to daylight and view out, with occupants demonstrating an overwhelming preference towards these attributes. As a result, the openings and shading systems in a space emerge as crucial design features, mediating access to daylight and view, and influencing the occupants' perception and preference towards their environment.

While direct sunlight is often treated a source of visual discomfort, there is growing evidence that sunlight patterns are not only accepted, but even desired by occupants. The presence of sunlight patches in the scene has been shown to affect an occupants' experience both *in* a space and *of* a space, leading to impressions of well-being, relaxation, visual interest, and potentially to glare tolerance. These findings are in line with research on the appraisal of artificial lighting, which indicates that the perception of a luminous environment can be represented by the dimensions of brightness and visual interest, relating to the intensity and diversity in luminances in the scene, respectively. Both dimensions are shown to be necessary for creating satisfactory lighting conditions. However, while impressions of brightness have been consistently linked with the mean luminance intensity in an occupants' field-of-vew, no commonly accepted objective indicator exists for visual interest. This shortcoming is partly due to the current gap of knowledge regarding the characteristics of luminance distribution in a scene and their effects on occupants. In the context of daylighting research, although a number of studies have examined the impact of continuous sunlight patches on occupant perception, little is known about the perceptual effects of varying the diversity, size, shape, and distribution of sunlight patterns.

In agreement with lighting research, studies in the field of environmental psychology argue that an moderate level of sensory stimulation is necessary for building occupants. Moreover, they place the focus on the role of the ornamentation on a building's façade as a source of stimulation, and particularly on decorative patterns that have visual qualities similar to natural elements. While contemporary architecture indeed shows a trend towards the use of such patterns through multilayered building skins and perforated walls —contrary to modernist architecture, which has been specifically criticized for a complete lack of ornamentation that is detrimental to occupants—, there is limited knowledge regarding the occupants' perception and preference towards these patterns.

In combination with the aforementioned limited understanding on how the spatial characteristics of sunlight patterns influence occupants, the subject of façade patterns and the resulting daylight composition that they create in the scene is shown to be a particularly promising research area. Recent studies that explore the impact of varying façade geometry on occupant perception suggest important perceptual effects of façade complexity, but lack a systematic and broad examination of façade characteristics. Moreover, existing research examines the perceptual effect of either varying daylight conditions in the same space, or varying features of façade openings in the same space and lighting conditions, leaving a gap of knowledge regarding the joint impact of façade geometry and daylight on perception.

The present thesis aims to address this research gap by investigating the influence of both façade and daylight patterns on occupants. The literature reveals two additional factors of importance, which are necessary for the generalizability of research findings in lighting research: the impact of the space function, and the influence of regional differences on occupants' appraisal of daylit space. To this end, this thesis will also investigate the effect of different expected uses of space on occupant perception, and replicate experimental studies across latitudes in Europe to investigate the applicability of findings in varying settings.

Chapter 3

Methodology

The state of the art in Chapter 2 identified a number of research gaps and challenges that are essential to address in the investigation of the central question of this thesis. These research aspects relate to the control and the content of the visual stimulus, as well as the characteristics of the observers, and were key factors in determining the methodological approach in the present thesis to ensure the validity and generalizability of the research findings.

This chapter presents an overview of the aforementioned research gaps and the consequent methodological decisions and research methods that were adopted in this work. In terms of structure, this chapter begins with an outline of the methodological approach that was followed in this thesis, presenting the targeted knowledge gaps, the relevant decisions regarding the direction of the undertaken studies, and the relation between these studies. The next section provides a summary of the research methods that were employed in this work, and presents their advantages and limitations. Lastly, the third section of this chapter discusses the expected research outcomes, as well as their novelty and scientific contributions.

3.1 Approach

The previous chapter highlighted the need for an experimental tool that can combine control of the visual stimulus with immersion, which are necessary features for the investigation of human responses to daylit scenes in the context of this thesis. Moreover, the literature review showed that little is known regarding the impact of façade and daylight pattern characteristics on occupants. While this lack of knowledge ensures the novelty of this research question, it simultaneously raises questions regarding its relevance and potential. Thus, this thesis begins with the development and testing of a novel experimental tool that combines virtual reality with scenes based on high dynamic range images, and continues by examining the magnitude of human responses to façade and daylight patterns before launching into an extensive experimental study that investigates the core questions of this work. The relevance of the present research is then examined further through additional studies related to the prediction and utilization of the key research findings resulting from this work. To summarize the core content of this thesis, Figure 3.1 presents an overview of the conducted studies —including the research methods, aims, and sample size, when applicable—, which will be discussed further in this section.

Figure 3.1 – Overview of the studies conducted in the present thesis.

3.1.1 Foundations of experimental method

The review of the literature in Section 2.5 revealed a central challenge in the investigation of the perception of daylit spaces, namely the variability of lighting conditions, “an unchanging problem when studying daylight” [Veitch and Davis, 2019]. Although virtual environments have been widely used in lighting research to address this issue, static virtual representations, such as monoscopic or stereoscopic images, have been shown to be unable to reproduce the enclosedness, pleasantness, and distribution of light in real daylit spaces [Cauwerts, 2013]. These dimensions, with the exception of enclosedness, were successfully replicated in interactive but non-immersive virtual environments [Cauwerts, 2013], illustrating the importance of interactivity in the virtual scene. Moreover, static interactive and immersive 360° scenes from low dynamic range photographs have been shown to adequately reproduce impressions of enclosedness of an artificially lit space [Higuera-Trujillo et al., 2017], highlighting the potential of immersion in the virtual environment as a means to accurately reproduce the experience of a real space. These findings outline an important gap in existing experimental methods, showing the need for virtual environments that are validated against real spaces and combine immersion and interactivity with visual stimuli that are generated from high dynamic range images, a necessary requirement for lighting research.

To address this research gap, this thesis begins with the development of a virtual reality-based experimental method that can overcome the aforementioned challenges, combining control of the visual stimulus, immersion, and high mobility. The first two attributes are crucial for the investigation of human responses to light patterns, while the mobility offered by a head-mounted display allows the replication of identical experiments in multiple locations, a feature that can greatly improve the validity of findings.

In order to ensure the adequacy of the developed method for the investigation of the research questions of this thesis, its validity is tested against real daylit spaces in two experimental studies that employ visual stimuli in both real and virtual environments. To establish the validity of a virtual environment, it is necessary to show that the exposure to the virtual stimulus evokes similar responses with the exposure to the equivalent real environment [Rohrmann and Bishop, 2002]. To this end, the first experimental study investigates the adequacy of immersive scenes that are generated using renderings from the validated lighting simulation tool *Radiance* and examines the perceptual accuracy of the virtual environment, the sense of presence in the virtual scenes, and the physical symptoms stemming from the use of the virtual reality headset. Given the importance of tone-mapping for the creation of virtual environments and the lack of knowledge regarding the suitability of existing tone-mapping operators for immersive environments, this experiment is followed by a preliminary study and a second dedicated experimental study that investigate the adequacy of existing tone-mapping operators for use in virtual reality. Building on the findings of the previous experiment, these two studies employ immersive scenes with a high level of detail, generated from photographs, with the aim to select the most perceptually accurate tone-mapping operator for virtual reality. These studies aim to refine and validate the developed experimental method, establishing the methodological foundations for the remainder of this thesis.

3.1.2 Magnitude, robustness, and relevance of façade-driven effects on human responses

Following the development and validation of this novel experimental method, subsequent empirical studies in the present thesis employ immersive virtual reality as the medium through which participants are exposed to the studied visual stimuli. Having overcome the critical challenge of controlling the visual stimulus, this thesis continues with the investigation of the central question of this work, namely the impact of façade and daylight patterns on human responses.

Considering the limited knowledge regarding the effects of façade and daylight patterns on perception that was revealed in the previous chapter, it is necessary to examine the relevance of this research topic and the extent of human responses to variations of the spatial composition of façade and daylight. Before conducting an extensive study that addresses multiple primary and secondary research objectives, a series of smaller studies are used to lay the foundations for this work. Specifically, a first experimental study in virtual reality investigates the impact of façade and daylight pattern variations on the subjective responses of participants, followed by a second study that introduces the use of physiological indicators —which were identified as promising in Section 2.5.2— as a complementary research tool. These two studies confirm not only the suitability of the developed experimental method for investigating the central research question of this thesis, but also the relevance and magnitude of this investigation. Building on the findings of these experiments, additional studies are conducted to select façade designs that are promising for further investigation. To this end, a paper-based survey is conducted to examine the consensus of architects regarding the expected perceptual effects of different façade variations. This survey allows the selection of the most promising façade variations in terms of expected perceptual responses, to be used as stimuli in the core study of this thesis.

The state of the art in Chapter 2 identified two factors of importance for lighting research: the effect of the function of the space and the effect of regional differences on perception. The investigation of these factors not only addresses current knowledge gaps in the field of lighting, but is also essential to establish the external validity and generalizability of findings in different settings and populations [Veitch et al., 2019]. To this end, the impact of the space function on participant responses is investigated alongside the effect of façade and daylight patterns, either through the use of scenarios without a visual reference (as in [Butler and Biner, 1987, 1989; Wang and Boubekri, 2010b]) or through the use of visual stimuli where the function of the space is implied by the furniture (as in [de Kort et al., 2003b; Moscoso et al., 2015a; Zhao et al., 2018]). In addition, the mobility offered by the virtual reality headset is exploited in the core investigation of this thesis for the replication of the same experimental study in Switzerland and Greece, and the subsequent investigation of regional differences in the participants' perception.

In this wider experimental study, the façade variations that were identified as promising based on the survey of architects are employed to examine the effect of façade geometry, lighting conditions, and scenario of space use on participant responses. At the same time, the comparison of participant responses between Switzerland and Greece allows the testing of the generalizability of experimental findings across latitudes in Europe. This experimental study forms the core investigation of this thesis, using a substantial sample size to examine the perceptual effects of a wide range of façade variations and to investigate the generalizability of these effects across latitudes and functions of the space. In addition, the robustness of the main façade-driven effects is tested against changes in the window size and type of space where the façade is applied, to examine the external validity of these experimental results.

Following this investigation, further research directions are examined in this thesis, stemming from the experimental findings that regard the effect of façade and daylight patterns on occupants. A natural progression of this work is the investigation of whether these façade-driven perceptual effects can be anticipated. Building on the literature review of Section 2.2 concerning the use of contrast and complexity as drivers of visual interest in architecture, the thesis continues with the investigation of the predictive capability of different image-based metrics for anticipating subjective responses to varying façade geometry. In a second research direction, the façade-driven effects that were identified in this thesis are used as a basis for the development of a kinetic façade with elements that change shape not only to respond to requirements of energy efficiency and comfort, but also to orchestrate the occupants' spatial experience, illustrating the relevance of the present research for real-world applications.

3.2 Overview of research methods

The central methodological approach of this thesis is the conduction of multiple studies to validate the adequacy of the developed experimental method and to establish the pertinence of the principal research question. While the objectives, method, protocol, and procedure of each study are described in depth in the relevant chapters, the present section focuses on the experiments that were conducted in this thesis and provides an overview of the main methodological decisions.

3.2.1 Experimental design

Relevant studies in the literature that compared real and virtual environments used either a between-subject design, with different participants assessing the real and virtual scenes [de Kort et al., 2003a; Cauwerts, 2013; Murdoch et al., 2015], or a within-subject design with a real environment and a single stimulus corresponding to the virtual representation of the real conditions [Bishop and Rohrmann, 2003; Newsham et al., 2010; Kuliga et al., 2015; Moscoso et al., 2015b]. Both methods present unique disadvantages, as the first method introduces inter-subject variability, and the second increases the differences between the lighting conditions that are shown in the real and virtual environments.

The experimental studies in the present thesis that compare real environments and their virtual representations follow a novel approach. In particular, participants are exposed to a visual stimulus that is either selected from a range of pre-rendered scenes according to its similarity with the conditions in the real space (in the case of simulated immersive scenes), or generated in real time (in the case of photograph-based immersive scenes). This approach greatly increases the similarity of conditions between the real and virtual environments and simultaneously eliminates the variance between participants through the use of repeated measures [Coolican, 2014]. Specifically, the presentation order of the two environments is randomized, and thus the first presented environment serves as a reference for the participant.

Existing studies that investigated the effect of façade geometry on perception have employed within-subject designs where the participant is exposed to all levels of the studied factor [Omidfar et al., 2015; Abboushi et al., 2019]. Similarly, in the present thesis, the most important variable —the type of environment, in the studies examining the adequacy of virtual reality as an experimental tool, and the façade geometry, in the studies investigating human responses to façade and daylight patterns— is consistently employed as a within-subject factor, an approach which increases the statistical power for that factor [Hoyle, 1999]. As a principal limitation of repeated measures is the presence of possible order effects [Coolican, 2014], the presentation order of the stimuli is randomized in all studies, and order effects are specifically analyzed and reported. Regarding statistical analyses, appropriate statistical tests are selected according to the type of data and the experimental design, and discussed in the relevant chapter. Similarly, effect sizes and their interpretation are reported for all significant results.

3.2.2 Independent variables

To make certain that the presented visual stimulus was the main focus of the experiment, experimental sessions were conducted in indoor environments, ensuring conditions that were not disturbing for the participants. Moreover, to ensure that participants experienced the virtual environment similarly, participants were asked to limit their body movements and explore the scene from a static position. Regarding visual acuity, eligibility criteria included normal or corrected-to-normal vision. In addition, a training scene with black background and white text was used as a reference in virtual reality to verify the correct adjustment of the headset.

As the fundamental question in this thesis revolves around the influence of the characteristics of façade and daylight patterns on humans, the studied stimuli in the virtual reality experiments consist of variations in the façade geometry and the lighting conditions in a scene. By using the façade geometry as a within-subject factor, the same participant is exposed to controlled variations of the façade geometry and the resulting daylight patterns, while the sky type and surrounding space is held constant. In order to draw valid conclusions, it is necessary to limit the number of varying façade characteristics. To this end, the perforation ratio, materials, and depth of the façade is kept constant within each experimental study where the façade geometry was one of the independent variables. Although the choice of keeping these factors constant limits the applicability of the findings, it ensures the robustness of the conclusions regarding the effect of the shape and the spatial distribution of façade openings.

This choice also restricts the representation of existing façade designs, introducing potential differences from real-world systems. For example, to ensure homogeneity in the depth and perforation ratio of the studied experimental stimuli, horizontal and vertical blind systems in this thesis are represented through simplified two-dimensional patterns which are assumed to have similar visual effects due to the repetition of elements, as suggested by Penacchio and Wilkins [2015]. While designs with thin horizontal and vertical elements exist, such as in brise soleil systems, this approach does not allow the representation of systems with curved or rotating lamellae. Such differences between the stimuli used in the present thesis and façade designs where depth is an additional degree of freedom can impact the visual appearance and the view through the façade, as well as the light distribution in the space, affecting also the perception of the space.

At the same time, the use of identical material, depth, and perforation ratio for the façades ensures that the lighting conditions are comparable across repeated measures within the same sky type. Specifically, the restriction of the façade depth minimizes possible reflections towards the ceiling and other surfaces, allowing better control of the light distribution in the space across the different façade variations. To verify the control of the visual stimulus and ensure that the spatial characteristics of façade and daylight patterns is the sole changing feature across variations of façade geometry, vertical illuminance and color differences between stimuli are reported and compared to relevant thresholds [Mahy et al., 1994; European Committee for Standardization (CEN), 2011] in each experimental study.

The adoption of virtual reality allows full control of the lighting conditions in the presented scene, which is a necessary feature for the investigation of the central research question in this thesis. Although the present work examines the perceptual effects of the shape and spatial distribution of façade and daylight patterns through the use of virtual reality, the luminance range of the virtual reality display is limited. As a result, it is not possible to examine the potential discomfort from light patterns with realistic luminances, which can be distracting or confusing for occupants [Osterhaus, 2009]. This is an important limitation of the method —and the resulting visual stimuli— adopted in this thesis, which warrants further studies to examine human responses in high luminance conditions.

3.2.3 Dependent variables

Regarding the selection of dependent variables, the principal focus of this work lies in the perceptual impressions of space, driven from the gaps of knowledge identified in Chapters 1 and 2. To this end, both scalable (such as brightness or spaciousness) and non-scalable (such as pleasantness, interest, or excitement) properties of the lit environment are employed, according to the definition by Tiller and Rea [1992]. The use of non-scalable properties of the environment is necessary to broaden our understanding of the effects of light on humans, as argued by Boyce [2003], who states that "if rating scales are to be restricted only to those that have a link to an obvious feature of the luminous environment, then there is little prospect of ever understanding the impact of lighting on what might be called high order perceptions, such as complexity, formality and interest".

The review of methods for quantifying the effects of the luminous environment on occupants in Section 2.5.2 showed that impressions that are projected to the environment, rather than the observer, are suggested as a more robust variable [Küller, 1991; Vogels, 2008]. Specifically, rating scales that address a participants' impression of the studied scene (i.e. "how exciting is this space?") are suggested as more stable and objective compared to scales that address the participants' state or mood (i.e. "how excited do you feel?"). On a similar note, Boyce [2003] advocates shifting the focus from how people perceive specific lighting conditions to how these lighting conditions alter the way people perceive the space they are in. Consequently, the present thesis employs rating scales that are assessing the participants' impressions of the environment (i.e "how exciting is this space?", "how interesting is this space?").

In terms of the question format, bipolar scales (i.e. "how would you rate this space from exciting to calming?") depend strongly on the choice of adjectives [Hyvärinen and others, 2015], which might not be perceived as antonyms. Rockcastle [2017] offers another perspective, arguing that even when using antonyms, a rating scale from calming to exciting does not offer a negative evaluation. As such, it does not allow to identify conditions that might range from exciting to disturbing, or from calming to dull. In addition, such a rating scale presumes that the stimulus cannot be both calming and exciting, or neither calming nor exciting. To address these shortcomings, this thesis adopts individual unipolar rating scales that represent potentially orthogonal dimensions, such as evaluations of a stimulus as *exciting* and *calming*, complemented additional scales representing an underlying dimension of interest, such as *pleasantness*, following Russel's circumplex model of affect [Russell, 1980]. The perceptual attributes that are chosen for investigation are based on the relevant literature, and specific choices are discussed in the corresponding chapters.

The adoption of virtual reality in the experimental studies of the present thesis prohibits the use of physical questionnaires. To avoid using a visual reference in virtual reality, which would impact the presented stimulus and reduce the participants' sense of presence in the scene, questionnaires were administered verbally. For consistency, verbal questionnaires were used both in the virtual and real environments, when applicable. Although the use of verbal questionnaires is not widespread in lighting research, such questionnaires are widely used in experimental research conducted in virtual reality [Pan et al., 2015; Higuera-Trujillo et al., 2017; Collingwoode-Williams et al., 2017] due to the aforementioned limitations. Previous research using verbally administered rating scales in real environments and their corresponding virtual representations in 360° static immersive scenes found no significant differences between the two environments for impressions of pleasantness, complexity, enclosedness, unity, or familiarity with the scene [Higuera-Trujillo et al., 2017], supporting the use of this method in the present thesis.

As discussed in Section 2.5.2, the use of rating scales has been criticized in lighting research. Studies using both paired-comparisons and rating scales to investigate the influence of light on the atmosphere of a scene reported that effect sizes were on average larger with paired comparisons than with the rating scales, but note that the outcomes from both methods were strongly correlated (with a ρ higher than 0.95 for perceived brightness, color, uniformity, cosiness, liveliness, and tenseness, and a ρ of 0.68 for perceived tenseness) [Stokkermans et al., 2017]. This finding suggests that rating scales might be less sensitive than paired comparisons, but they lead to the same outcomes. As the majority of the studies in lighting research use rating scales, this method was also adopted in the present thesis. Nevertheless, following current recommendations for the use of multiple methods in lighting research [Veitch and Davis, 2019], this thesis explores the use of both explicit (i.e. an explicit response to a stimulus) and implicit measurements (such as physiological or behavioral measurements), as defined in [Commission International de l'Eclairage (CIE), 2014]. Specifically, physiological indicators of heart rate and skin conductance, which have been identified as promising in the literature, are examined as complementary measures of perception. Both measures, as well as the recording device that is employed in the present thesis, have been used in studies comparing human responses in real spaces and in equivalent 360° static immersive scenes, where no significant differences were found between the two environments [Higuera-Trujillo et al., 2017], confirming the validity of these measures in virtual reality.

3.3 Expected outcomes

The expected outcomes of this work range from new knowledge that concerns the core question of this thesis to contributions with wider implications for the fields of lighting, architecture, psychology, and vision. Figure 3.2 presents an overview of the main studies, their outcomes, as well as their dependence, summarizing the present method.

The methodological foundation of this thesis lies in the development and validation of a novel experimental method that overcomes the obstacle of changing lighting conditions, offering immersion and full control of the visual stimulus. The novelty of this method resides in the combination of virtual reality with scenes that are based on high dynamic range images, which renders it particularly promising for experiments that investigate the perception of space and light. Moreover, this experimental method offers high mobility, allowing the seamless reproduction of stimuli and facilitating the replication of experiments. The validity of this virtual reality-based experimental method is tested against real environments, providing an essential reference for the suitability of virtual reality as a surrogate to real spaces in empirical studies. In addition, the investigation of the adequacy of the developed method extends to the identification of tone-mapping operators that can successfully reproduce the experience of a real space in virtual reality, addressing an critical gap in the existing literature.

The principal aim of this thesis is to broaden our understanding of human responses to façade and daylight patterns. Through a series of investigations, this thesis systematically examines the joint impact of the façade geometry and of the corresponding daylight patterns on perception, uncovering new knowledge on how the built environment can influence the human experience. Moreover, the present work examines the impact of façade and daylight patterns on physiological responses, seeking to demonstrate that architectural elements and their interaction with light can have a quantifiable effect on occupants. In addition to these research objectives, this thesis examines the effect of space function on the perceptual impressions of daylit scenes, with the aim to extend our knowledge on how the expected use of space can influence the preference and perception of occupants. The present thesis adopts a linear methodological approach, beginning with the validation of the experimental method and continuing with studies that examine the relevance of the research objectives and lay the foundations for an extensive experimental study that is replicated in Switzerland and Greece. This study aims to bring important evidence not only on the perceptual effects of façade and daylight patterns, but also on the generalizability of such effects, by testing their robustness across latitudes in Europe and across design features of the space where the façade is applied.

Lastly, this thesis explores the prediction and utilization of the main research findings that regard the perceptual effects of façade and daylight patterns. To this end, the findings are used to investigate the capabilities of image-based metrics as predictors of human responses, contributing to the fields of architecture and lighting, as well as to current research on human vision and environmental psychology. Moreover, to demonstrate the relevance of the present research for applications in architecture, this thesis explores the integration of findings in the design of a novel shading system, outlining new directions in the design of static and kinetic façades with a focus on occupant perception.

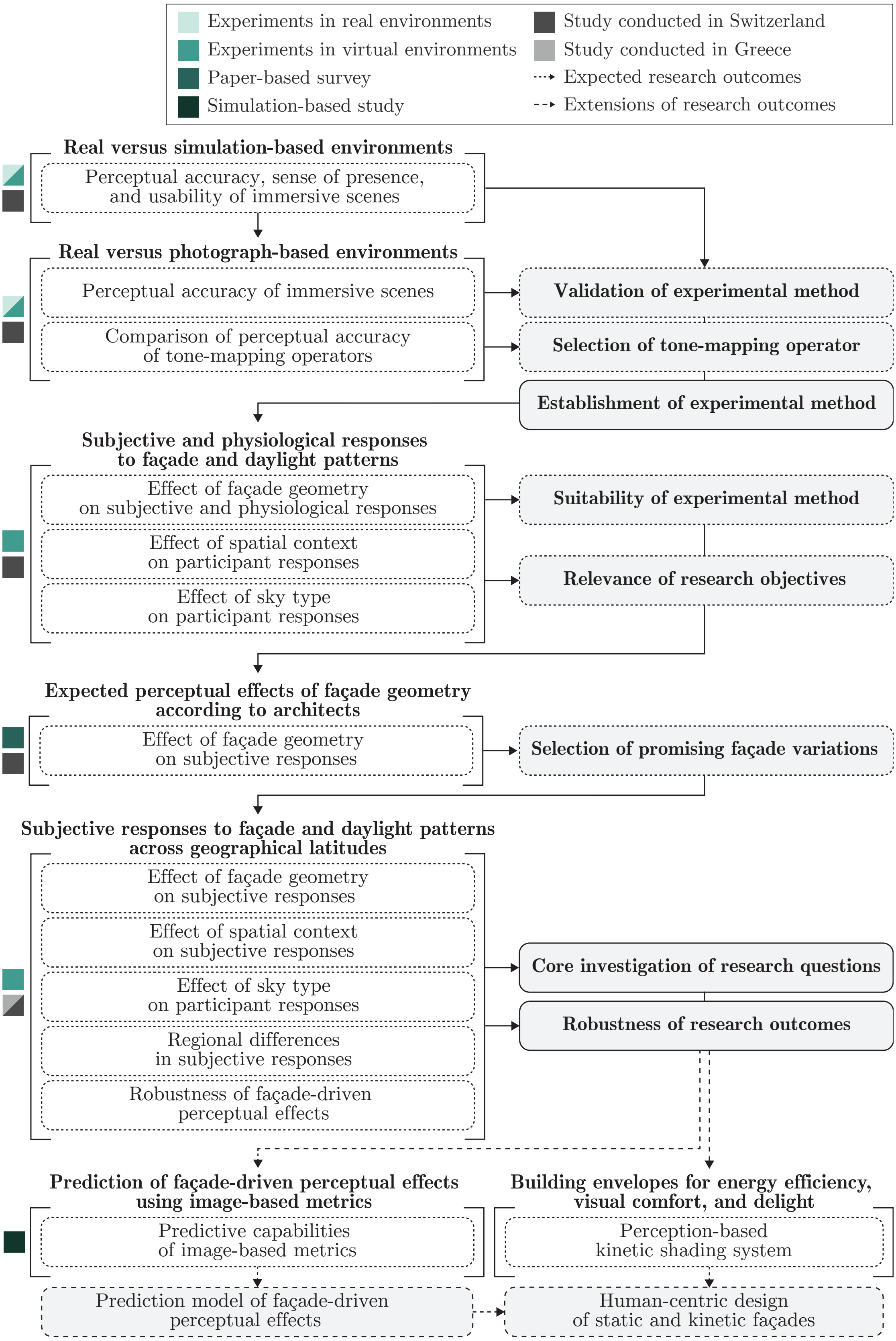

Figure 3.2 – Overview of the main studies, their outcomes, and the links between them.

Chapter 4

Virtual reality as an experimental tool

The literature review in the previous chapter revealed that a significant stumbling block in the acceleration of knowledge on the perceptual qualities of daylight lies in the difficulty of controlling the lighting conditions in an experimental setting, which in turn limits the reproducibility of findings. In the pursuit of creating virtual environments that can be used as a substitute for real spaces in empirical research, studies have highlighted several factors of importance. Firstly, when investigating the effects of light on perceptual impressions, such as the perceived pleasantness or interest of a scene, the virtual environment needs to both represent conditions that are photometrically accurate and to recreate the impressions of a real scene. In addition, the user interactivity and immersion in the virtual space have been identified as essential in adequately reproducing the human experience in the real space. Although considerable research has been devoted to comparing and validating methods that aim to couple these features, so far existing methods are lacking in the depth of user immersion within the virtual environment.

This chapter presents an novel experimental method that uses a Virtual Reality (VR) headset for the conduction of experiments that investigate the perceptual effects of daylight. The proposed method produces an immersive virtual environment from high dynamic range images, combining a wide field of view, interactive viewing mode, and stereoscopy for the main view direction. This technology has the potential to overcome important barriers in the conduction of experiments in real environments by allowing the control, replication, and rapid alternation of visual stimuli, while offering a high degree of immersion. Following the approach of Bishop and Rohrmann [2003], who urged researchers to conduct validity assessments when introducing a novel experimental method, the present chapter presents the results of two experimental studies that investigate the adequacy of virtual reality as an experimental tool using simulation- and photograph-based immersive virtual environments, respectively. This chapter aims to test and establish the methodological instruments to be used in the empirical studies that form the core of this thesis.

Structurally, this chapter consists of three sections. The first section introduces an experimental study that used real environments and the corresponding simulation-based immersive scenes to test the participants' perception, physical symptoms, and sense of presence in the virtual scene. The second section builds on the findings of this first experimental study and investigates the tone reproduction of photograph-based immersive scenes. Lastly, the third section includes a summary of the findings of this chapter and introduces the focus of the following chapter.

4.1 Real versus simulation-based virtual environments*

In order to recreate the experience of a real environment, two factors are essential: the level of detail in the scene and the reproduction of an observer's perception of the light in the scene. Studies examining the perceptual accuracy of virtual environments have shown that the presence of objects in the scene and the use of materials based on real reflectances can lead to sufficiently perceptually accurate virtual scenes [Cauwerts, 2013; Murdoch et al., 2015]. Regarding the reproduction of the lighting conditions in a real environment, current rendering simulation software can generate physically-based high dynamic range renderings that accurately recreate the photometric quantities in a real environment. However, high dynamic range images, whether generated through simulations or photographs, have to be compressed to the dynamic range of conventional displays. This compression makes the subject of the tone-mapping process, and particularly the tone-mapping operators (TMOs) —algorithms that dictate this tone reproduction from a high dynamic range to a limited dynamic range— crucial for the creation of virtual environments [Salters et al., 2012]. However, there is a gap of knowledge regarding the suitability of existing tone-mapping operators for immersive virtual environments.

This chapter presents a novel experimental method which uses a VR headset to project visual stimuli, aiming to provide an alternative environment for the conduction of subjective assessments in daylit spaces. The novelty of this method lies in the generation of immersive virtual environments from high dynamic range images. In order to test the adequacy of the developed method, both real environments and their virtual representation in VR were employed, using the real environment as a benchmark for the perceptual impressions of the presented scene. This chapter begins by introducing an experimental study that used real and simulated immersive scenes, generated from physically-based renderings using *Radiance* [Ward, 1994], a widely validated lighting simulation software [Mardaljevic, 1995; Reinhart and Herkel, 2000; Ng, 2001; Ruppertsberg and Bloj, 2006; Reinhart and Andersen, 2006]. The focus of this study lies in the investigation of the adequacy of the proposed method when employing simulated scenes and a modeling level of detail similar to non-immersive virtual environments in the literature [Cauwerts, 2013; Murdoch et al., 2015]. For this experiment, the high dynamic

*The content of this section is partly based on a published journal article [Chamilothori et al., 2019c]: K. Chamilothori, J. Wienold, and M. Andersen, "Adequacy of Immersive Virtual Reality for the Perception of Daylit Spaces: Comparison of Real and Virtual Environments," *LEUKOS*, vol. 15, no 2-3, pp. 203-226, 2019. The text is reproduced here as a courtesy of the publisher and with the agreement of the co-authors.

range scenes were mapped to low dynamic range through gamma conversion, without the use of a dedicated tone-mapping operator. The subject of tone-mapping operators is discussed in Section 4.2, followed by a second experimental study that investigated the perceptual accuracy of different operators.

This section introduces the developed virtual reality-based experimental method, and tests the adequacy of simulated immersive scenes against the corresponding real environments. The adequacy of the proposed method is evaluated in three different areas that were identified as crucial in the literature review of Section 2.5.1: its perceptual accuracy, the physiological effects of using the head-mounted display, and the reported presence of participants in the virtual environment.

4.1.1 Testing immersive VR scenes from physically-based renderings

The aim of this experimental study is threefold: to examine whether the use of VR influences the appraisal of a daylit space, to investigate possible adverse physiological effects from the use of the VR headset, and lastly, to evaluate the level of perceived presence in the virtual scenes. The method followed in this study consists of the selection of visual stimuli in the real and virtual environments, and the design of an experiment that allows the investigation of the adequacy of VR in the three areas of perceptual accuracy, physical symptoms, and perceived presence, as illustrated in Figure 4.1.

The perceptual accuracy of the virtual environment and the influence of the use of VR on the physical symptoms of participants were assessed through repeated measures, as shown in Figure 4.1 (2a) and (2b), by collecting the participants' responses in the real and virtual environment, as well as before and after the use of the head-mounted display, respectively. In addition, the reported presence in the virtual scene is evaluated through a verbal questionnaire after immersion to the VR scene (Figure 4.1, (2c)).

1 Visual stimuli in the real and virtual environment

a. **Real Environment**	selection of **experimental space**
b. **Virtual Environment**	generation of **physically-based renderings**, **tone-mapping** and **projection** in the VR headset

2 Experimental design to investigate the adequacy of VR as an experimental tool

a. **Perceptual Accuracy**	evaluation of **participant perception** in the **real and virtual environment** (within-subject)
b. **Physical Symptoms**	reported **physical symptoms** **before and after using the headset** (within-subject)
c. **Reported Presence**	evaluation of **perceived presence** in the virtual scene after using the VR headset

Figure 4.1 – Illustration of the methodological approach in the study.

This section begins by describing the experimental study and the workflow for generating the simulation-based immersive scenes, and continues by presenting the findings regarding the adequacy of the virtual environment in the three areas of investigation.

4.1.1.1 Experimental design

The present study employs a within-subject design, where the stimulus that shown in VR is selected from a range of pre-rendered scenes according to their similarity with the conditions in the real environment. Specifically, participants were shown both the real and the virtual environment, and the presentation order of the two environments was counterbalanced between participants. The use of repeated measures has the advantage of eliminating the effect of variance between individual participants, as each subject acts as their own control. In particular, by randomizing the presentation order of the two environments between participants, the first environment a participant was exposed to functions as a reference for their subsequent evaluations.

4.1.1.2 Equipment

The VR headset used for presenting the virtual environments in this study was the Oculus Rift Development Kit 2 (DK2). This headset has a 1920x1080 pixel low persistence OLED display with a refresh rate up to 75Hz, resulting in a resolution of 960 x 1080 pixels per eye. The display offers a 100° horizontal and 110° vertical field of view. Although the maximum luminance of the display is up to 300 cd/m^2, in this experiment the maximum measured luminance was 80 cd/m^2 on the display and 40 cd/m^2 on the lens due to software limitations. In the development and execution of this study, the software used was *Oculus Runtime 0.7.0.0*, in combination with *Unity Game Engine 4.9.6* and the corresponding Unity Package *OculusUtilities* (from https://unity3d.com/ and https://www.oculus.com/ respectively).

4.1.1.3 Description of the real environment

In order to test the perceptual accuracy of the virtual reality as an experimental tool, we set to compare the subjective evaluations of a real space and its representation in virtual reality. Aiming to keep in line with the characteristics of experimental spaces in relevant studies, the criteria that were established for the selection of the test room were a small-to-medium size [Moscoso et al., 2015b], implied office use [Heydarian et al., 2015; Murdoch et al., 2015], and daylight access from the south façade to allow for experimental conditions with direct sunlight.

Another important criterion for the selection of the test room was its accessibility, which was necessary to allow the measurement of the material properties of the main surfaces, as well as the control of the furniture present in the room, to ensure similarity between the real environment and the generated virtual scenes. The DEMONA (Module de demonstration en éclairage naturel) test room on the EPFL campus, shown in Figure 4.2(a)-(b), was selected as it fulfilled these criteria and was also accessible by the participants. The test room has a width of 3.05 m, a length of 6.55 m and a height of 3.05 meters, basically achromatic surfaces -—white walls and ceiling, gray carpet— and windows on the north and south façade. The test room was set to resemble an office with a desk and two chairs and the north façade was covered, allowing daylight to enter only from the south. A point in the center of the room, shown in Figure 4.2(c), was selected as the viewpoint for the participants in the real environment, as well as for the simulations of the corresponding virtual scenes.

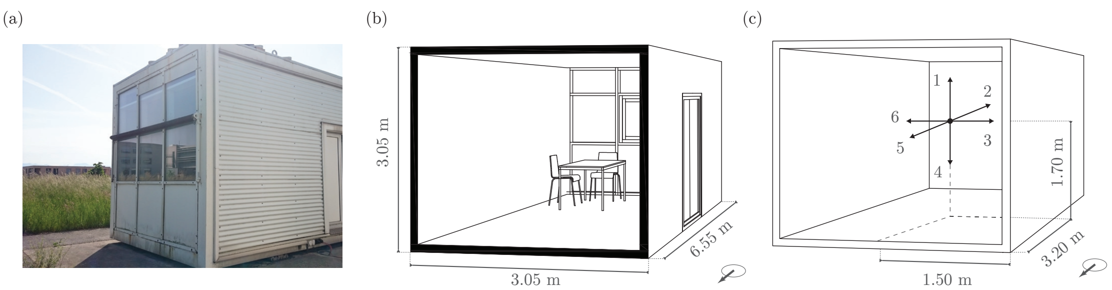

Figure 4.2 – Photograph of the test room (a), illustration of the interior in the 3D model (b), and placement of the viewpoint and corresponding six view directions for the generation of the immersive scenes (c).

4.1.1.4 Workflow for the generation of the virtual environment

Using an existing 3D model (courtesy of LESO Laboratory, EPFL [Thanachareonkit et al., 2013]) as a starting point, the test room was modeled in *Rhinoceros 5.0* and then exported through the *DIVA-for-Rhino* [Jakubiec and Reinhart, 2011] toolbar to *Radiance* [Ward, 1994]. The scene preparation and simulation protocol followed well-established workflows for producing high accuracy visualizations with *Radiance*, specifying the material properties from spectrophotometer measurements [Ward and Shakespeare, 2004], generating sky descriptions based on radiation measures with *gendaylit* [Ward and Shakespeare, 2004; Cauwerts and Bodart, 2011], described in Appendix A.1.1, and using high accuracy rendering parameters [Reinhart, 2005], shown in Table 4.1.

The color and specularity of the surfaces and furniture in the experimental room were measured with a Konica Minolta CM-600d Spectrophotometer and translated to *Radiance* material properties, shown in Table 4.2. A series of perspective view HDR renderings were generated with the *Radiance* function *rpict* using the viewpoint shown in Figure 4.2(c), dividing the 360 degree field of view in 6 sections with 90° horizontal and vertical field of view.

Table 4.1 – *Radiance rpict* parameters for the perspective view renderings (-vtv).

-vs	-vl	-ab	-s	-st	-lv	-ad	-as	-aa	-ar	-ps	-pj
0	0	5	1	0	0.00001	20000	10000	0.05	512	0	0

Resolution: 3600x3600 pixels (scaled down to 1200x1200 pixels using *pfilt*).
Rendering time: 16 hours for the two sets of six view directions.

Table 4.2 – *Radiance* material properties for the main surfaces.

Surface	Type	R	G	B	Reflectance	Specularity	TVis
Ceiling	plastic	0.93	0.92	0.86	92%	0	
Floor	plastic	0.46	0.47	0.48	47%	0	
Walls	plastic	0.92	0.92	0.89	92%	0.01	
Table	plastic	0.75	0.75	0.73	75%	0.01	
Window*	glass	0.96	0.96	0.96			88%

*A non-coated double paned glazing was used for the window.

By keeping the viewpoint fixed and varying the view direction, the produced set of renderings forms an expanded cube, illustrated in Figure 4.3(a) and (b). The exposure of the HDR renderings was adjusted intuitively to match the appearance of the real space by using the function *pfilt* to apply a uniform exposure multiplier. The images were then converted to low dynamic range BMP files using the *Radiance* function *ra_bmp* with a gamma correction factor of 2.2 and ensuring the application of identical settings for all six view directions. The function *ra_bmp* converts directly the HDR image to a 24-bit RGB output with the set gamma factor, without applying an additional tone-mapping algorithm. Given the focus of this experiment on the perceptual impact of the use of the headset and the level of detail in a simulated scene, this approach is suitable and leads to uniformly mapped cube faces, which is the primary requirement to create a seamless immersive environment. However, the use of a dedicated tone-mapping operator might better represent human vision and improve the realism of the virtual scene. This topic is explored further in Section 4.2.

Figure 4.3 – Example of resulting renderings of the 360° virtual space divided in six sections of 90° vertical and 90° horizontal field of view (a) and their application to a cubemap projection.

To create the perception of depth with two dimensional images, a stereoscopic scene can be generated by projecting a different picture to each eye (Figure 4.4, right) simultaneously. If the viewpoints of these images have a disparity in the horizontal axis in a measure equal to the interpupillary distance d of the observer's eyes (Figure 4.4, left), the resulting image is perceived as three-dimensional.

Figure 4.4 – The principle of stereopsis used for the main view direction in the VR Headset (left) and an example of projected stereoscopic image (right).

Following this principle, the simulation procedure described above was repeated for two viewpoints in the digital model with a horizontal distance of 65 mm between them, suggested as the average interpupillary distance in the Oculus documentation [Oculus VR, 2015]. As the participants of the experiment would be mostly looking in front of them, shown as view direction 2 in Figure 4.2(c), the selected viewpoints correspond to the eyes of a participant looking towards this view direction. Although the stereoscopic effect is correct for the view directions of front and back, it is not the case for the other view directions, where the two viewpoints will not correspond any more to the eyes of a subject turning their head in the virtual space. This was a result of software limitations in the time of the study, although current versions of *Radiance* offer the possibility to render omnidirectional stereoscopic projection types, which are employed in Chapter 6. When experiencing the virtual scene, the discrepancy was imperceptible as the non-stereoscopic view directions did not contain objects, leading to a minimal effect on the user's perception of depth.

In consideration of how prevalent is an order bias in relevant studies, where the subjects are first exposed to the real environment and the conditions at the time of the experimental session are recorded to generate the virtual environment [Cauwerts and Bodart, 2011; Murdoch et al., 2015], we decided to create the simulated scenes before the experiment, lowering the accuracy of virtual scene in order to eliminate this bias. The experiment took place in November 2015 during the course of eight days, which were represented through a selection of virtual scenes corresponding to different times of day, sky type and view out. Due to time constraints, the variations of the scene were simulated only for one date in November, although minor changes in sun angle occurred in this period.

Aiming to address the daylight variation, seven scenes were rendered for clear sky type corresponding to every hour from 9:30 to 15:30, shown in Figure 4.5(a) to (g), and two scenes for overcast sky type, using 12:30 as the time of day, shown in Figure 4.5(h) and (i). The two scenes of overcast sky differed only in their view out of the window, through the use of two different panoramas, mapped on the *Radiance* sky to account for the prevalent views in overcast conditions the weeks before the experiment. For each scene, we rendered two sets of six images: each image corresponded to a perspective view of 90° horizontal and 90° vertical field of view from the same viewpoint, shown in Figure 4.3, while each set of images corresponded to the viewpoint of one eye of a person looking towards the main frontal view direction of the scene, as shown in Figure 4.4.

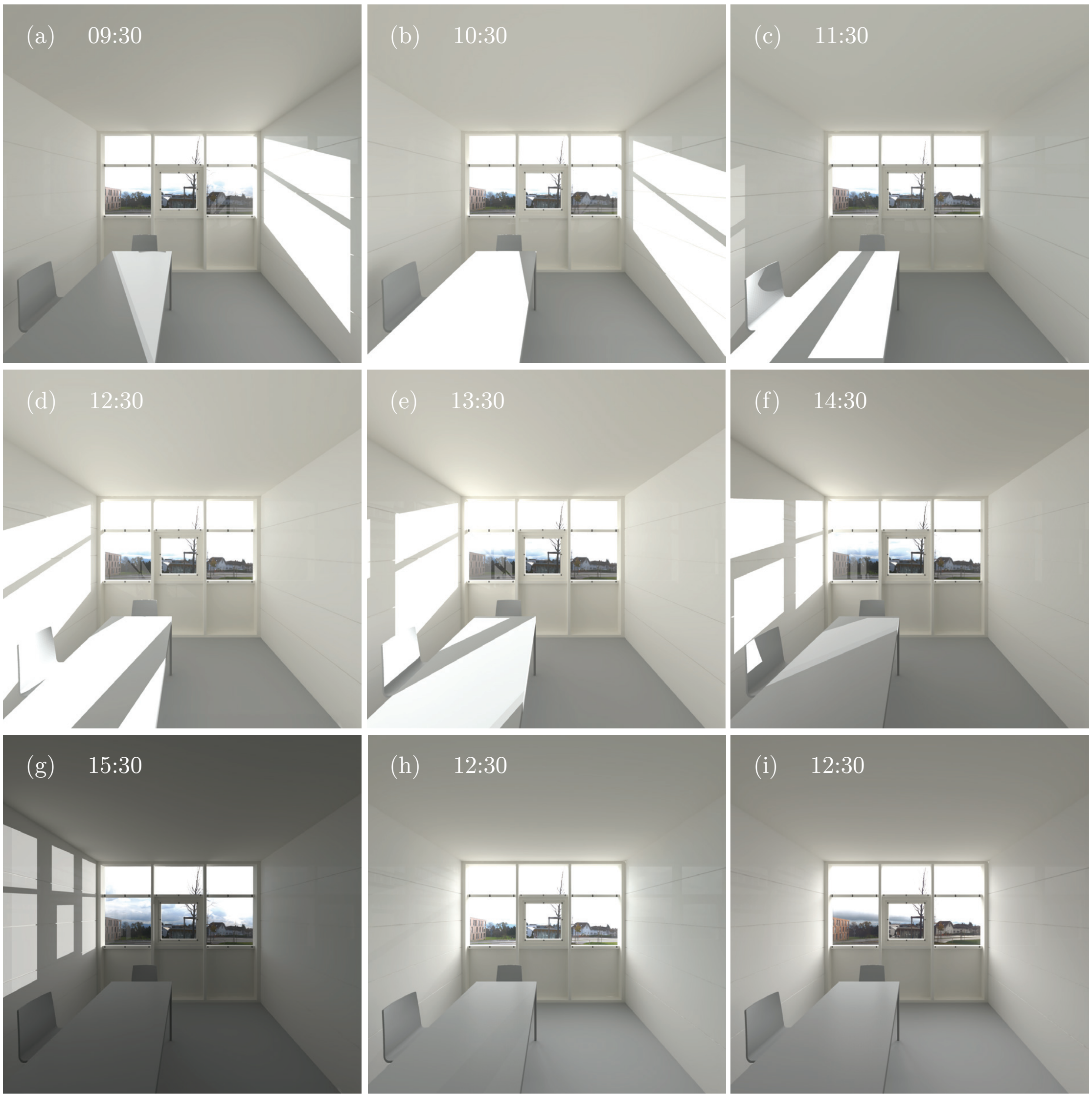

Figure 4.5 – The front view direction for the right eye used in each of the nine scenes. The scenes from (a) to (g) were rendered in hourly time steps from 09:30 to 15:30 for a clear sky type, and the scenes (h) and (i) were rendered for 12:30 and an overcast sky type using two different panoramas mapped on the Radiance sky.

The game engine *Unity* was used to create virtual reality scenes from the Radiance visualizations. Drawing from the field of game design where a textured cubemap has been widely used to produce an immersive environment mapping [Greene, 1986], we recreated this projection type in Unity. In a cubemap, or cube projection, the environment is projected onto a cube as seen from a particular viewpoint (illustrated in Figure 4.3, (c) and (d)). A significant advantage of this projection mapping, as noted by Greene [1986], is that it can be produced with any rendering program that can generate perspective view visualizations. Figure 4.6 illustrates the process of creating a cubemap projection in Unity, applying the renderings from *Radiance* to the corresponding faces of a cube as textures (more information about this procedure can be found in Appendix A.1.2). Two cubes were created to simulate the principle of stereoscopy, each using as textures the renderings generated from the viewpoint of the equivalent eye, visible only to the corresponding half of the screen of the VR headset.

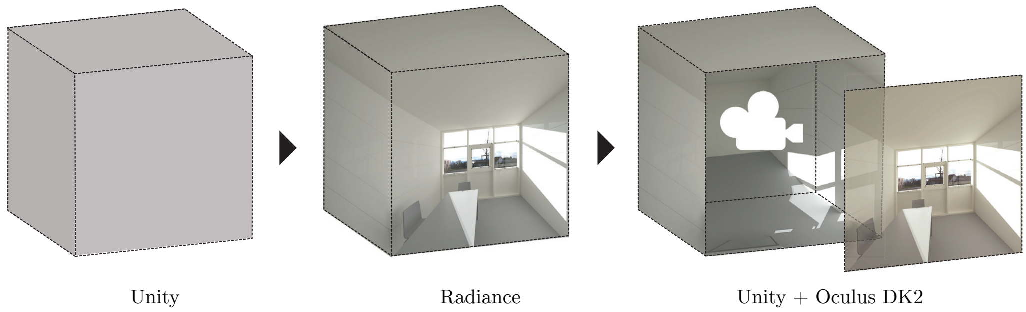

Figure 4.6 – Illustration of workflow for the generation of simulation-based immersive 360° scenes using cubemap projection.

A virtual camera was placed in the center of each cube (Figure 4.6, right) using the *OVRCameraRig* function in Unity, which allowed the control of the camera through the head-tracking feature of the Oculus Rift headset. By placing the camera in the middle of this textured cube, the user's viewpoint corresponds to the one used to generate each set of renderings. Through this process, we are able to produce immersive scenes shown in VR, where the user is able to look around and explore the space from a selected viewpoint. The scene is perceived as fully immersive and three-dimensional, as illustrated in Figure 4.7.

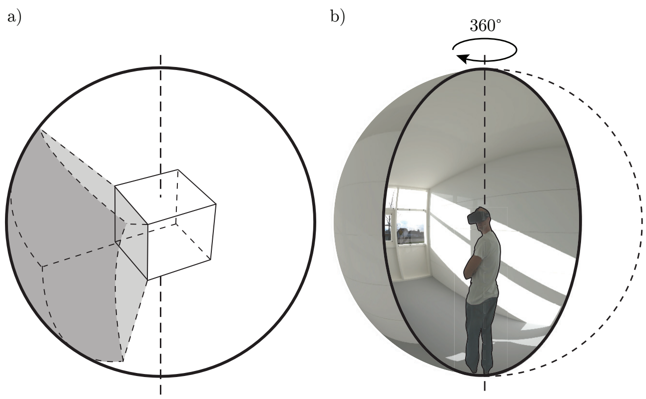

Figure 4.7 – Diagram of the word-to-cubemap projection for one cube face (a) and illustration of the freedom of movement in the projected virtual reality scene (b).

4.1.1.5 Dependent variables

The experimental data was collected through a verbal questionnaire, shown in Table 3 and grouped in three sections relating to the investigation of the perceptual accuracy of the method (Perceptual Impressions), the effect of using the VR headset on the user's physiological reactions (Physical Symptoms), and the user's perceived presence in the virtual space (Reported Presence).

Table 4.3 – Overview of experimental variables.

Independent Variables	
IV.1	Environment: real or virtual environment
Dependent Variables	
Perceptual Impressions	
PI.1	How pleasant is this space?*
PI.2	How interesting is this space?*
PI.3	How complex is this space?*
PI.4	How exciting is this space?*
PI.5	How satisfied are you with the amount of view in this space?*
Physical Symptoms	
PS.1	How sore do your eyes feel?*
PS.2	How fresh does your head feel?*
PS.3	How clear is your vision?*
PS.4	How fatigued do you feel?*
PS.5	Do you have any other symptoms? (open question)
Reported Presence	
RP.1	How much did your experience in the virtual space seem consistent with your experience in the real space?*
RP.2	How much did you feel like 'being there' in the virtual space?*
RP.3	How much did the virtual space become the reality for you?*

*A scale from 1 to 5, 1 corresponding to 'Not at all' and 5 to 'Very much', was used for the marked questions.

The studied perceptual impressions relate to the component of emotional response rather than the light appearance in the perception of the luminous conditions [Van Erp, 2008], placing the focus of the study in investigating further than the evident features of the luminous environment [Boyce, 2003]. Drawing from the pioneering work of Flynn [1973], Vogels [2008] identified two factors that can represent the atmosphere of a space, which is suggested as a more objective variable to measure the perception of luminous conditions: cosiness and liveliness, which are suggested to correspond to the dimensions of pleasantness (affect) and interest (arousal) found in emotion theory [Russell, 1980]. The questionnaire items for *Perceptual Impressions* were based on the work of Vogels [2008] and Rockcastle et al. [2017a], adapted to unipolar scales and focusing on the dimensions of pleasantness, visual interest and scene complexity, with the addition of a question regarding the amount of view in the space, a factor that has been shown to affect the perceived pleasantness of the space [Moscoso et al., 2015b].

The questionnaire to assess adverse physiological reactions to the use of the virtual reality headset was based on literature investigating visual comfort in near-eye displays, focusing on symptoms of eye strain, vision clarity, headache, [Sheedy and Bergstrom, 2002; Shibata et al., 2011] and fatigue [Shibata et al., 2011]. The rating scales regarding physical symptoms were based on the widely adopted questionnaire developed by Hoffman et al. [2008] for the effects of three-dimensional display technologies on user discomfort and fatigue.

Lastly, the three items for Reported Presence correspond to the questionnaire items and the dimensions of presence in the work of Schubert et al. [2001], and address the dimensions of realness, spatial presence and involvement (Table 4.3, RP.1, RP.2, and RP.3, respectively). A 5-point scale with verbal anchors at the end points (1 corresponding to “Not at all” and 5 corresponding to “Very much”) was used for all questions except for PS.5, “Do you have any other symptoms?”, which had an open response. Both the order of the questions within each section and the polarity of the scale for each question were randomized. The 5-point range of the scale was selected due to its ease of use and reliability [Preston and Colman, 2000], and was chosen over the most commonly used 7-point range after a previously conducted pilot study that showed that participants had difficulty answering a verbal questionnaire with 7-point scales as they had no visual reference of the scale range in virtual reality.

4.1.1.6 Participants

The experimental study was conducted with 29 participants, 16 women and 13 men. As one participant did not respond to all the questions due to a technical problem, the sample size is reported separately for each studied attribute in the following sections. All articipants reported normal or corrected-to-normal vision. Of the 29 participants, three were aged between 21 and 25 years old, fourteen were aged between 26-30, ten were aged between 31-35, and two were aged over 35 years old. Participants were unpaid volunteers and were recruited through e-mail and social media.

4.1.1.7 Experimental protocol

The duration of the experiment was 30 minutes per participant, conducted in scheduled appointments from 9:00 to 15:30. At the start of each session, participants were asked to read a document containing information about the experiment and sign a form of consent in order to proceed. After this step, they were asked to respond to a series of demographic questions concerning their age, gender and vision correction, followed by questions presented in random order regarding their physical symptoms before the experimental session (Table 4.3, Physical Symptoms).

The participants were randomly assigned to evaluate the real or the virtual space first, counterbalancing the order of stimuli between subjects. In the second case, they entered the room with their eyes closed, ensuring that they saw only the virtual environment first. In both cases, the participants were guided to stand on a mark in the center of the room (Figure 4.8, middle) and were told they could explore the space by rotating on this spot. After having explored the environment, they were asked a series of questions in randomized order regarding their perception (Table 4.3, Perceptual Impressions).

Figure 4.8 – Photographs showing subjects exploring the virtual (left) and the real (right) space, and the experimental space with the mark for the participant's position, corresponding to the viewpoint in the virtual space (middle).

This procedure was repeated for the evaluation of both environments, after confirming with the participants that the headset was adjusted correctly in the case of the virtual environment. After the subjects had experienced both environments and responded to the equivalent questions, they were asked to remove the headset (if applicable) and respond to a questionnaire regarding their perceived presence (Table 4.3, Reported Presence). Lastly, they were asked once again to evaluate their physical symptoms with the same questionnaire that was used in the beginning of the experiment. In each session, an HDR photograph of the real space was captured from the back of the room (Figure 4.8, middle), using a Canon EOS 70D camera, a 180° SIGMA 4.5mm F2.8 EX DC HSM lens and automated exposure bracketing. These HDR photographs were used to compare the luminance between the real and the virtual environments, which is presented in Appendix A.1.3.

The scene that was shown in virtual reality in each experimental session was selected from the pre-rendered scenes based on its similarity with the daylight conditions in the real space. An example of the two environments is given in Figure 4.9.

4.1.1.8 Data analysis

Our main focus in this study is the effect of the environment: whether there is a difference in the responses between the real and virtual space, and whether there is a difference in the reported physical symptoms after the use of the VR headset. As the experimental data would be ordinal with paired responses, a Wilcoxon Matched-Pairs Signed-Ranks test was used to perform the power analysis for this experiment. Having a final sample size of 29 subjects (28 for some attributes due to a technical problem), we conducted an a priori power analysis with the software *G*Power* [Faul et al., 2007] to estimate the power and effect size that can be obtained with this number of observations. Aiming

Figure 4.9 – Photograph of the real space taken from the participant's viewpoint (left) and the corresponding virtual environment (right).

for the conventional threshold of a statistical power equal to 0.80, our sample size was sufficient to detect medium to large effects as defined by the thresholds set by Cohen [1988], with an effect size d_z of 0.57 and 0.56 for 28 and 29 observations, respectively. The counterbalancing of conditions between participants and the conducted power analysis ensure an adequate experimental design and population size for the purpose of this study.

Most studies using ordinal subjective assessments to investigate the agreement between a real environment and its virtual representation use analyses of variance [Mahdavi and Eissa, 2002; Bishop and Rohrmann, 2003; Newsham et al., 2010]. Such tests provide evidence of whether the null hypothesis of no difference between groups can be rejected [Siegel, 1956], but cannot prove that the null hypothesis is true, a problem that has been highlighted in the literature [Salters et al., 2012; Murdoch et al., 2015].

A one-sample Kolmogorov-Smirnov test revealed the non-normality of our data for all the studied variables, leading us to apply non-parametric statistical tests. Knowing the above mentioned limitations of hypothesis testing and following the approach suggested by Murdoch et al. [2015], two indicators were employed for the analysis of the data with paired responses: the result of a Wilcoxon Matched-Pairs Signed-Ranks test at the significance level α of 0.05 and Cohen's d effect size. In order to establish a threshold for an accepted mean difference between the evaluations of the two environments, Cohen's d is used to assess the relative magnitude of the observed differences. For two paired samples x and y, Cohen's effect size d_z, is based on their paired differences $z = x - y$, and is calculated by dividing the mean difference of two conditions by the standard deviation of the distribution of the differences, as shown in Equation 1.

$$d_z = \frac{\mu_z}{\sigma_z} \tag{4.1}$$

An absolute d of 0.2 has been suggested by Cohen [1992] as a small effect size.

Using this cut-off point which is commonly found in the literature, we can establish a threshold of maximum accepted absolute effect size $|d_{max}|$ equal to 0.2, corresponding to a small effect size. Although Cohen's threshold have been criticized as too low, and thus too generous as an effect size threshold [Ferguson, 2009; Lipsey and Hurley, 2009], for our purpose the lowest threshold is the most conservative. We can thus define the combination of a Wilcoxon Matched-Pairs Signed-Ranks result of no statistical difference at a significance level α of 0.05 and a $|d_z|$ effect size equal or lower than 0.2 as a result of accepted similarity between the paired responses for an attribute.

4.1.2 Adequacy of the simulation-based virtual environment

The results of the experimental study are presented in three parts, introducing the perceptual accuracy of the VR method, the effect of using the VR headset on the users' physical symptoms, and the perceived presence of subjects in the virtual space. An analysis of the effect of the environment presentation order on the participant responses can be found in Appendix A.2.

4.1.2.1 Perceptual accuracy of the simulation-based virtual environment

For each of the studied perceptual attributes, participants evaluated the scene in both the real environment and in its virtual representation. We can thus evaluate the perceptual accuracy of the VR method by calculating the difference between this pair of responses for each participant; a difference of zero would mean that the paired evaluations are identical.

Table 4.4 – Frequency distribution of absolute differences between the subjective evaluations in the real and virtual environment.

	Percentage of pairs with absolute difference (%):				
	0	1	2	3	4	≤ 1
How pleasant is this space?	**50**	32	18	0	0	**82**
How interesting is this space?	**52**	31	14	3	0	**83**
How complex is this space?	**76**	24	0	0	0	**100**
How exciting is this space?	43	46	7	4	0	**89**
How satisfied are you with the amount of view in this space?	**52**	45	3	0	0	**97**

Individual values are rounded to the nearest integer and are marked in bold if equal to or higher than 50%.

Table 4.4 shows the frequency distribution of the absolute differences between the paired responses in the two environments within our sample size. The pairs with a difference of zero equal to 50% or more of our sample for all questionnaire items, except for perceived excitement, while at least 82% of the responses for all questions had an absolute difference lower or equal to one between the pairs of evaluations in the real and virtual environment. These measures are particularly relevant for this study, as an absolute difference of one is the smallest possible non-zero difference when comparing responses in the rating scale that was used in the present study.

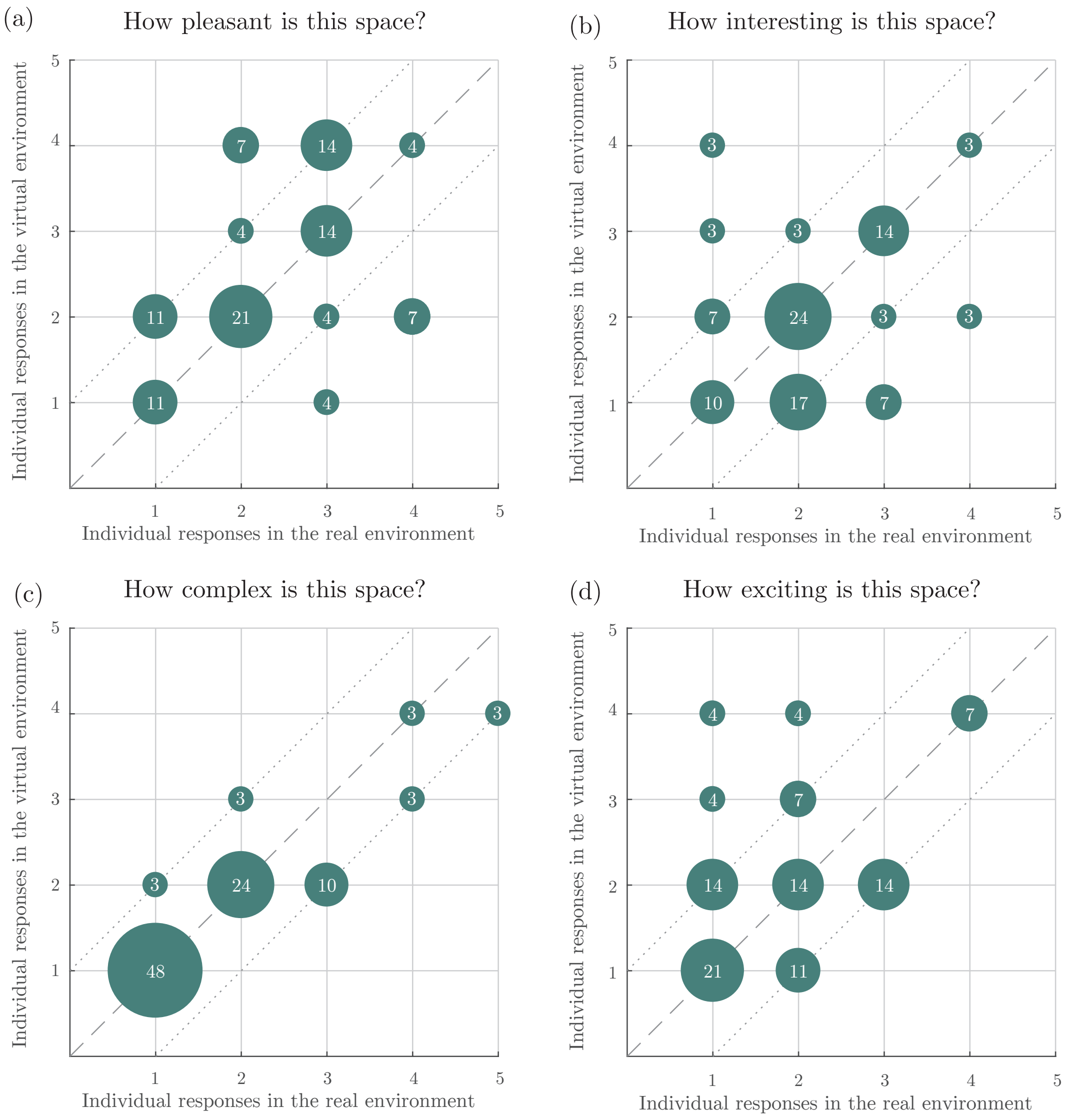

Figure 4.10 – Distribution of responses in the real (x axis) and the virtual (y axis) environment from each participant for each of the studied attributes of the scene. The size and label of the circles correspond to the percentage of paired responses with identical values, rounded to the nearest integer. The dashed diagonal line marks the paired responses with a difference of zero while the dotted lines mark the responses with a difference of of ±1 between the two environments.

To better illustrate the agreement between responses, Figures 4.10 and 4.11 show a series of scatter plots with the paired responses of the participants in the real (x axis) and virtual (y axis) environment. In this graph, one can observe not only the agreement between the responses of the same participant —those that are closer to the diagonal line— but also the agreement of responses between participants in the

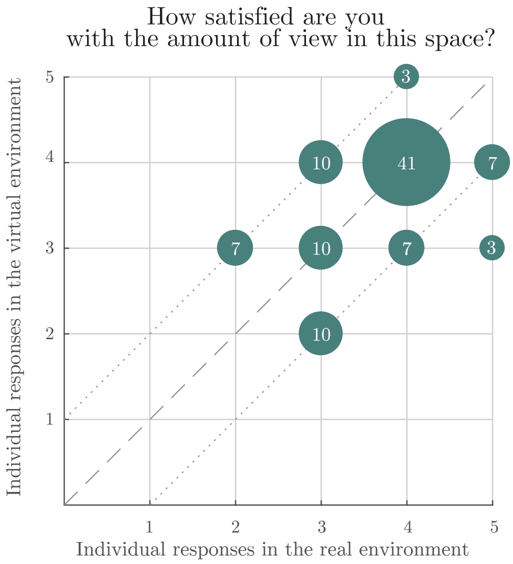

Figure 4.11 – Distribution of responses in the real (x axis) and the virtual (y axis) environment from each participant. The size and label of the circles correspond to the percentage of paired responses with identical values, rounded to the nearest integer. The dashed diagonal line marks the paired responses with a difference of zero while the dotted lines mark the responses with a difference of of ±1 between the two environments.

different experimental conditions. Responses to questions of a more subjective nature (pleasant, interesting, and exciting) have a higher variation both within and between subjects. In contrast, the responses regarding the complexity and satisfaction with the amount of view show high agreement both between the responses in the real and the virtual space and also between participants, with a clustering of responses in the negative and positive range respectively. These observations show that a difference in the visual conditions —either between the two environments in one session, or between the experimental sessions— produced a stronger variation in impressions of pleasantness and visual interest.

The statistical analysis of the responses with the Wilcoxon Matched-Pairs Signed-Rank test at a significance level α of 0.05 indicates no significant differences between the responses in the real and the virtual environment for any of the studied variables (all $ps > 0.28$). Although our data is ordinal, we are accepting the treatment of differences between the responses in the two presentation modes as interval. The inherent limitations of ordinal scales, such as the uncertainty of equidistance between the scale items due to subjectivity, are not present when considering the differences of the matched pairs where the participants act as a control for their own response. Assuming that each participant uses the same subjective distance in their evaluation of presentation modes, we can use the mean difference of the responses to gain insight into the similarity between the perception of virtual and real-world stimuli.

Following the approach described in Section 4.1.1.8, we are using two indices to assess the perceptual accuracy of the studied method: the result of the Wilcoxon Matched-Pairs Signed-Ranks test at a significance level α of 0.05 and Cohen's $|d_z|$ effect size. Since there were no observed statistically significant differences for any of the studied attributes, a result of accepted perceptual accuracy corresponds to a $|d_z|$ effect size equal or lower than our set threshold of 0.2, equivalent to a small effect size, and is symbolized with ✓ in Table 4.5.

Table 4.5 – Overview of studied attributes and their perceptual accuracy based on the indices of the Wilcoxon Signed-Ranks Matched-Pairs test and effect size d_z.

	N	N_{diff}	μ_z	$\mu_{\lvert z \rvert}$	d_z	
How pleasant is this space?	28	14	-0.179	0.679	-0.175	✓
How interesting is this space?	29	14	0.138	0.690	0.126	✓
How complex is this space?	29	7	0.103	0.241	0.212	(✓)
How exciting is this space?	28	16	-0.214	0.714	-0.208	(✓)
How satisfied are you with the amount of view in this space?	29	14	0.103	0.517	0.134	✓

An effect size d_z lower than or equal to 0.20, marked with ✓, indicates an acceptable result.

From Table 4.5, we can see that three out of five attributes match our conditions for accepted perceptual accuracy. The attributes of perceived complexity and excitement fail to reach the threshold of a $|d_z| < 0.20$ by a very small difference and can be considered marginally acceptable. In order to provide standardized measures for comparison with the literature, Table 4.5 contains both the mean difference $\mu_z = \overline{(x-y)}$ and the mean absolute difference $\mu_{|z|} = \overline{|(x-y)|}$ between the responses in the real and virtual environment for each studied attribute. It is worth noting that most of the mean differences μ_z that were observed in our experiment are smaller than the maximum accepted mean differences in other relevant studies: 0.167 [Murdoch et al., 2015], 0.667 [Moscoso et al., 2015b], 0.889 [Manyoky, 2015], comparing values that are normalized based on a maximum possible difference of 4 units, corresponding to the 5-point scale used in our study.

Another topic of interest is whether the agreement in the responses between the two environments could be a result of the repeated measures experimental design, as each participant was exposed to both environments. By comparing the evaluations of subjects that saw a similar condition (in this case, scenes with overcast sky) and using only the responses for the first environment they were exposed to, we can create a between-subjects dataset. A Wilcoxon Ranked-Sums test between 11 subjects that saw the real environment first and 13 that saw the virtual environment first, both groups in overcast sky conditions, indicated no significant differences between the two environments for a significance level α of 0.05 for any of the studied attributes, in accordance with our findings from the paired-responses analysis.

In summary, the results indicate a high level of perceptual accuracy of the virtual reality method. A Wilcoxon Signed-Ranks Matched-Pairs test showed no statistically significant differences between the responses in the real and virtual environments for any of the studied attributes. In addition, the application of a second indicator for perceptual accuracy based on Cohen's *d* showed marginally acceptable results regarding how complex and how exciting the space was perceived, and acceptable for all other attributes, demonstrating that the perceptual evaluations in the virtual environment match closely those in the real environment.

4.1.2.2 Physical symptoms after the use of the headset

As the experimental data regarding the self-reported physical symptoms of the participants follows the same structure with perceptual impressions, consisting of paired ordinal responses before and after the experimental sessions, we will conduct the same analysis to investigate the possible adverse physiological effects from using the VR headset.

Table 4.6 – Frequency distribution of absolute differences between the reported physical symptoms before and after the use of the virtual reality headset.

	Percentage of pairs with absolute difference (%):					
	0	1	2	3	4	≤ 1
How sore do your eyes feel?	**65**	22	6	3	0	**87**
How fresh does your head feel?	41	44	14	0	0	**85**
How clear is your vision?	**79**	17	3%	0	0	**96**
How fatigued do you feel?	**58**	34	6%	0	0	**92**

Individual values are rounded to the nearest integer and are marked in bold if equal to or higher than 50%.

The distribution of absolute differences within our sample size is shown in Table 4.6, binning the paired responses before and after the experimental session based on the absolute difference between the two evaluations. With the exception of the question "How fresh does your head feel?", more than 50% of the sample had identical responses before and after using the VR headset, while for all studied questions, more than 85% of the pairs had an absolute difference lower or equal to one. The distribution of the subjects' responses are illustrated in Figure 4.12 through a series of scatter plots where each data point corresponds to a pair of responses from the same participant, with the x and y axes indicating the response before and after the experimental session, respectively.

We can observe a clustering of points in the top right quadrant of positive evaluations for both responses in the graphs (b) and (c), indicating a high agreement between the subjects. For all questions, there are few deviations from the diagonal lines marking a difference of zero and ± 1 between the paired responses, showing agreement within subjects in their responses before and after using the headset.

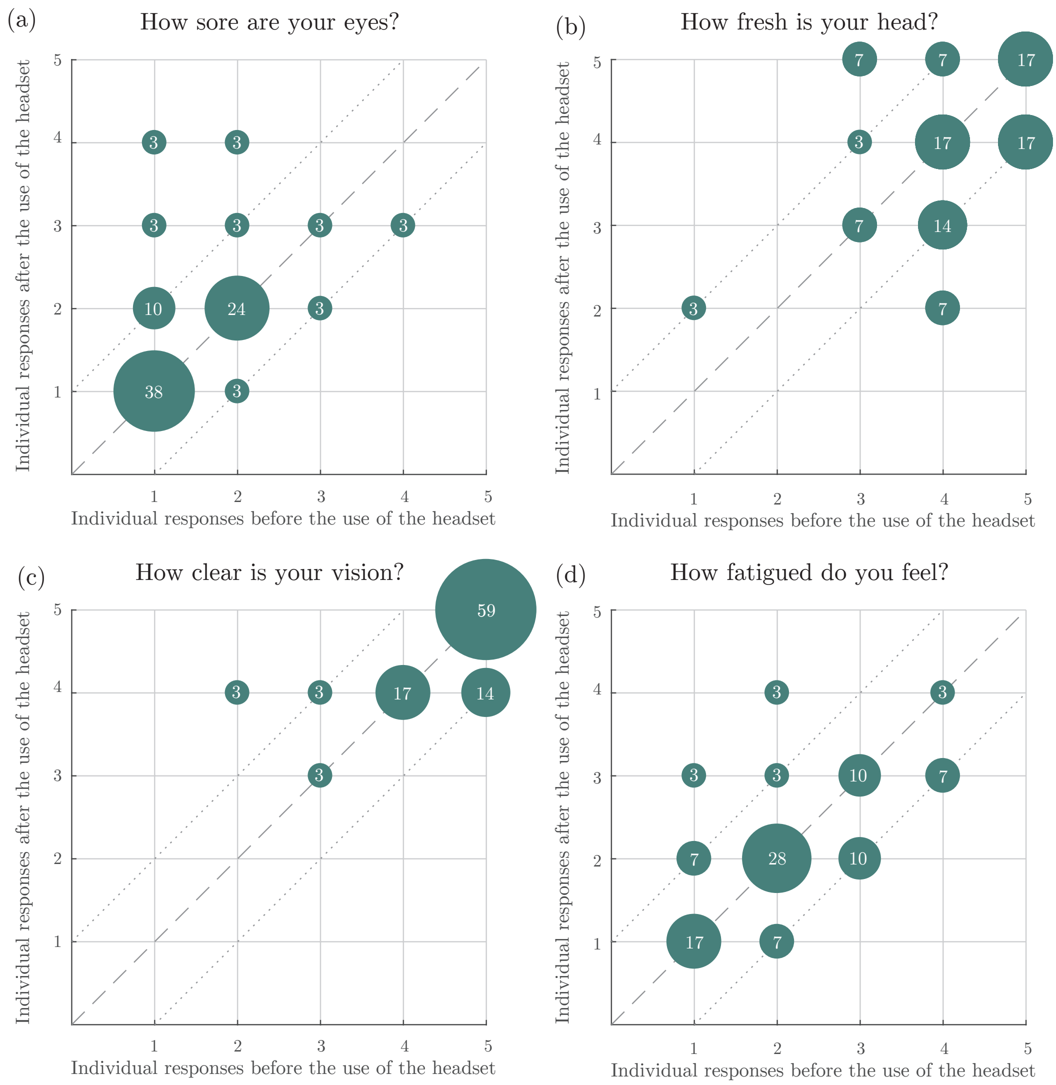

Figure 4.12 – Distribution of responses before (x axis) and after (y axis) the experimental session for each participant. The size and label of the circles correspond to the percentage of paired responses with identical values, rounded to the nearest integer. The dashed diagonal line marks the paired responses with a difference of zero while the dotted lines mark the responses with a difference of ±1 in the evaluation before and after the use of the headset.

Similarly, the results of a Wilcoxon Matched-Pairs Signed-Ranks test show no statistically significant differences for a significance level α of 0.05 between the responses before and after the experimental session for the studied attributes. N_{diff} indicates the number of matched pairs with a non-zero difference used in the test, from the initial dataset of N pairs. Following the conservative approach described in Section 4.1.1.8, we use two thresholds, an absolute effect size $|d_z|$ equal or lower than 0.20, and the result of non-statistically significant differences, shown in Table 4.7, to evaluate whether the use of the VR headset had an adverse effect on the subjects' self-reported physical symptoms.

Table 4.7 – Overview of the effect of using the VR headset on the reported physical symptoms based on the indices of the Wilcoxon Signed-Ranks Matched-Pairs test and effect size d_z.

	N	N_{diff}	μ_z	$\mu_{\|z\|}$	d_z	
How sore do your eyes feel?	29	10	-0.276	0.483	-0.313	
How fresh does your head feel?	29	17	0.172	0.724	0.172	✓
How clear is your vision?	29	6	0.035	0.241	0.061	✓
How fatigued do you feel?	29	12	0	0.483	0	✓

An effect size d_z lower than or equal to 0.20, marked with ✓, indicates an acceptable result.

From the four questionnaire items, only the question "How sore do your eyes feel?" fails to meet these requirements. Lastly, the participants responded to the open question "Do you have any other symptoms?" (Table 4.3, PS.5) at the end of the experimental session. Out of 29 participants, 4 reported feeling slightly dizzy, while 25 reported no other symptoms, corresponding to 14% and 86% of our sample size.

To summarize, the results regarding the participants' reported physical symptoms demonstrate no effect of using the VR headset, with the exception of the question "How sore do your eyes feel?". A Wilcoxon Matched-Pairs Signed-Ranks test showed no statistically significant differences between the reported symptoms before and after using the headset for any of the questionnaire items. However, when using Cohen's d as a second index, the self-reported of eye soreness failed to meet our set threshold. These findings are in alignment with the literature, where eye strain has been found to be an adverse physical symptom of using head-mounted displays [Abd-Alhamid et al., 2019]. Virtual-reality induced symptoms, often referred to as cyber-sickness, have been identified as a recurrent issue in virtual reality [Sharples et al., 2008]. Although a combination of subjective evaluations and physiological measurements is suggested as a more reliable assessment method for cyber-sickness [Kim et al., 2005], the present experimental study relied on questionnaires to evaluate the perceptible symptoms that were experienced by the participants. Virtual reality applications that have low conflict between visual and proprioceptive senses, which is the case of our immersive virtual environment, are not expected to generate cyber-sickness [McCauley and Sharkey, 1992], which is consistent with our own findings.

4.1.2.3 Perceived presence in the simulation-based virtual environment

As discussed in earlier sections, the questionnaire items regarding the subjects' perceived presence in the virtual environment were designed to correspond to the three factors of presence defined by Schubert et al. [2001], realness, involvement and spatial presence. The Cronbach's alpha reliability measure of 0.78 for the questionnaire indicates good internal consistency, showing that the items indeed measure the same structure [Cronbach, 1951]. Figure 4.13 shows the distribution of the responses for each question.

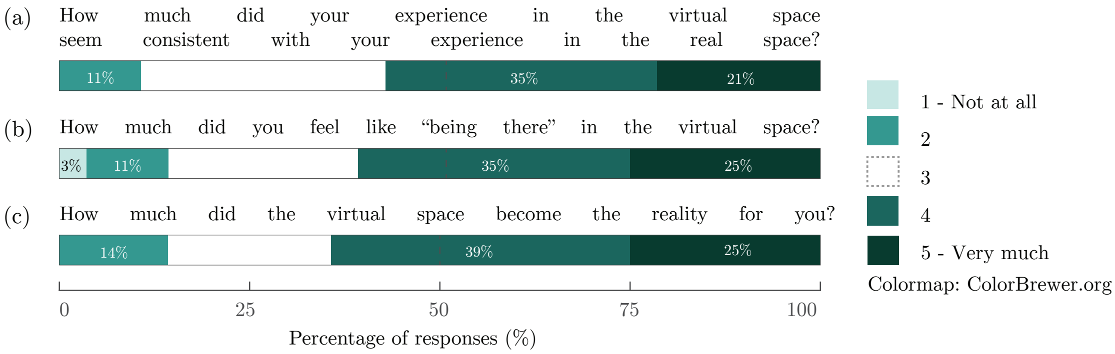

Figure 4.13 – Distribution of the participants' responses to the questions related to their perceived presence. Each stacked bar is labelled according to the percentage of responses in each point of the scale, out of a sample size of 29 participants. The midpoint of the scale (3) is not shown in order to highlight trends towards the extreme ends of the scale.

Along with the distribution of responses, we are reporting the mean and standard deviation for each attribute —although our data is ordinal— to provide commonly used measures of comparison with the literature. From a sample size of 28 participants, 56% of the population responded in the positive range of the scale, while 11% responded in the negative range when evaluating the consistency of the experience between the real and the virtual environment ($\mu = 3.680$, $\sigma = 0.94$). Regarding their sense of being there in the virtual environment, 60% of the participants evaluated this attribute positively and 14% evaluated it negatively (μ=3.685, σ=1.09). Lastly, 64% of the participants rated positively their sense of the virtual environment being perceived as the reality, while 14% that rated this aspect negatively (μ=3.750, σ= 1.04).

Using the mean of the responses as a point of reference, we can compare our results with those from the second experimental study described in Kuliga et al. [2015], where participants engaged in a tour in a real environment and the corresponding 2D virtual environment projected on a large screen. Our reported mean values for the perceived involvement and consistency of experience between the two environments are higher than those reported in the study by Kuliga et al., although by a small margin. This is particularly interesting when considering the limitations mentioned in Kuliga et al. [2015] regarding the limited realism and field of view of the virtual environment used in their study, possibly suggesting that the high interaction of the participants with the environment through their navigation in the virtual space compensated for these limitations.

4.1.3 Discussion

The participants of the study were invited to discuss their thoughts on the experiment at the end of each experimental session. These comments, omitted for brevity, allow the identification of specific limitations of the current study. The participants pinpointed the difference in sky conditions in the two spaces and the lack of details in the virtual environment as a possible factor of discrepancies between the evaluations of the two environments. Another limitation, which could also be considered as a matter of level of detail, was the representation of view from the window, as the scenery could change in the real space but not in the virtual one, due to the changing weather conditions or people passing.

Although the statistical analysis of the subjective showed that the two environments were perceived very similarly, there were inevitable differences between the real conditions and those pictured in the virtual environment, such as the luminance of the scenes (discussed further in Appendix A.1.3). Even though it could be a limiting factor for the perceptual accuracy and reported presence in this experiment, this might not pose a problem for studies in the virtual environment if there is no need for immediate representation and comparison with the real environment. The positive results regarding the perceptual accuracy of VR method demonstrate that the immersive virtual environment could be used to adequately convey the visual experience of a real space for the studied perceptual attributes. These findings, along with the mobility offered by this technology, are encouraging for a wide range of possible applications, from education and practice in lighting design and architecture to lighting research, as a means to experience and evaluate luminous conditions in indoor spaces. However, the limited luminance range of the current head-mounted displays is a limiting factor for the investigation of visual discomfort, as it can be problematic to reproduce conditions inducing discomfort such as glare in the virtual reality environment.

Due to the nature of this study, where we are seeking the absence of significant differences between the evaluations in the real and virtual environment, it is important to note that these findings cannot be generalized to other parameters without further investigation. Moreover, the sample size of the present study was adequate for detecting medium to large effects, but limiting in identifying an effect of small magnitude. However, such an effect, as described by Cohen [1992], would be smaller than something noticeable by the naked eye of an observer, and thus would be unlikely to affect the overarching findings and usability of the proposed experimental method.

The compression of high range dynamic images to the dynamic range of the selected display is an essential step in the process of creating a virtual environment [Reinhard et al., 2002; Salters et al., 2012; Murdoch et al., 2015]. In the present study, a direct gamma conversion was used to create the low dynamic range scenes, without employing a dedicated tone-mapping operator. This is an important limitation, as the use of a tone-mapping operator can significantly influence the contrast, naturalness, and realism of the virtual scene [Drago et al., 2002; Irawan et al., 2005; Yoshida et al., 2005]. However, little is known about the adequacy of existing tone-mapping operators for virtual reality applications. The selection and application of a tone-mapping operator is particularly challenging in the context of an immersive virtual scene, as the content and contrast of the scene changes with the user's head movement. Current tone-mapping operators are static and applied to the whole virtual scene, while an adaptive dynamic behavior would correspond more accurately to human perception. It is thus essential for the establishment of the proposed experimental method to examine the perceptual accuracy of existing tone-mapping operators for virtual reality, and particularly for daylit scenes.

Given the importance of validation for the establishment of any new method or technological advancement, further studies are encouraged to test the adequacy of immersive virtual reality scenes in different settings. Indicative settings could include omni-directional stereoscopic content, improvements on the tone reproduction, and different spatial and luminous conditions or levels of user interaction with the environment. To this end, the next section will investigate the perceptual accuracy of different tone-mapping algorithms across a wider range of scenes in immersive virtual reality, while employing a newer device which provides a higher resolution and refresh rate, with the ultimate aim to further improve the developed virtual reality experimental method.

4.2 Real versus photograph-based virtual environments

The previous section presented the results of an experimental study that investigated the adequacy and limitations of a novel experimental method that couples physically-based simulations with projection in a VR headset. Findings are highly promising for the suitability of the presented method as surrogate to real spaces for empirical research in lighting —and thus for the next step of this thesis—, demonstrating a high level of perceptual accuracy and perceived presence in the virtual environment, and no adverse physiological effects. However, this study also allowed the identification of specific limitations of the proposed method, and specifically the level of detail in the virtual scene, the resolution of the VR display, and the tone reproduction method used to compress the scene to the dynamic range of the VR display.

In view of these findings, the present section focuses on improving further the developed experimental method and addressing the aforementioned challenges. The aim of this section is two-fold: to investigate the perceptual accuracy of a newer version of the VR headset (Oculus Rift CV1) with a higher screen resolution, and to identify the most perceptually accurate tone-mapping operator for virtual reality, using immersive scenes with a high degree of realism and level of detail.

1 Preliminary study: Rank-order comparison of tone-mapping operators in VR

Perceived Realism ranking of four **TMOs** identified as promising from the literature across 10 **photograph-based immersive scenes** (within-subject design)

▶ Selection of **three most positively rated TMOs** for immersive daylit scenes

2 Testing immersive VR scenes from high-dynamic-range photographs

Perceptual Accuracy evaluation of participant perception in the **real** and **virtual environment** across **three TMOs** and **three experimental spaces** (mixed design)

▶ Selection of the **most perceptually accurate TMO** for immersive daylit scenes

▶ Validation of the **adequacy of the virtual reality-based experimental method**

Figure 4.14 – Overview of the aims and method in this section.

Figure 4.14 provides an outline of the methodological approach in the present section. An overview of the literature was used to identify the four most promising operators for reproducing the perception of daylit scenes. In order to limit the number of candidate tone-mapping operators, a preliminary user assessment study was conducted to select the three operators that were perceived as the most realistic. In this preliminary study, participants were asked to rank four variations of ten daylit interior scenes —each variation resulting from one of the studied tone-mapping operators— according to their realism. The three best-performing operators were then employed in a study that compared the user impressions of photograph-based tone-mapped immersive scenes against those of the corresponding real environments in three experimental spaces. The results of this experimental study were used to identify the most perceptually accurate tone-mapping operator for immersive daylit scenes, and to validate the adequacy of the virtual-reality based experimental method across different spaces. The findings from this study build upon the outcomes of the previous section and provide the methodological foundations for the remaining chapters of this thesis.

4.2.1 Selection of tone-mapping operators

As discussed earlier in this chapter, the tone-mapping operator (TMO) used to compress a high dynamic range image to the limited dynamic range of the display plays an central role in the creation of a virtual environment. In experimental studies that compared the visual perception of static images tone-mapped with different operators, the choice of TMO has been shown to affect the perceived brightness, the perceived contrast, the reproduction of details [Yoshida et al., 2005; Čadík et al., 2008] as well as the perceived naturalness of the scene [Yoshida et al., 2005]. Numerous studies have assessed the relative performance of different TMOs as a means to increase the perceptual accuracy of static images. Such studies employ experimental designs that use a high dynamic range image as a reference, such as real world scenes [Yoshida et al., 2005; Ashikhmin and Goyal, 2006; Kuang et al., 2006] and HDR images projected onto high dynamic range displays [Ledda et al., 2005], or comparison-based experimental designs without a reference, where each participant is exposed solely to low dynamic range (LDR) images tone-mapped with different operators.

Although there seems to be substantial consensus regarding the best-performing TMOs in terms of perceptual accuracy, the current state of the literature is limited to evaluations of static viewing conditions. While a few studies address the tone-mapping of dynamic HDR content, they regard the use of small screen displays [Al-Juboori et al., 2016; Melo et al., 2014]. This leaves a gap of knowledge for the suitability of TMOs for virtual reality applications, where the user is fully immersed and visually adapted to the scene, and the content in the user's field of view (and consecutively, the contrast and luminance distribution) changes as they explore the virtual environment. Specifically, experimental studies that compared the reported perceptual performance of static TMOs when applied to day- and night-time scenes shown in an LDR display and a VR headset showed that the viewing condition significantly affected the participants' evaluations for two out of the three studied operators [Mishra, 2018]. The sole study that investigated the perceptual accuracy of tone-mapping operators for immersive virtual reality against real spaces used only night-time scenes as stimuli [Petit et al., 2013], leaving a gap of knowledge for their adequacy in daylit scenes. As a result, for the purpose of this thesis and the development of a perceptually accurate immersive virtual environment, it is necessary to identify the most promising operators drawing from the literature, and test their adequacy when applied in virtual reality. To this end, the following section will present an overview of experimental studies that investigated the perceptual performance of different TMOs.

4.2.1.1 Overview of studies comparing the performance of tone-mapping operators

In the first study comparing the perception of different TMOs, Drago et al. [2002] used multidimensional scaling techniques to reveal the dimensions of naturalness and reproduction of detail as the most representative of participant responses, and showed that the photographic tone reproduction algorithm developed by Reinhard [2002] produced images closer to an ideal preference point in these two dimensions. In an experimental study that used real scenes as a reference, the same operator was the second highest rated regarding whether the resulting image represented the real-world reference [Villa and Labayrade, 2010]. Another experiment, where participants were asked to use an HDR image projected on a display as a reference for their evaluations, showed that images tone-mapped with the photographic tone reproduction algorithm were the second most highly rated in terms of their similarity with the reference, while the iCam operator, developed by Johnson and Fairchild [2003], was the most highly rated [Ledda et al., 2005].

While studies that explore the performance of TMOs traditionally use photographs as a visual stimulus, an experiment by Murdoch et al. [2015] investigated the effect of different simulation, tone-mapping, and display parameters on the perceptual accuracy of the resulting simulated virtual environments. This study showed that a combination of a calibrated display, an interactive panoramic view mode, and the use of the photographic tone reproduction operator [2002] resulted in the most perceptually accurate scene compared to the ratings of photographs of the same scene, a finding which is particularly relevant for this thesis.

Studies investigating the performance of different TMOs in static images through paired comparisons reveal the fast bilateral filtering method by Durand and Dorsey [2002] as the highest rated in overall rendering performance in experimental designs that did not use a reference scene [Kuang et al., 2004], as well as the highest rated in overall accuracy when a real-world reference scene is used [Kuang et al., 2006]. Additional user assessment studies that employed a real world scene as reference for the participants' evaluations revealed that images tone-mapped with the adaptive logarithmic mapping developed by Drago [2003] were the most highly rated with regards to their naturalness [Yoshida et al., 2005], as well as the best performing in terms of whether the resulting image represents the real world scene [Villa and Labayrade, 2010]. Lastly, the histogram adjustment method developed by Ward [1997] was rated as second-best in terms of overall rendering performance in studies using paired comparisons [Kuang et al., 2004], as well as second-best regarding the naturalness of the resulting scene in studies were each stimulus was evaluated individually [Yoshida et al., 2005].

4.2.1.2 Selection of promising tone-mapping operators for immersive environments

This overview of the literature in Section 4.2.1.1 reveals four operators which consistently appear as the best performing: the photographic tone reproduction method by Reinhard [2002], the fast bilateral filtering method by Durand and Dorsey [2002], the adaptive logarithmic mapping by Drago [2003], and the histogram adjustment method by Ward [1997], which will be referred to as "Reinhard02","Durand02", "Drago03", and "Ward97" henceforth. It is worth noting that these comparative studies were conducted using static interior scenes lit with artificial or natural light. Studies comparing the performance of TMOs applied to dynamic night-time urban scenes in both immersive and non-immersive virtual environments showed that another algorithm, developed by Irawan et al. [2005], was the most highly rated in terms of the realism of the resulting scene, while the operators by Durand and Dorsey, Ward, and Reinhard were the most negatively rated [Petit et al., 2013], in contrast with the aforementioned literature. These findings illustrate the importance of testing the adequacy of tone-mapping operators for a particular application and, in combination with the current lack of knowledge on the perceptual performance of TMOs in immersive daylit environments, motivate the conduction of a dedicated experimental study to identify the most suitable operator for interior daylit scenes shown in VR in the context of this thesis. To this end, we will investigate the perceptual accuracy of different TMOs in an experimental study that uses real-world daylit scenes as a baseline for participants' perceptual impressions, following the method introduced by Murdoch et al. [2015].

In order to narrow down the number of TMOs to be used as factors in the comparative experimental study, a preliminary study was conducted, where participants ranked these four most promising TMOs according to their realism across different scenes shown in VR. These scenes were generated from 180° fisheye HDR photographs of daylit spaces that were calibrated using spot luminance measurements, tone-mapped with each TMO, and shown in VR using a cubemap projection, following a procedure which will be described in detail in Section 4.2.2.3. For this preliminary study we use a ranking-based experiment conducted solely in VR, following the results of Čadík et al. [2008], which found no effect on the perceptual comparison of different TMOs between a rating-based experiment with real world scenes used as a reference and a ranking-based experiment with no real world references.

4.2.1.3 Rank-order comparison of tone-mapping operators in VR

Workflow for the generation of tone-mapped photograph-based immersive scenes
In this preliminary study, participants were asked to rank four variations of ten interior scene shown in VR according to their realism. These variations were generated from previously acquired 180° HDR photographs of ten interior scenes, calibrated using two reference luminance measurements, and tone-mapped with the four studied TMOs. The ten scenes were selected to cover a range of lighting conditions, and are shown across the different tone-mapping variations in Figures 4.15 and 4.16, using the front view direction of the cubemap projection to illustrate the scenes (note that the displayed images were generated using a gamma of 2.0 and thus appear different than in virtual reality). The individual cubemaps for each tone-mapped scene used in this study can be found in Appendix A.1.4.

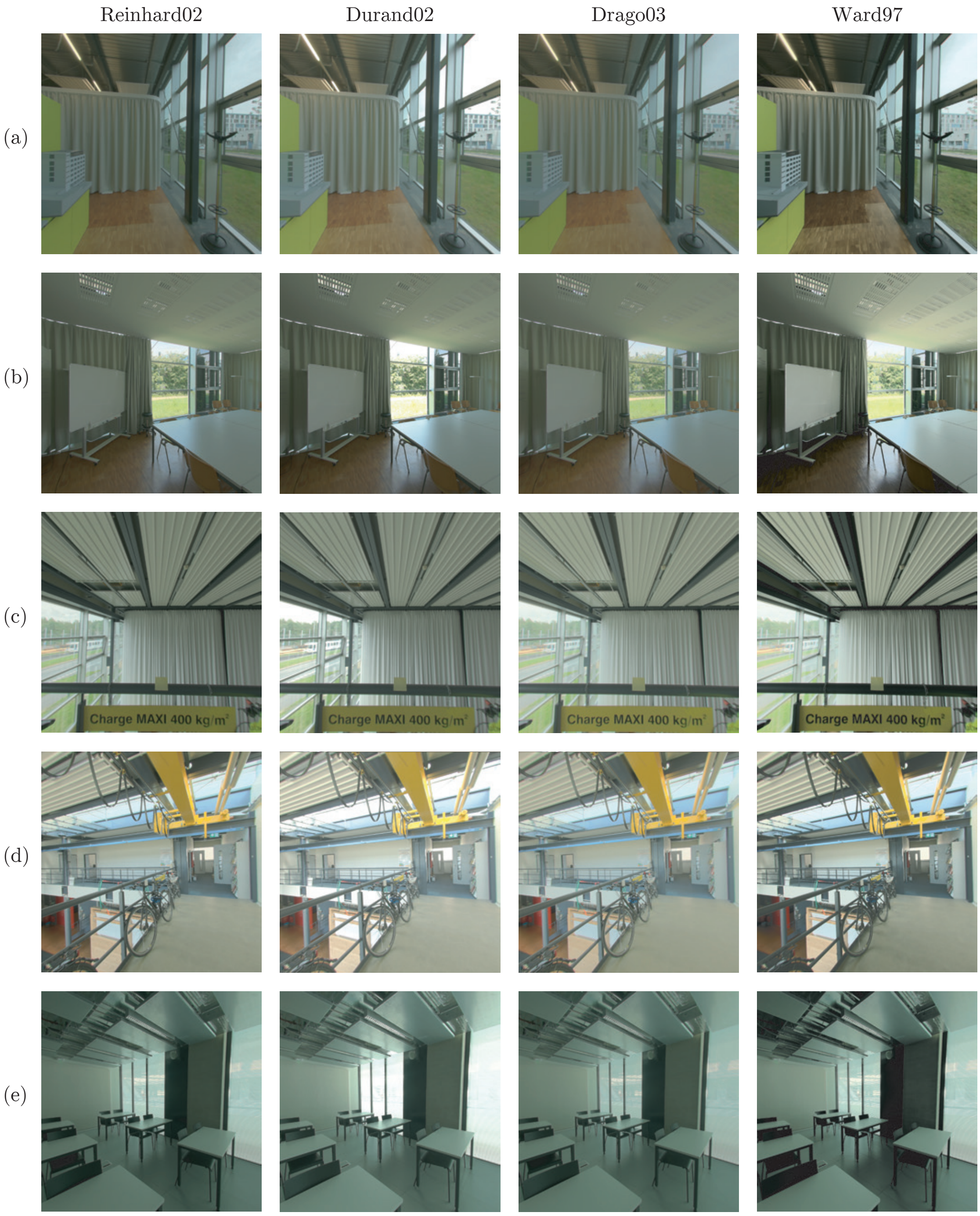

Figure 4.15 – Front view directions of the cubemap projections used in the preliminary study across the four tone-mapped variations of the first to the fifth studied scene. Scenes six to ten are shown in Figure 4.16. Both the variations within each set and the ten scene sets were presented in random order.

Figure 4.16 – Front view directions of the cubemap projections used in the preliminary study across the four tone-mapped variations of the sixth to the tenth studied scene. Scenes one to five are shown in Figure 4.15. Both the variations within each set and the ten scene sets were presented in random order.

Each scene was tone-mapped using the following software and settings: the *pfstools* package was used to apply the *Drago03* TMO through the function *pfstmo_drago03* with default settings, the *Durand02* TMO through the function *pfstmo_durand02* with default settings, and the *Reinhard02* TMO through the function *pfstmo_reinhard02* with the setting "–s" to apply the model for local adaptation which has been found to improve the quality of the resulting image [Drago et al., 2003]. Lastly, the *Ward97* TMO was applied using the function *pcond*, available within the *Radiance* software, with the settings "-s + -c + -u [maximum luminance of display] -d [ratio of maximum to minimum luminance of display]" to enable the human contrast sensitivity function, the loss of color visibility depending on the luminance range of the input image, and the mapping of the resulting image considering the maximum luminance and luminance range of the target display device. Due to technical issues at the time of the study, the maximum luminance of the VR display used in this study, the Oculus Rift CV1, was specified as being 60 cd/m^2 (and thus the corresponding ratio of maximum to minimum luminance within *pcond* was also set to 60), but it was later identified as being slightly higher. Specifically, the maximum luminance of the VR display, measured with a Konica Minolta LS-110 hand-held luminance meter, is 80 cd/m^2 for a fully white scene, and the minimum measured luminance is 0.02 cd/m^2 for a fully black scene.

The resulting tone-mapped HDR scenes were transformed into PNG files using *pfsgamma* for the images tone-mapped with *Reinhard02*, *Durand02*, and *Drago03*, and into BMP files using *ra_bmp* for the images tone-mapped with *Ward97*. In all cases, the images were gamma-corrected using the setting "-g 2.0", corresponding to a gamma correction of 2.0, which was specified through luminance measurements at the lens of the headset across a series of projected uniform grayscale scenes spanning 8 RGB levels from 0 to 255. As the maximum luminance of the display was at the time measured to be 60 rather than 80 cd/m^2, the applied gamma correction factor is slightly lower than the ideal one (a gamma of 2.3) for this device. The final images were projected in an Oculus CV1 headset, the successor of the Oculus DK2 headset that was used in the experimental study described in Section 4.1. This headset has an improved display with a resolution of 1080×1200 pixels per eye at a 90 Hz refresh rate, and a diagonal field of view of 110°.

Participants and experimental procedure
This preliminary study was conducted with 13 participants in August 2016 in individual experimental sessions that lasted roughly 15 minutes. Each participant saw in VR ten sets of four scene variations, where each scene variation in a set was tone-mapped with one of the four studied operators.

For each scene, participants were asked to rank the four variations based on the question "How would you order these scenes according to their realism, with the first one being the best?", resulting to a total of 40 evaluations per participant. Both the order of each set of scene variations and the order of scene variations within each set were randomized. Participants were able to cycle through the four tone-mapping variations of the same scene in VR until they were ready to give their evaluations.

Realism-based ranking of tone-mapping operators

The participant responses are presented in Table 4.8, showing how often (in percentage of the 130 responses in each rank) each TMO was ranked first, second, third, or fourth regarding the realism of the resulting scenes. The number of times that a scene tone-mapped with a specific TMO was ranked first identifies Reinhard02 as the best performing TMO by a large margin, followed by Ward97, Durand02, and lastly Drago03. The same findings, although with Durand02 rather than Ward97 being second best, apply when considering the weighted sum of the percentages using rank-order centroid [Barron and Barrett, 1996] weights (0.52 for the first rank, 0.27 for the second, 0.15 for the third, and 0.06 for the fourth), a weighting method which is suggested in the literature as the best performing rank-based scheme for choice accuracy [Roszkowska, 2013].

Table 4.8 – Percentage of frequency of placement of the TMOs in each ordered rank across all photograph-based VR scenes in the preliminary study, and weighted sum of percentages for each TMO using rank-order centroid (ROC) weights.

	How would you order these scenes according to their realism? (%)				
TMO	First	Second	Third	Fourth	Weighted Sum (ROC)
Reinhard02	43.1	34.6	17.7	3.8	34.6
Durand02	20	27.7	23.1	30	23.1
Drago03	13.1	29.2	31.5	2.2	20.9
Ward97	23.8	8.5	27.7	40	21.2
Sum	100	100	100	100	100

Our findings are in agreement with previous work by Drago et al., where participants were asked to evaluate four images tone-mapped with seven different operators by choosing in paired comparisons which of the two tone-mapped variations was the most preferred in a general sense. When comparing the number of times that each TMO was chosen as the most preferred over others, Reinhard02 was the most often chosen method, followed by Ward97 [Drago et al., 2002]. Following the outcome of this preliminary study, and specifically the lower relative performance of Drago03 compared to the other operators, we will investigate the perceptual accuracy of the Reinhard02, Ward97, and Durand02 TMOs in a dedicated experimental study, which is presented in the following section.

4.2.2 Testing immersive VR scenes from high-dynamic-range photographs

Drawing from insights obtained from the experimental study that was described in Section 4.1, which compared the participant evaluations of real environments against their corresponding simulation-based immersive scenes shown with the Oculus DK2 VR headset, we set to improve the developed VR experimental method by investigating the suitability of different tone reproduction methods as well as the potential of a newer head-mounted display. To this end, this section presents an experimental study that compares the subjective impressions of participants in real and virtual environments, in line with the experimental method from Section 4.1, while testing the perceptual accuracy of different tone-mapping operators and employing a VR headset with improved display characteristics. The objectives of this investigation are to identify the most perceptually accurate tone-mapping operator for immersive daylit scenes, and to validate the adequacy of the proposed experimental method with a larger sample size and across multiple experimental spaces.

In order to eliminate any impact of the virtual scene's level of detail on the perceptual accuracy of the experimental method, in this study we use scenes generated from HDR photographs, rather than simulation, as visual stimuli in the virtual environment. In addition, the real environment is employed as reference for the perceptual comparison of the tone-mapping operators, following methodological recommendations from the literature [Ashikhmin and Goyal, 2006]. The following section will introduce the experimental method followed in this study, as well as the workflow for the generation of photograph-based immersive scenes.

4.2.2.1 Experimental design

A mixed experimental design was chosen for this study, corresponding to the dual aim of investigating both the perceptual accuracy of the photograph-based immersive scenes and the effect of different tone-mapping operators on this perceptual accuracy. The *environment* was used as a within-subject factor with two levels, corresponding to the real environment and its virtual representation from tone-mapped TMO photographs, while the *tone-mapping operator* (with three levels, corresponding to the operators Reinhard02, Ward97, and Durand03) was used as a between-subject factor. Lastly, the *experimental space* (with three levels, two office spaces and one atrium) in which the experimental session took place was used as a between-subject factor, following methodological recommendations that suggest the use of multiple scenes to investigate the perceptual accuracy of different TMOs [Kuang et al., 2004; Yoshida et al., 2005]. Figure 4.17 shows an example overview of all combinations between the factors *experimental space* and *tone-mapping operator*.

The novelty of this experiment lies not only in the investigation of the perceptual accuracy of TMOs for virtual reality, but also in the unique experimental procedure employed in this study, where the photograph-based virtual scenes are generated within a few minutes of the participant's arrival. Thanks to this procedure, the participant is exposed to a virtual environment that accurately represents the actual conditions in the real space, something which is usually problematic in daylit scenes. This is a unique feature of the current study, as, until now, studies that compare TMOs and use real world scenes as a reference are either limited to artificially lit scenes [Kuang et al., 2006; Petit et al., 2013] or, in the case of daylit scenes, ask participants to rely on their memory of a previously seen environment [Villa and Labayrade, 2010].

Figure 4.17 – Overview of the combinations of the between-subject factors used in this study: the tone-mapping operator —Reinhard02, Ward07, Durand03— applied in the virtual scene (x axis) and the experimental space —(a) a front-lit office, (b) a side-lit office, and (c) a top-lit atrium— (y axis).

4.2.2.2 Description of the real environments

Experiments took place in three different locations, chosen to represent a variety of conditions for daylight access. Specifically, the selected locations consisted of a front-lit workspace, a side-lit workspace, and a top-lit atrium. Figure 4.18 shows the fisheye 180° views of the selected locations (left) and their corresponding cubemap projections, with the areas that are not visible shown in black (right).

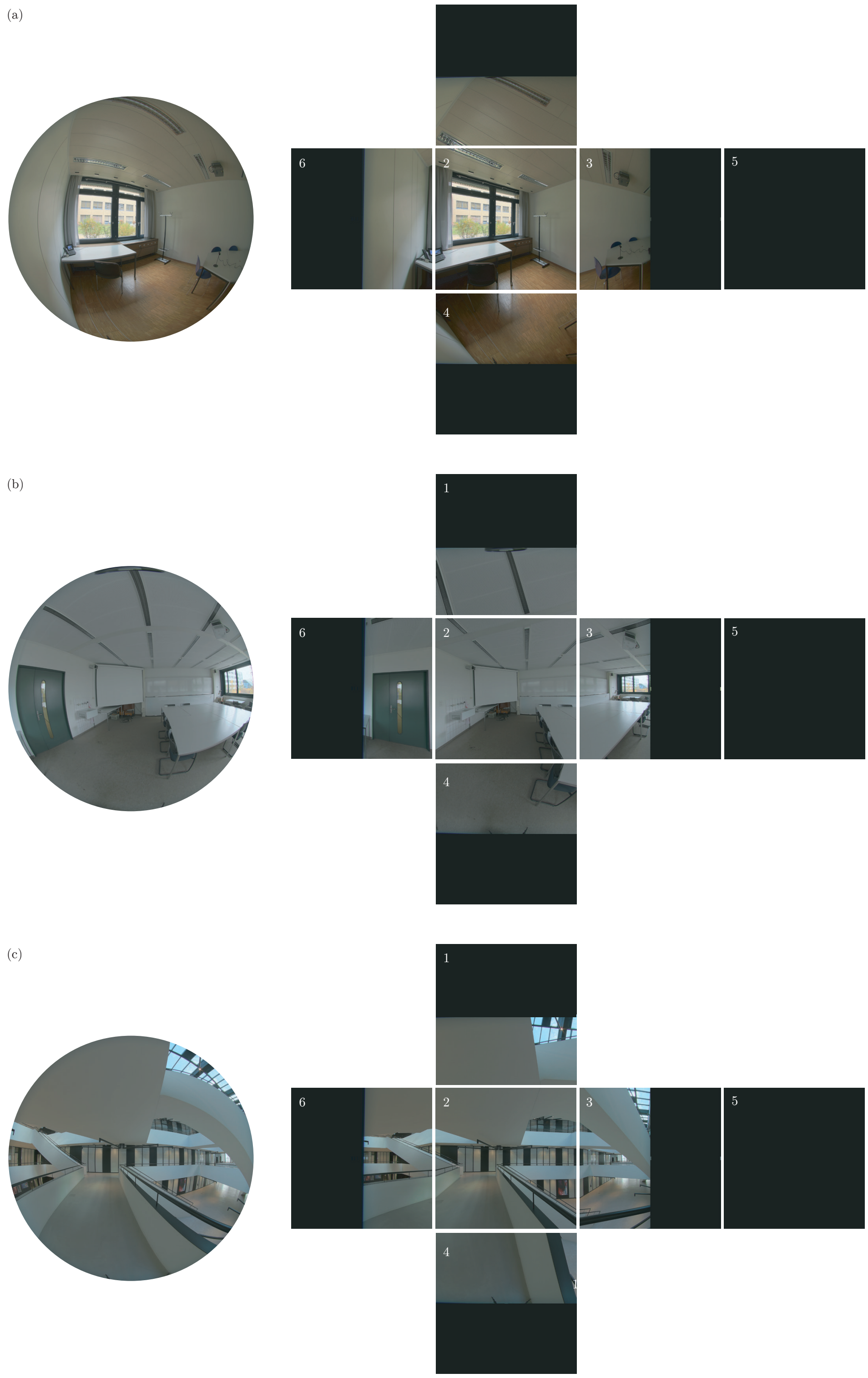

Figure 4.18 – Examples of the three experimental spaces, comprising of (a) a front-lit office, (b) a side-lit office, and (c) a top-lit atrium, shown in 180° fisheye (left) and cubemap (right) projections and tone-mapped with the Reinhard02 operator.

In each location, a designated spot was used to place the camera tripod and capture the conditions in the scene with multiple exposure photographs, following a procedure that will be described in the next section. To ensure similarity between the real and virtual environments, participants were instructed to stand on the same spot and were oriented to face the same view direction as the camera. The same spot was used for each location across experimental sessions. For each session, reference luminance measurements were taken with a Konica Minolta LS-110 luminance meter using two white cards placed at a bright and dark location in the scene, immediately after photographing the real environment for each experimental session, to be used in the calibration adjustment of the HDR photographs. Lastly, the vertical illuminance was measured at the level of the camera lens using an LMT Pocket Lux 2 illuminance meter to provide an additional measure of lighting conditions in the scene. These vertical illuminance measurements were employed after the experimental sessions to verify the validity of the HDR images that were used to generate the immersive scenes, which is discussed further in Appendix A.1.5.

4.2.2.3 Workflow for the generation of the immersive virtual scenes

In each experimental session, the scene was captured using automatic exposure bracketing with a Canon EOS 70D camera and a 180° SIGMA 4.5mm F2.8 EX DC HSM lens. The camera was placed on a designated spot for each experimental location using a tripod. For each session, the tripod was adjusted so that the lens height corresponded to the participants' eye height. Seven LDR photographs were taken for each scene using an aperture size of f/5.6, varying shutter speed and established camera settings for the capture of HDR images such as an ISO-100, white balance set to Daylight, and lens focus set to infinity [Inanici, 2006; Reinhard et al., 2010]. No vignetting correction was applied, as the relative loss of luminance due to vignetting effects was identified as maximum 2% for an aperture of f/5.6, measured with the procedure described in Pierson et al. [2017] and using a uniform light source in a dark room and 18° intervals for the rotation of the camera. This finding which is in agreement with the investigation by Cauwerts et al., who found decreasing vignetting at smaller aperture sizes and negligible effects for apertures smaller than f/5.6 [Cauwerts et al., 2012].

The sequence of LDR photographs from each experimental session were merged into HDR through the Radiance function *hdrgen* with the settings "-a" and "-r" to toggle off the automatic exposure alignment, which is recommended for tripod-stabilized photograph sequences, and to set a specified camera response curve file, respectively. The response curve file for the camera used in this experiment was identified through *hdrgen*, using a sequence of LDR photographs of an interior daylit scene and ensuring that the LDR images were separated by one EV and did not contain RGB values higher than 200 or lower than 20 [Inanici, 2006; Reinhard et al., 2010].

The resulting HDR image was cropped to a square that frames the fisheye view using the Radiance function *pcompos*, resulting to an image of 3073 by 3073 pixels. The header of the image is modified to specify an equidistant 180° fisheye view ("-vta -vh 180 -vv 180"), without a re-projection of the image, as it was not known at the time that the actual projection function of the lens might not correspond to a true equidistant projection [Pierson et al., 2017]. Any header lines referring to exposure were also removed to allow for correct luminance calibration. Following this step, the image was calibrated using an exposure adjustment factor. This factor is equal to the average ratio between the measured luminance values and those derived from the HDR image [Jacobs, 2007] (identified using *ximage*) for the two reference white cards that were placed in the scene. Lastly, the surrounding black area at the corners of the fisheye image was replaced with the average RGB values within the circle of the fisheye projection using a custom script. This step aimed to minimize the impact of the black area surrounding the original fisheye view on the tone-mapping function, as only the Ward97 operator considers the projection type.

Depending on the allocation of a participant in one of the three groups of the tone-mapping algorithm variable, the HDR scene was then tone-mapped with the Reinhard02, Ward97, or Durand02 operator, using the procedure that was described in Section 4.2.1.3. Then, the image area surrounding the fisheye view was set to black once more using the same custom script, and the tone-mapped angular fisheye HDR image was converted to a cubemap projection using the Radiance function *pinterp*. Lastly, the individual HDR files, which corresponded to the six faces of the cubemap, were transformed to BMP or PNG files depending on the TMO that was used, and gamma-corrected with a factor of 2.0. Figure 4.19 shows an example of the same scene and the corresponding cubemap projection, tone-mapped with the three operators. It is of interest to note that the differences between the operators are not that apparent in print, as again we are limited by the dynamic range of print media.

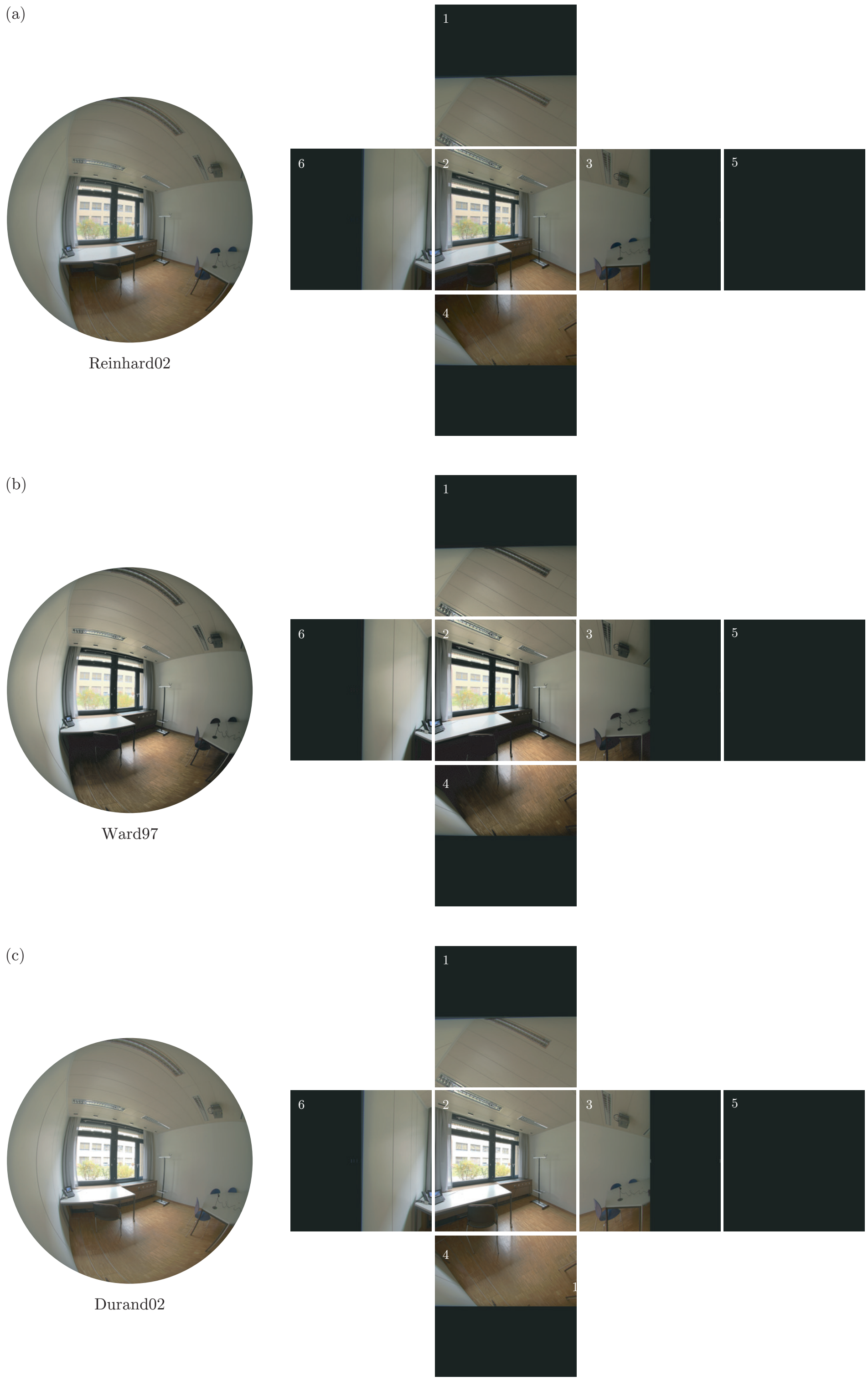

Figure 4.19 – Examples of tone-mapped variations of the same scene in 180° fisheye (left) and cubemap (right) projections, using the (a) Reinhard02, (b) Ward97, and (c) Durand02 operators.

The resulting LDR cubemap projections were used to generate immersive scenes for VR using the game engine *Unity*, following the workflow that was introduced in Section 4.1.1.4. As in this experiment we were limited to capturing the scene from one sole viewpoint, the generated VR scenes are monoscopic, and the same cubemap projection is shown to both eyes in the VR display. The resulting scene is experienced as a fully immersive environment from a static viewpoint, with only half of the scene visible as it corresponds to the 180° photograph. An individual executable file was created for each experimental session, containing the virtual reality environment to be projected in the VR headset.

Figure 4.20 – Illustration of workflow for the generation of photograph-based immersive 180° scenes.

The whole procedure for generating these immersive scenes, from the capturing of the photographs to the development of the VR scenes, which is illustrated in Figure 4.20, was automated as much as possible and completed in roughly 8 minutes. This allowed the creation of immersive scenes in real time, and ensured that the actual lighting conditions in the real scene were represented as closely as possible, which, to our knowledge, is a unique feature of this study.

4.2.2.4 Dependent variables

Participants were asked to evaluate the presented scene on a verbal questionnaire consisting of four questions related to the atmosphere of the space and four questions relating to the lighting in the scene, following the methodological approach by Cauwerts, which addressed both the visual appearance of the space and the visual appearance of the lighting [Cauwerts, 2013]. Specifically, participants were asked to rate how *pleasant*, *interesting*, *exciting*, and *calming* they perceived the space to be, drawing from experimental studies that investigated the light-induced perceptual impressions of interior spaces [Flynn et al., 1973; Loe et al., 1994; Vogels, 2008; Cauwerts, 2013; Rockcastle, 2017] and are particularly relevant for this thesis. In addition, participants were asked four questions related to the lighting in the space (how *diffuse*, *contrasted*, and *uniform* the light was in the space, and how *bright* was the space), corresponding to commonly used attributes from literature on the visual appearance of luminous environments [Flynn et al., 1973; Van Erp, 2008; Cauwerts, 2013; Rockcastle, 2017]. The order of the questions was randomized, and participants were asked to evaluate the presented scene on a scale from 1 ("Not at all") to 10 ("Very"). This scale range was selected over the 5-point scale that was used in the previous section following findings in the literature which demonstrated that this scale range was the most preferred [Preston and Colman, 2000], and addressing participants' comments from the previous study in Section 4.1 regarding the limited range of the 5-point scale. The questionnaire was administered verbally, without a visual reference, to avoid interactions with the projected virtual scene. Table 4.9 presents an overview of the studied experimental variables.

Table 4.9 – Overview of experimental variables.

Independent Variables	
IV.1	Environment: real or virtual environment
IV.2	Tone-mapping operator in VR: Reinhard02, Ward97, or Durand02
IV.3	Scene: side-lit space, front-lit space, or top-lit space
Dependent Variables	
Perceptual impressions of the scene	
PI.1	How pleasant is this space?*
PI.2	How interesting is this space?*
PI.3	How exciting is this space?*
PI.4	How calming is this space?*
Visual appearance of the scene	
VA.1	How diffuse is the light in this space?*
VA.2	How contrasted is the light in this space?*
VA.3	How uniform is the light in this space?*
VA.4	How bright is this space?*

*A scale from 1 to 10, 1 corresponding to 'Not at all' and 10 to 'Very much', was used for the marked questions.

4.2.2.5 Equipment

This experiment was conducted with the Oculus Rift CV1, a newer version of the headset that was used in the study of Section 4.1, with the aim to test the adequacy of this improved headset and address the device-related limitations of the previously tested experimental method. As this headset was also used in the preliminary study that was presented earlier in this section, the specifications of the device are described in the Section 4.2.1.3. The Oculus CV1 headset was used in combination with a dedicated Acer Predator 17-X laptop, which allowed the replication of the experiment in multiple locations. In addition to this equipment, a camera, 180° fisheye lens, tripod, as well as luminance and illuminance meters, described in Sections 4.2.2.2 and 4.2.2.3, were used to capture the experimental scene and generate the corresponding virtual environment.

4.2.2.6 Participants

Sixty-three subjects took part in this study, consisting of 42 men and 21 women aged 18 to 50 years (men: μ=26.88 years, σ=5.66 years; women: μ=27.33 years, σ=8.21 years). Participants were unpaid volunteers and were recruited via e-mail, social media, and posters placed in the EPFL campus. Eligible participants were selected based on the criteria of a generally healthy condition, age between 18 and 50 years (this upper limit was specified to avoid the occurrence of presbyopia [Brückner, 1967] which would be problematic for the use of a VR headset), normal or corrected-to-normal vision, and English language proficiency of C1 or higher. As the experiments took place in three different locations, participants were randomly distributed in each location. Table 4.10 presents the sample size for each combination of these two factors.

Table 4.10 – Sample size per experimental space and tone-mapping operator.

	Experimental space		
TMO	Top-lit Room	Side-lit Room	Front-lit Room
Reinhard	8	9	6
Ward	8	6	6
Durand	6	7	7

4.2.2.7 Experimental protocol

Experimental sessions lasted roughly 30 minutes and were scheduled through appointments with each participant from 9:00 to 16:30, ensuring the presence of daylight in the scene. Experiments were conducted during the month of November 2016 in three different locations in EPFL, corresponding to the three levels of the between-subject factor *experimental space*. Upon arriving to the location, participants were randomly allocated in three groups, which dictated the tone-mapping operator that would be used to create the photograph-based scene that the participant would experience in virtual reality.

In the beginning of each session, the participant was guided to read a document with information about the study and provided written consent prior to the experiment. Following this step, the participant was asked to respond to a demographic questionnaire through a tablet, providing information such as age, gender, and vision correction. In these initial stages of the experimental session, participants were placed in a position which ensured they would not be exposed to the real environment from the viewpoint that would be later used for the evaluation of the scene.

While the participant read the provided documents and answered the demographic questionnaire, the researcher recorded the real scene through multiple exposure photographs taken from a specified viewpoint for each location and measured the vertical illuminance at the level of the camera lens. In addition, the luminance of the scene was measured using two reference points with white cards placed in the brightest and darkest point of the scene. Through these measurements, a unique photograph-based virtual environment was generated for each experimental session and tone-mapped with one of the three studied TMOs, following the procedure described in Section 4.2.2.3.

When participants were ready to proceed, they were guided to stand on a marked spot on the floor and were either asked to look towards the front, or guided to wear the VR headset, depending on the presentation order of the two environments. For consistency with the 180° virtual environment, participants were asked to restrict their head movements in the real environment and were shown the boundaries of these movements in order to limit their field of view as required. Participants were requested to remain on the same spot and keep their hands close to their body while exploring the presented scene, and were informed that the researcher would be behind them to avoid obstructing their view.

During immersion to each environment, participants were asked to inform the researcher when they were ready to answer the questionnaire, and to were instructed to consider the presented scene as a whole in their evaluations. The two environments were shown in random order, with the second one shown in quick succession to ensure similarity in the presented conditions. To illustrate this procedure, Figure 4.21 shows a participant in the real environment, experiencing the corresponding virtual scene through the headset. The photograph-based scene that the participant is seeing in VR can be seen on the computer display on the right (it is worth noting that the display is anti-reflective, and the displayed image is the projection of the participant's viewpoint in virtual reality in real-time, rather than a reflection).

Figure 4.21 – Photograph of a participant in the real environment, exploring its virtual representation in VR.

Before exposure to the virtual environment, participants were guided to wear the headset, and were shown a training scene with a black background and white text to ensure that the headset was correctly adjusted and that they would be facing the same view direction as the one in the real environment.

This research was approved by the EPFL Human Research Ethics Committee (HREC 008-2016) and complied with the tenets of the Declaration of Helsinki.

4.2.2.8 Data analysis

Following one-sample Kolmogorov-Smirnov tests that showed the non-normality of our data for all the studied variables, non-parametric tests were used for the statistical analyses. All statistical tests were two-tailed and performed at a 0.05 significance level using the Statistics and Machine Learning Toolbox in *MATLAB 2017b*.

The perceptual accuracy of the photograph-based experimental method was evaluated through the two indices that were employed in the analysis of the equivalent experiment in Section 4.1 for the within-subject factor *environment*. Specifically, the result of Wilcoxon Matched-Pairs Signed-Ranks test, conducted using the paired responses in the real and virtual environment, in combination with Cohen's d_z effect size, applied to the difference z between the paired responses in the two environments, were used as measures of perceptual accuracy of the virtual medium. A positive result of adequate perceptual accuracy for an attribute is defined as the absence of a statistically significant result from a Wilcoxon Matched-Pairs Signed-Ranks test conducted at a significance level α of 0.05, in combination with an absolute effect size $|d_z|$ equal to or lower than 0.2, corresponding to a small effect size [Cohen, 1992].

For the between-subject factors *tone-mapping operator* and *experimental space*, a Kruskal-Wallis one-way analysis of variance test was used to determine main effects on the perceptual accuracy of the virtual environment, by applying the test to the difference between the paired responses in the two environments (subtracting the responses in the virtual environment from those in the real environment). In the case of absence of a significant effect of the tone-mapping operator on the differences between the paired responses, the combined indicators for perceptual accuracy (the Wilcoxon Matched-Pairs Signed-Ranks test and the effect size $|d_z|$) were applied individually to each tone-mapping operator to compare their performance.

4.2.3 Perceptual accuracy of the photograph-based virtual environment

This section will present the findings of the experimental study in three parts, addressing the overall perceptual accuracy of the photograph-based immersive VR scenes, as well as the effects of the factors *tone-mapping operator* and *experimental space* on this perceptual accuracy. Effects of stimuli presentation order on the perceptual accuracy of the virtual environment are presented in the Appendix A.2, as they are of interest for methodological considerations.

4.2.3.1 Overall perceptual accuracy of the photograph-based virtual environment

In order to investigate the perceptual accuracy of the VR environment, we first analyse jointly the participant responses across all experimental spaces and tone-mapping operators, corresponding to a sample of 63 paired responses in the real environment and its virtual representation. The difference between the responses of the same participant in the real and the virtual environment can be used as a measure of perceptual accuracy. The frequency distribution of the absolute differences between these paired responses is shown in Table 4.11.

Table 4.11 – Frequency distribution of absolute differences between the subjective evaluations in the real and virtual environment.

	Percentage of pairs with absolute difference (%):											
	0	1	2	3	4	5	6	7	8	9	≤ 1	≤ 2
pleasant	22	33	17	19	5	2	0	2	0	0	**56**	**73**
interesting	35	30	19	13	2	2	0	0	0	0	**65**	**84**
exciting	40	33	17	2	3	2	3	0	0	0	**73**	**90**
calming	41	30	14	8	5	2	0	0	0	0	**71**	**86**
diffuse	21	46	14	6	10	3	0	0	0	0	**67**	**81**
contrasted	19	32	32	6	8	0	2	2	0	0	**51**	**83**
uniform	25	35	22	11	5	2	0	0	0	0	**60**	**83**
bright	27	37	19	13	2	2	2	0	0	0	**63**	**83**

Individual values are rounded to the nearest integer and are marked in bold if equal to or higher than 50%.

We can observe that the percentage of paired responses with an absolute difference of zero varies widely between attributes, ranging from 41% of our sample for the evaluations of how *calming* the space is perceived, to 19%, for the evaluations of how *contrasted* is the light in the space. Overall, the percentage of identical responses in the two environments is lower in this experimental study compared to the experiment presented in the previous section. This is an expected outcome, considering the wider rating scale range (a 10-point scale, instead of the 5-point scale used in the experimental study of Section 4.1) that is employed in the current study, which allows for a higher variation in participants' responses. We observe that at least 51% of the paired responses have an absolute difference lower or equal to one, corresponding to the smallest possible non-zero difference, while at least 73% of the responses for all questions have an absolute difference lower or equal to two, a difference comparable to that of one unit in a 5-point scale.

Figures 4.22 and 4.23 show the distribution of paired responses in the real and virtual environment regarding the perceptual impressions of the space and the visual appearance of the light in the scene, respectively. In these figures, the dashed diagonal line shows the paired responses with no difference between them, while the dotted lines demarcate the range of responses with a difference of ±1 unit. We can observe that the evaluations are more scattered for certain attributes, such as how bright the scene is perceived, compared to others, such as how exciting the scene is perceived. The same figures can be used to observe whether there is consensus in the participants' responses across the presented experimental conditions. Figure 4.22 shows a clustering of responses in the positive range of the scale (>5 units) for the evaluations of how calming the space was perceived.

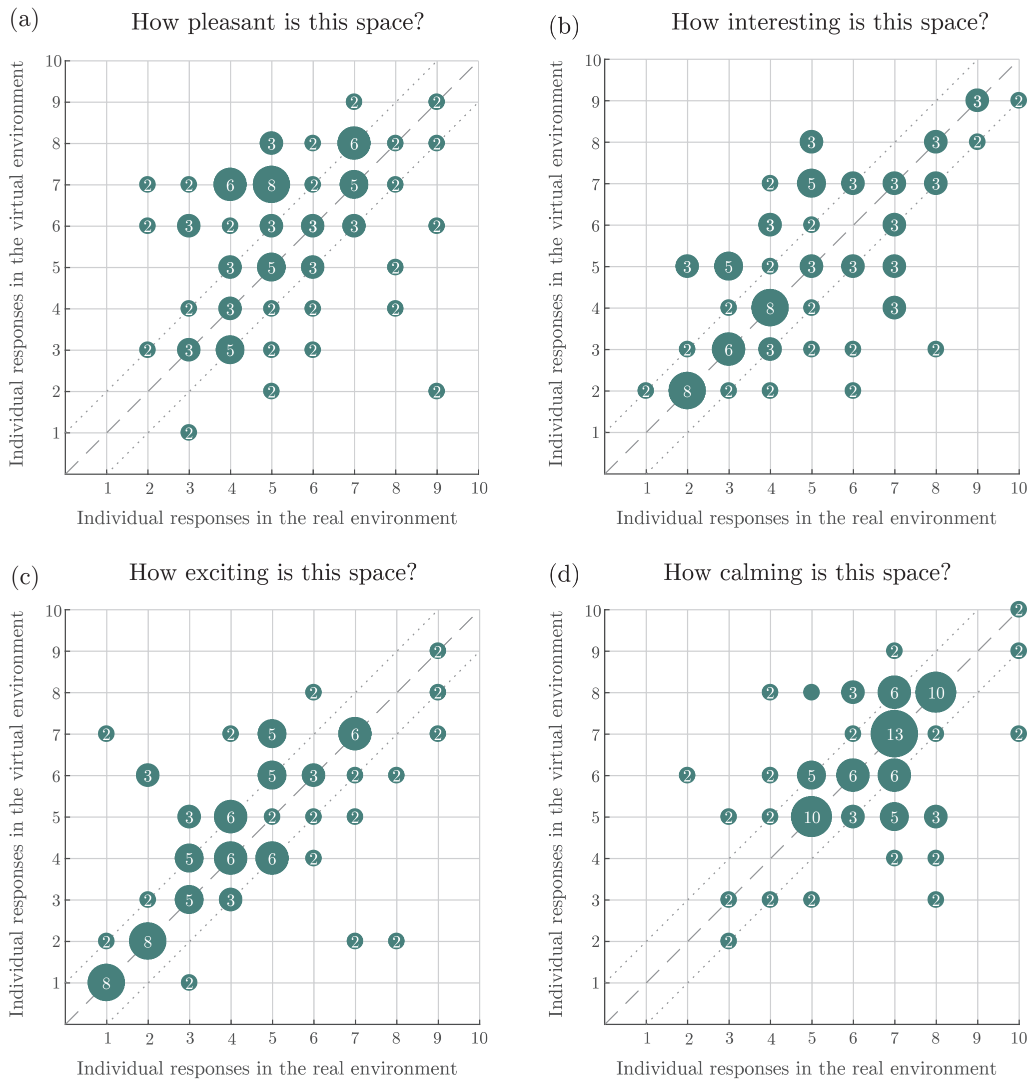

Figure 4.22 – Distribution of responses in the real (x axis) and the virtual (y axis) environment from each participant for each of the studied attributes relating to the evaluation of the space. The size and label of the circles correspond to the percentage of paired responses with identical values, rounded to the nearest integer. The dashed diagonal line marks the paired responses with a difference of zero while the dotted lines mark the responses with a difference of ±1 between the two environments.

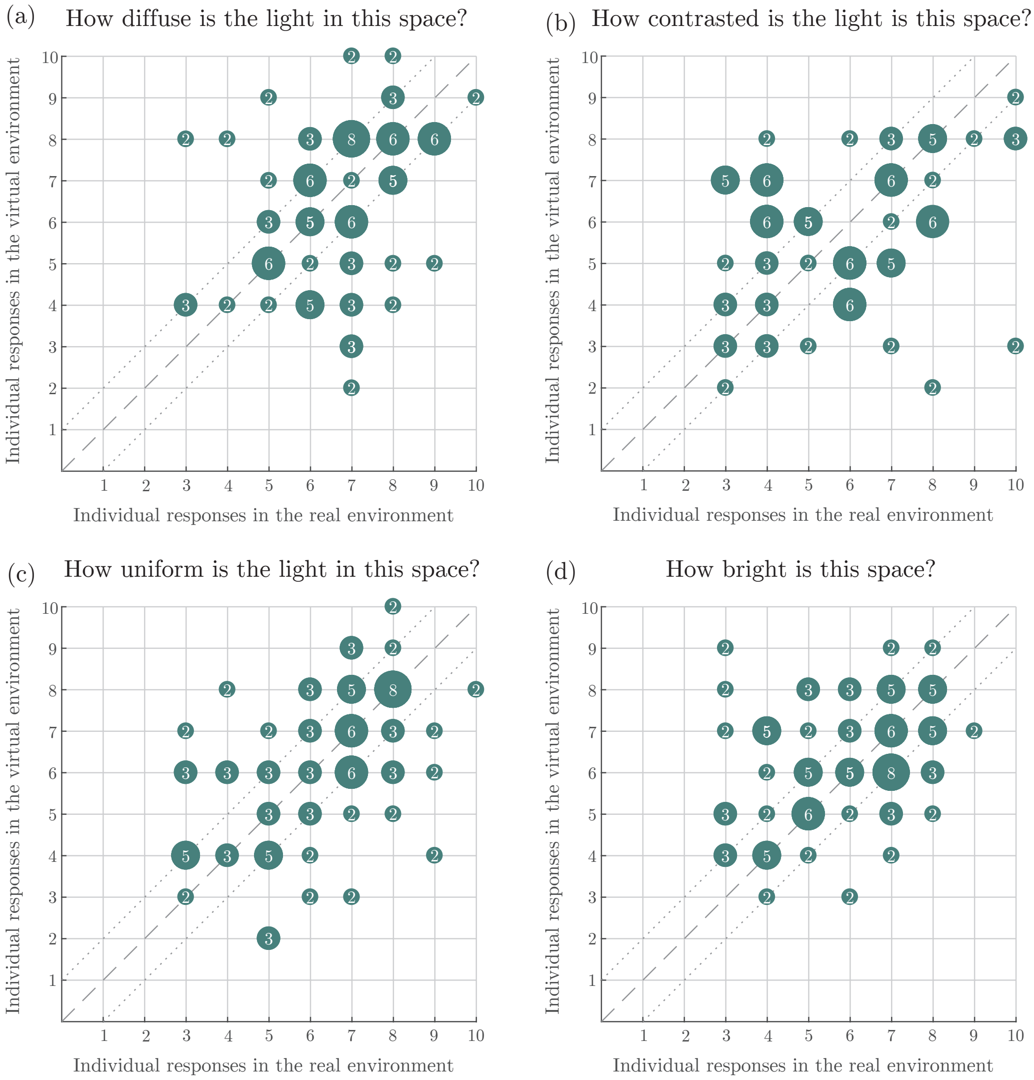

Figure 4.23 – Distribution of responses in the real (x axis) and the virtual (y axis) environment from each participant for each of the studied attributes relating to the evaluation of the space. The size and label of the circles correspond to the percentage of paired responses with identical values, rounded to the nearest integer. The dashed diagonal line marks the paired responses with a difference of zero while the dotted lines mark the responses with a difference of ±1 between the two environments.

A Wilcoxon Matched-Pairs Signed-Ranks test conducted at a significance level α of 0.05 showed no significant differences between the responses in the real and the photograph-based virtual environment for any of the studied attributes (all $ps > 0.08$), consistent with our findings for the simulation-based immersive scenes in Section 4.1. Following this result, we used Cohen's d_z and specifically the threshold of a $|d_z|$ of 0.2 as a measure of perceptual accuracy, shown in Table 4.12. This second indicator revealed that all studied attributes match our conditions for an acceptable perceptual accuracy, with the exception of how bright the scene is perceived. This finding is not surprising, considering the wide differences in the dynamic range of the two environments, and is in agreement with the results of Cauwerts in experimental studies that compared the perception of brightness in real and virtual environments [Cauwerts, 2013]. However, it is worth noting that Cauwerts found significant differences between the evaluation of brightness in the real world and its virtual representations, while in the current study we did not find such an effect, possibly due to the positive effects of the participants' immersion and visual adaptation in the VR headset. Table 4.12 contains the mean difference μ_z and the mean absolute difference $\mu_{|z|}$ between the paired responses in the two environments to provide additional measures of comparison with relevant studies, a topic which will be discussed in Section 4.2.4.

Table 4.12 – Overview of studied attributes and their perceptual accuracy based on the indices of the Wilcoxon Signed-Ranks Matched-Pairs test and effect size d_z, for all tone-mapping operators.

	N	N_{diff}	μ_z	$\mu_{\|z\|}$	d_z	
pleasant	63	51	0.3968	1.7937	0.1851	✓
interesting	63	41	0	1.2063	0	✓
exciting	63	38	-0.1746	1.1270	-0.0970	✓
calming	63	37	0.1429	1.0952	0.0858	✓
diffuse	63	50	0.2381	1.4762	0.1202	✓
contrasted	63	51	0.1111	1.6667	0.0505	✓
uniform	63	47	0.0952	1.3968	0.0513	✓
bright	63	46	-0.4127	1.3651	-0.2246	

An effect size d_z lower than or equal to 0.20, marked with ✓, indicates an acceptable result.

4.2.3.2 Comparison of perceptual accuracy between tone-mapping operators

Following the results on the overall perceptual accuracy of the photograph-based immersive scenes across all TMOs and experimental spaces, this section focuses on the perceptual performance of the individual operators. Specifically, we will compare the perceptual accuracy of the three studied TMOs by investigating the influence of the choice of TMO on the difference z between the paired responses in the real and the virtual environment for all attributes.

A Kruskal-Wallis one-way analysis of variance showed no significant effect of TMO on the differences between the paired responses for any of the studied attributes (all $ps > 0.15$). Similarly, the same test showed no effect of TMO on the vertical illuminance of the scenes (all $ps > 0.89$), an analysis that was conducted to ensure that the lighting conditions were comparable across the three TMO groups.

In order to investigate further possible differences in the perceptual performance of the studied TMOs, we repeat the analysis described in the previous section for the individual datasets related to each TMO, and use a Wilcoxon Matched-Pairs Signed-

Ranks test and Cohen's d_z effect size as additional measures of perceptual accuracy. The Wilcoxon Matched-Pairs Signed-Ranks tests showed no significant differences between the paired responses for any of the studied attributes in the three datasets (all $ps > 0.08$). However, the calculation of Cohen's d_z showed notable differences between the different operators. Figure 4.24 shows the calculated d_z across the studied attributes for each TMO, and marks the threshold of ± 0.2 d_z with dotted lines, to delineate the range of an acceptable result.

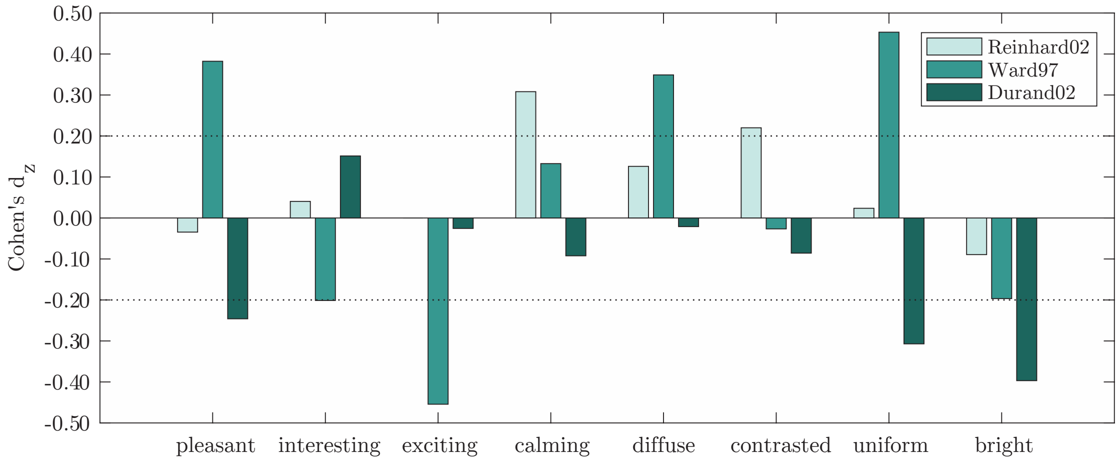

Figure 4.24 – Distribution of Cohen's d_z across the scenes with different tone-mapping operators for each of the studied variables.

Table 4.13 – Comparison of perceptual accuracy of tone-mapping operators based on the indices of the Wilcoxon Signed-Ranks Matched-Pairs test and effect size $|d_z|$.

	Reinhard02	Ward97	Durand02
pleasant	✓		
interesting	✓		✓
exciting	✓		✓
calming		✓	✓
diffuse	✓		✓
contrasted		✓	✓
uniform	✓		
bright	✓	✓	

Cells marked with a ✓ indicate an acceptable result of perceptual accuracy based on the two indices. As no significant differences were found between the evaluations in the real and virtual environment for any of the studied attributes or operators, such a result represents solely the effect size $|d_z|$.

For clarity, Table 4.13 presents an overview of the perceptual accuracy of each TMO across the studied attributes based on the combined indices of a Wilcoxon Signed-Ranks Matched-Pairs test and a $|d_z|$ effect size, where a checkmark (✓) indicates a successful outcome. Since no significant differences were found between the responses in the real and the virtual environments for any of the studied attributes and tone-mapping operators, $|d_z|$ is the sole index differentiating the performance of the tone-mapping operators. The results reveal that the Reinhard02 outperformed the other operators, with six out of eight attributes deemed as acceptable, and an additional attribute deemed as marginally acceptable ("contrasted", with a $|d_z|$ of 0.22). The second most perceptually accurate TMO was Durand02 with five out of eight attributes deemed as acceptable. Table 4.13 reveals that the Ward97 is the least perceptually accurate TMO in this study, with only three attributes matching our conditions for accepted perceptual accuracy. Table 4.13 shows that specific operators are more perceptually accurate for certain attributes. Reinhard02 was the sole operator able to sufficiently recreate the impressions of pleasantness and uniformity of light in the real environment. On the other hand, it failed to meet our set threshold for the attributes "calming" and "contrasted", for which both Ward97 and Durand02 were successful. These results can thus be used to select the most appropriate tone-mapping operator according to the studied attributes.

4.2.3.3 Influence of experimental space on perceptual accuracy

In order to investigate possible influences of the experimental space on the perceptual accuracy of the virtual environment, a Kruskal-Wallis one-way analysis of variance was conducted on the differences between the paired responses in the real and the virtual environment, comparing the three groups of data from each experimental location. Results indicate no significant differences between the three spaces for any of the studied attributes (all $ps > 0.06$). Although other studies suggested an effect of the presented scene on the reported realism [Villa and Labayrade, 2010] and the reported accuracy [Kuang et al., 2006] of tone-mapping operators, these results cannot be directly compared with our findings, as in the current study we employ the actual differences between the responses in the real and virtual environments as a measure of perceptual accuracy, rather than the participants' judgments of that accuracy.

4.2.4 Discussion

The work presented in this section brings forth two important outcomes for this thesis. Firstly, the analysis of the overall perceptual accuracy of the improved experimental method showed that the combination of tone reproduction algorithms, a newer device, and a highly detailed virtual scene led to very positive results with seven out of the eight studied attributes satisfying the set accuracy thresholds. These findings validate the use of the developed experimental method for the perception of daylit environments, confirming the outcomes of Section 4.1 with a larger sample size and across different experimental spaces. Secondly, the comparison of the perceptual accuracy of the three most promising tone-mapping operators revealed the Reinhard02 operator as the most perceptually accurate operator for the studied attributes. Consistent with this result, the preliminary study described in Section 4.2.1.3 also showed the Reinhard02 operator as the most highly rated in terms of perceived realism of the tone-mapped scenes shown in VR.

To our knowledge, this is the first study investigating the perceptual accuracy of tone-mapping operators when applied to immersive daylit scenes. As such, it provides unique insights about the perceptual performance of established tone-mapping operators when they are applied to a dynamic and immersive environment. The comparison of the studied operators in a virtual reality setting reveals a discrepancy between the low perceptual accuracy of the Ward97 operator in the current study and its perceptual performance in static viewing conditions as shown in the overview of the literature in Section 4.2.1.1, which could be explained by the effect of immersion on the perception of tone reproduction.

In the same vein, a study by Mishra [2018] found that user assessments regarding the resemblance of a tone-mapped scene to an outdoor scene differed significantly between static versions of scenes tone-mapped with Ward97, shown in a LDR display, and dynamic versions of the scenes, shown in an Oculus DK2 VR display. Although this study did not directly compare the participant evaluations in the virtual environment with a real-world reference, it corroborates our finding regarding the inconsistency in the perceptual performance of this operator between non-immersive and immersive virtual environments.

4.2.4.1 Limitations

The results of this section demonstrate that this novel experimental method is a valid alternative to real environments for investigating the perception of sunlight patterns in the context of this thesis, overcoming the challenge of changing daylight conditions. In addition, Reinhard02 is revealed to be the most suitable operator for immersive daylit scenes, a finding which is particularly relevant for the experimental stimuli in the next steps of the thesis as well as for wider applications in the field of head-mounted displays. The comparison of the perceptual accuracy of the studied tone-mapping operators also revealed specific operators as more accurate for investigating certain perceptual attributes, and can thus be used as a reference for the selection of the most suitable algorithm depending on the studied attributes. However, it is important to note that the limited luminance range of the virtual reality display restricts the applicability of this experimental method in investigations where high luminance conditions are necessary, such as for the perception of discomfort glare. The outcomes of the present study, along with those from Section 4.1, showed no significant differences between the real and virtual environments in the perception of how pleasant, interesting, exciting, complex, calming, and bright was the space, how contrasted, diffuse, and uniform was the light in the space, and how satisfied the observer was with the amount of view in the scene, providing a substantial range of perceptual attributes. Future studies are encouraged to replicate and extend these findings using additional settings and perceptual attributes.

Although the immersive scenes used in this study were greatly improved in terms of their level of detail, the image resolution, and the tone reproduction, they also presented some shortcomings compared to the simulation-based scenes in the previous section. Specifically, as we used HDR photographs to capture the actual conditions in real time —contrary to the pre-rendered scenes used in the simulation-based environment—, the field of view in the virtual scene was limited to the 180° of the fisheye lens. This restricted field of view was also followed by the restriction of the participants' movements to ensure that they remained within the boundaries of the visible virtual scene, which might have affected their sense of presence in the virtual scene. The use of immersive scenes derived HDR photographs also led to monoscopic VR environments, since the same photograph was projected to both eyes of the participant. Although this lack of stereopsis did not lead to significant differences between the evaluations of the real and virtual environment, future studies are encouraged to study the perceptual accuracy of the proposed method in both highly detailed and stereoscopic virtual scenes. Moreover, the choice of TMO could also possibly impact the participant's sense of depth in the virtual scene, as contrast has been shown to influence depth perception [Cormack et al., 1991], and thus motivates further investigation.

Another limitation is the gamma correction factor in the virtual scenes, which was set —both in the current study and those that follow in the thesis— to 2.0 rather than 2.3 due to a measurement error regarding the maximum luminance of the VR display. However, judging from the overall perceptual accuracy of the photograph-based scenes, this inconsistency did not seem to affect the participant responses and can be considered a minor limitation of the immersive scenes.

4.2.4.2 Comparison between simulated- and photograph-based scenes

The common studied perceptual attributes in the two experimental studies that were presented in this chapter, testing the developed simulated- and photograph-based immersive scenes, allow the comparison of the two methods. In particular, we can use the mean absolute differences between the paired responses in the real and the equivalent virtual environment as a measure of perceptual accuracy, and divide this value with the maximum possible difference in the corresponding scale to normalize this measure (dividing by 4 for the 5-point scale and 9 for the 10-point scale, respectively).

The normalized mean absolute differences in the two experiments ($\mu_{|z|simu}$ and $\mu_{|z|photo}$) show a higher accuracy of the simulation-based environment for the evaluations of how pleasant the space was perceived ($\mu_{|z|simu} = 0.170$, $\mu_{|z|photo} = 0.199$), and higher accuracy for the photograph-based environment for the evaluations of how interesting ($\mu_{|z|simu} = 0.172$, $\mu_{|z|photo} = 0.134$) and how exciting ($\mu_{|z|simu} = 0.179$, $\mu_{|z|photo} = 0.125$) the space was perceived. However, a Wilcoxon Rank Sum test showed no significant effect of method on the perceptual accuracy for any of the attributes (all ps $> .39$), indicating that the aforementioned discrepancies in normalized mean absolute differences between simulation- and photograph-based environments are negligible.

4.3 Chapter summary

This chapter began with the introduction a novel experimental method for assessing the perception of daylit scenes. The novelty of this method lies in the generation of immersive virtual reality scenes based on photometrically accurate lighting simulations. In order to test the suitability of this method as an alternative environment for empirical studies, the first section presented a within-subject experimental study that used both real scenes and their simulation-based representations in VR as visual stimuli. Specifically, the adequacy of this method was assessed in three different areas: the perceptual accuracy of subjective evaluations (how pleasant, interesting, exciting, and complex the space is perceived, as well as the level of satisfaction with the amount of view) in the virtual scenes when compared to the equivalent real environment, the effect of the virtual reality headset on the users' physical symptoms, and the level of perceived presence in the virtual environment.

The performance of the produced virtual scenes across these three dimensions demonstrates that this environment is a particularly promising medium for empirical research. Following these highly positive findings, the next section explored the potential of changes in the employed head-mounted display as well as the tone reproduction of the virtual scene to further improve the proposed experimental method. As the tone reproduction is a central element in the creation of virtual environments, we set forth to identify the most suitable tone-mapping operator for the virtual-reality based experimental method used in this thesis. In addition, we developed this method further by increasing the level of detail in the virtual scene and using a VR headset that offers a higher resolution, and tested it against real environments.

The second section began with an overview of the best performing tone-mapping operators for static LDR images based on comparative experimental studies found in the literature. This overview revealed four promising tone-mapping operators (Reinhard02, Durand02, Ward97, and Drago03) in terms of the perceived realism, naturalness, and reported preference of the resulting tonemapped images. These four operators were then tested in a preliminary study where participants ranked four tone-mapping variations of ten photograph-based interior scenes shown in VR according to their realism. This preliminary study revealed the Reinhard02, Durand02, and Ward97 operators as the three most highly rated, with the Reinhard02 operator ranked most often as the most realistic.

In continuation to these findings, the second section introduced an experimental study that tested the perceptual accuracy of immersive scenes that were generated from HDR photographs and tone-mapped with the three previously identified tone-mapping operators, and shown in the improved Oculus CV1 VR headset. The novelty of this study lies in not only in the investigation of the performance of tone-mapping operators in a virtual setting, but also in the use of photograph-based virtual stimuli that are generated in real time, providing a high level of detail and similarity with the real scene. The results reveal a high level of perceptual accuracy for the produced immersive scenes, especially for attributes of particular interest for this thesis, such as how *pleasant*, *interesting*, and *exciting* the scene is perceived.

Chapter 5 will employ the developed experimental method to produce immersive scenes with varying lighting conditions and façade characteristics and broaden our understanding on how these aspects of the scene influence our spatial experience through subjective experiments.

Chapter 5

Identifying the magnitude of human responses to varying façade and daylight patterns

The previous chapter introduced a novel experimental method that uses immersive VR scenes from photometrically accurate images and demonstrated through two experimental studies that this method can be used as a surrogate to real environments for the investigation of the perceptual qualities of daylit spaces. Building on these methodological foundations, this chapter will present the findings of two additional experimental studies that employ the developed method to explore the core question of this thesis: can the façade geometry and its interplay with light in a space influence its occupants? Specifically, the purpose of the present chapter is to provide evidence about the impact of façade and daylight variations on occupants and thus demonstrate that this research topic merits further investigation.

While the importance of daylight on our perception of space has been broadly acknowledged both in the field of architecture and in lighting research, there is a lack of established knowledge about its positive effects on occupants. In particular, little information is known about the impact of the spatial distribution of sunlight, and how a façade and the corresponding sunlight pattern can affect the experience of a space. Although considerable research has been devoted to investigations in working environments, less attention has been paid to different uses of a space, despite the fact that the spatial context —the function of the space— has been suggested as a factor that can influence the occupant's expectations and perception of a daylit environment. In the specific case of daylit spaces, the spatial context is thus particularly important for the investigation of the perceptual effects of façade and sunlight pattern geometry.

The present chapter aims to evaluate the potential of this research area through two experimental studies in VR which explore the impact of façade and daylight patterns on occupant perception, acting as a proof-of-concept for the research objective of this thesis. Both studies employ the same façade geometry variations, and examine also the effect of different scenarios of space use on participant responses. The first study is a preliminary investigation, which is followed by a second more extensive experimental study. This second experimental study also explores the physiological responses of participants to the presented scenes, with the aim to uncover quantifiable effects of façade and sunlight geometry variations on occupants. Building on the findings of these two experimental studies, this chapter continues by identifying façade geometry variations that are promising for further investigation through a paper-based survey that examines the consensus of architects on the expected perceptual effects of contemporary façade designs.

This chapter consists of four sections. The first section introduces the preliminary experimental study that investigates the participant impressions of an interior scene across variations of façade geometry, sky types, and scenarios of use of the space. Building on the findings of this preliminary experiment, the second section continues by introducing an additional experimental study with a larger sample size, which uses the same façade geometry variations to examine both the subjective and the physiological responses of participants, coupling the virtual reality headset with a wearable biometric sensor. Moving on to the expected perceptual effects of a wider range of façade geometry variations, the third section of this chapter presents a paper-based survey that examined the intuition of architects in Switzerland regarding how occupants would respond to a series of façade geometry variations. Lastly, the chapter ends with a summary of the findings from these three studies and discusses how they drive the direction of this thesis.

5.1 Preliminary investigation of subjective responses to façade and daylight patterns*

This section investigates the importance of façade geometry and its interplay with light as a driver of our spatial experience. To this end, the presentation of real and virtual stimuli in the experiment that was introduced in Section 4.1 was followed by a second experimental phase, where the same participant was exposed to a series of façade geometry variations of an interior scene in VR. The studied façade variations were designed to differ both in the geometry and the spatial distribution of the openings, relating to characteristics of complexity which have been identified as important in the literature [Abboushi et al., 2019; Omidfar et al., 2015].

The aim of this experimental study was to examine the joint effect of façade geometry and the resulting daylight patterns on the participants' appraisal of a daylit space,

*The content of this section is partly based on a published conference article [Chamilothori et al., 2016] and a published journal article [Chamilothori et al., 2019a]:
K. Chamilothori, J. Wienold, and M. Andersen, "Daylight patterns as a means to influence the spatial ambiance: a preliminary study," in *Proceedings of the 3rd International Congress on Ambiances*, Volos, Greece, 2016.
K. Chamilothori, G. Chinazzo, J. Rodrigues, E. S. Dan-Glauser, J. Wienold, and M. Andersen, "Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality," *Building and Environment*, vol. 150, pp. 144–155, 2019.
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showcasing the potential of this research direction for the present thesis. Following the highly positive findings of the previous chapter, we employed immersive scenes generated from physically-based simulations as the visual stimulus. Specifically, we investigated both the effect of sky type and of façade geometry on participants' responses by using immersive scenes that depicted the same interior space, and differed in the lighting conditions and the openings of the façade. To limit fatigue, each participant was immersed in three variations of the same scene in VR, and was exposed to different façade designs under the same sky type. Lastly, in order to ensure that the studied conditions are comparable, the same perforation ratio was used for all façade geometry variations.

5.1.1 Experimental method

5.1.1.1 Experimental design

A mixed experimental design was chosen for this study, with the façade geometry as a within-subject factor with three levels (three façade variations, referred to as "Irregular", "Regular", and "Stripes"), and the sky type as a between-subject factor with two levels (clear and overcast sky). As our main focus in this study is the influence of the spatial distribution of façade openings on occupant perception, the façade geometry is selected as a within-subject factor to eliminate the variance due to individual differences between participants. The resulting variations span a matrix of different façade and lighting conditions in the same scene, illustrated in Figure 5.1.

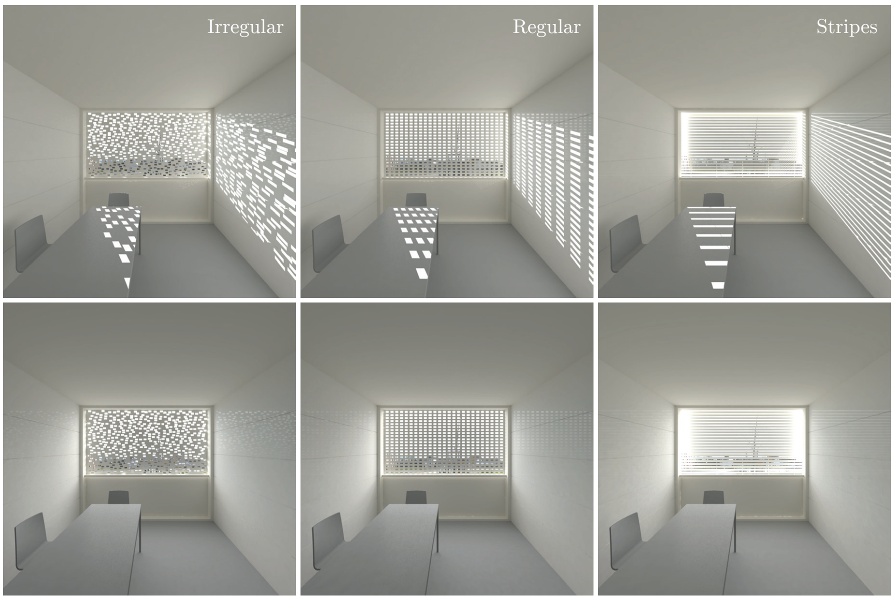


Figure 5.1 – Variations façade geometry under clear sky (top row) and overcast sky (bottom row). The frontal view direction of the cubemap projection is used here to represent the 360° immersive scene.

5.1.1.2 Independent variables

The studied façade variations consist of horizontal Stripes, used to provide a benchmark of a shading system that is commonly used in Europe, and two perforated façades with regularly and non-regularly distributed openings, used to investigate the effect of the spatial composition of façade openings. These three façade variations will be referred to as “Irregular”, “Regular” and “Stripes”, respectively. All three façade variations have an equal aperture ratio of 25% (open to total window area), and differ either in the geometry of the aperture or in the spatial distribution of the openings on the façade. Regarding the geometry of the aperture, the “Stripes” variation, with horizontal openings, differs from “Irregular” and “Regular”, which have rectangular openings. The “Stripes” variation is based on the existing horizontal blinds of the space that was used as a reference, simplified to ensure a two-dimensional pattern and an identical perforation ratio to the other stimuli, as discussed in Chapter 3. The variation “Irregular” has an irregular distribution of openings, differing from the regular spatial distribution of the openings in the variations “Regular” and “Stripes”. An overview of the shared and unique attributes between the façade variations is presented in Table 5.1.

Table 5.1 – Overview of the shared (✓) and unique (×) attributes between the façade variations.

Façade variation	Irregular	Regular	Stripes
Aperture ratio	✓	✓	✓
Geometry of aperture	✓	✓	×
Spatial distribution of openings	×	✓	✓

The three façade geometries were applied to the digital model of the DEMONA daylighting test module, introduced in Section 4.1, where the experiment took place. Three variations of the test room were generated using the *Rhinoceros* modelling software, each with a different shading system applied to the south façade. The room has mainly achromatic surfaces, windows on the south façade, and is equipped with a table and two chairs. Each test room variation was exported to *Radiance* format through the *DIVA-for-Rhino* toolbar. A Konica Minolta CM-600d spectrophotometer was used to measure the color and specularity of the surfaces in the real room, which were translated to *Radiance* material properties used in the simulation (shown in Table 5.2). The material of the existing Venetian blinds in the experimental room was used for all three façade variations. Following the workflow that was described in Section 4.1, a total of six scenes were rendered in *Radiance*, one for each combination of façade and sky type variation. The *Radiance* sky descriptions were generated with the *gendaylit* function. The specific settings for *gendaylit* (calculated for 9:30 for the clear sky and 12:30 for the overcast sky) can be found in the Appendix A.1.1. The *Radiance* rendering parameters are summarized in Table 5.3.

The exposure of the HDR renderings from *Radiance* was adjusted by applying a uniform exposure multiplier with the function *pfilt*, and the resulting images were then converted to low dynamic range BMP files using *ra_bmp* with a gamma correction factor of 2.2. The renderings that were obtained from *Radiance* consisted of two cubemap projections for each scene, generated from the viewpoint of each eye of a person looking

Table 5.2 – *Radiance* material properties for the main surfaces.

Surface	Type	R	G	B	Reflectance	Specularity	TVis
Ceiling	plastic	0.93	0.92	0.86	92%	0	
Floor	plastic	0.46	0.47	0.48	47%	0	
Walls	plastic	0.92	0.92	0.89	92%	0.01	
Table	plastic	0.75	0.75	0.73	75%	0.01	
Façade	plastic	0.90	0.89	0.86	89%	0	
Window*	glass	0.96	0.96	0.96			88%

*A non-coated double paned glazing was used for the window.

Table 5.3 – *Radiance* rendering parameters.

-vs	-vl	-ab	-s	-st	-lv	-ad	-as	-aa	-ar	-ps	-pj
0	0	5	1	0	0.00001	20000	10000	0.05	512	0	0

Resolution: 3600x3600 pixels (scaled down to 1200x1200 pixels using *pfilt*)
Rendering time: 16 hours for the two sets of six view directions.

towards the main view direction of the scene (Figure 5.2(a)). These projections were used to generate a scene for VR through cubemap projection mapping (Figure 5.2(b)), following the workflow for creating immersive VR scenes from physically-based renderings that was described in Section 4.1.1.4. The resulting scene is experienced in VR as a fully immersive 360° environment seen from a static viewpoint, as illustrated in Figure 5.2(c).

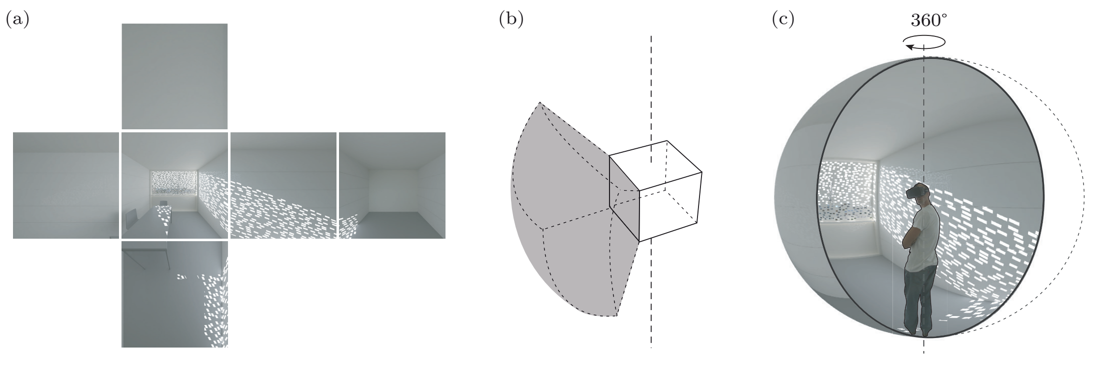


Figure 5.2 – Example of the cubemap renderings for the right eye projection (a), and illustration of the world-to-cubemap projection (b) and the user's freedom of movement in the immersive scene (c).

The average RGB values of the cubemap projection, as well as the vertical illuminance at the center of each VR lens from the viewpoint of a participant, were measured for each façade variation to provide a measure of similarity between the scenes. The RGB values were transformed to the L*a*b color space to calculate the color difference ΔE*ab. The maximum ΔE*ab between scenes was found to be equal to 0.83, well below the threshold of 2.3 for color differences that are noticeable by the human eye [Mahy et al., 1994]. Similarly, the three scenes differ between them in vertical illuminance with a maximum factor of 1.14, below the threshold of 1.5 which represents the smallest significant difference for a just noticeable change in illuminance [European Committee for Standardization (CEN), 2011].

5.1.1.3 Dependent variables

While immersed in each VR scene, participants were asked to respond to a verbal questionnaire which included the attributes relating to the perceptual impressions of the space from the experimental study in Section 4.1. Specifically, participants were asked to evaluate how pleasant, interesting, and exciting they found the space, as well as how satisfied they were with the amount of view in the space. The attributes *pleasant* and *exciting* correspond to the first quadrant of the two-dimensional space of Russel's circumplex model of affect [Russell, 1980] that was discussed in Chapter 2, while the attribute *interesting* stems from existing literature in lighting research that relates luminous conditions with interest [Loe et al., 1994; Veitch, 2001; Parpairi et al., 2002; Rockcastle, 2017]. Moreover, participants were asked how complex they found the space with the aim to examine the effect of the spatial distribution of the façade and daylight patterns on the perceived complexity of the scene. In addition, in order to investigate the influence of spatial context on the perception of the daylit scene, a subset of participants who were exposed only to clear sky conditions were asked to rate their satisfaction with the light composition in the space in two scenarios of space function: a discussion with friends (social context) and their everyday working activity (work context) across all façade variations. An overview of the studied variables can be found in Table 5.4. A 5-point scale with verbal anchors at the end points ("Not at all" to "Very much") was used for all questions. Both the order of the questions and the polarity of the scale was randomized.

Table 5.4 – Overview of experimental variables.

Independent Variables	
IV.1	Façade geometry: Irregular, Regular, or Stripes
IV.2	Sky type: Clear or overcast sky
Dependent Variables	
DV.1	How pleasant is this space?*
DV.2	How interesting is this space?*
DV.3	How complex is this space?*
DV.4	How exciting is this space?*
DV.5	How satisfied are you with the amount of view in this space?*
DV.6	Imagine you had to do your daily office work under this lighting condition. How satisfied would you be with the light composition in the room, provided that there was no direct light on your task?*
DV.7	Imagine you had a conversation with friends under this lighting condition. How satisfied would you be with the light composition in the room, provided that there was no direct light where you were sitting?*

*A scale from 1 to 5, 1 corresponding to 'Not at all' and 5 to 'Very much', was used for the marked questions.

5.1.1.4 Participants and experimental procedure

As mentioned previously, this study was conducted in a second experimental phase that followed the experiment described in Section 4.1 in the previous chapter. A total of 30 participants (16 women, 14 men) took part in this study, of which 29 participated first in the Experimental Study I. Regarding age, three participants were aged between 21 and 25 years old, fifteen were aged between 26-30, ten were aged between 31-35, and two were aged over 35 years old. Participants were unpaid volunteers. The documents regarding general information about the study as well as the participant consent were common with the experiment described in Section 4.1 and were presented in the beginning of the experimental session. Participants were randomly assigned to two groups corresponding to which sky type (clear or overcast) they would be shown in VR. Following a small break after the first experimental phase of Section 4.1, each participant was guided to wear the Oculus Rift DK2 VR headset and was then exposed in random order to all three façade variations under the same sky type, clear or overcast. Due to time constraints, from the total sample size of 30 participants, 21 saw the scenes with clear sky and 9 saw the scenes with overcast sky. For each variation, participants were asked to evaluate the presented scene through the verbal questionnaire in Table 5.4, and their answers were recorded by the researcher on a tablet.

5.1.1.5 Data analysis

A Kolmogorov-Smirnov test revealed the non-normality of our data for all studied attributes, and led to the conduction of non-parametric statistical tests. As our limited sample size does not allow mixed-design analyses, we analyzed the main effects of façade geometry and of sky type on the studied perceptual attributes (DV.1-5 in Table 5.4) separately with a Friedman's test for related samples and a Wilcoxon Rank Sum test for independent samples, respectively. Lastly, we conducted a Wilcoxon Matched-Pairs Signed-Ranks test between the two context scenarios (DV.6 and DV.7 in Table 5.4) for each of the three studied façade variations to investigate the effect of context on the satisfaction with the light composition in the scene. For these 13 planned analyses, we employ a Bonferroni-corrected significance level α', dividing the commonly used significance level of 0.05 with the total number of analyses, $0.05/13 = 0.0038$. In the case of significant effects of façade geometry on the studied perceptual attributes, post-hoc Wilcoxon Matched-Pairs Signed-Ranks tests were conducted for all pairwise comparisons. Effect sizes r [Rosenthal, 1994] are reported for statistically significant effects and they should be interpreted using the thresholds for a recommended minimum, moderate, and strong effect size of 0.20, 0.50 and 0.80, respectively [Ferguson, 2009]. All conducted statistical tests were two tailed, performed at a 0.05 significance level using the the Statistics and Machine Learning Toolbox in *MATLAB 2017b*.

5.1.2 Subjective responses to façade, sky type, and spatial context

5.1.2.1 Influence of façade geometry on subjective responses

A one-way Friedman's ANOVA test on the three groups of responses under exposure to each façade variation revealed a statistically significant effect of façade geometry on the evaluations of how pleasant ($\chi^2(2, N = 30) = 14.76$, $p = 0.0006$), interesting ($\chi^2(2, N = 30) = 13.76$, $p = 0.001$), complex ($\chi^2(2, N = 30) = 19.55$, $p = 0.00001$), and exciting ($\chi^2(2, N = 30) = 21.15$, $p = 0.00001$) the space was perceived. As expected, no statistically significant effect was found for the participants' satisfaction with the amount of view in the space ($p = 0.17$). These results demonstrate that the combined effect of façade and daylight pattern significantly influence the participants' appraisal of the space, as well as their perception of complexity in the scene.

Post-hoc pairwise comparisons for all façade geometry variations were conducted with a Wilcoxon Matched-Pairs Signed-Ranks test for the four studied variables that showed a significant effect of façade geometry, using the corresponding paired responses ($N = 30$). For these analyses, we use a Bonferroni-corrected significance level of $0.05/25 = 0.002$, dividing the significance level of 0.05 with the total number of planned and post-hoc comparisons. Results show significant differences between the Irregular and Regular variations, affecting how pleasant ($z = 3.62, p = 0.0006, r = 0.66$) and exciting ($z = 4.03, p = 0.00006, r = 0.74$) the space is perceived, with a moderate-to-strong effect for both cases. The equivalent results for the evaluations of how interesting and complex the space is perceived failed to meet our significance threshold α'' ($p = 0.008$ and $p = 0.004$, respectively). In the same vein, significant differences were found between the Irregular and Stripes variations regarding how interesting ($z = 3.34, p = 0.0008, r = 0.61$), complex ($z = 3.86, p = 0.0001, r = 0.71$), and exciting ($z = 3.55, p = 0.0004, r = 0.65$) the space was perceived, but not how pleasant ($p = 0.02$). No significant differences were found between the Regular and Stripes variations (all $ps > 0.03$).

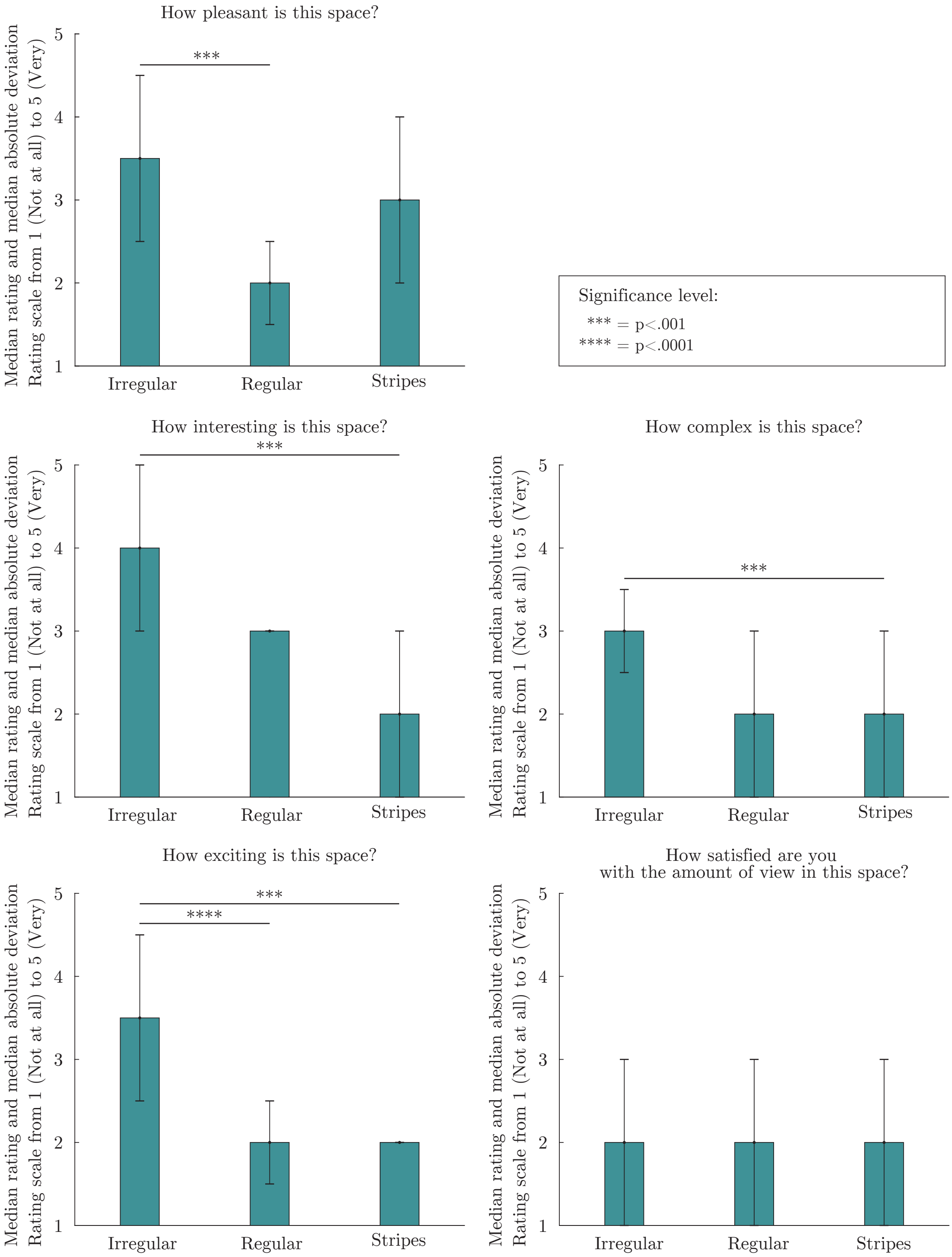


Figure 5.3 – Median ratings and median absolute deviations for evaluations of the studied attributes across façade geometry variations, with marked significant differences in the pairwise comparisons.

Table 5.5 – Descriptive statistics for the Irregular, Regular, and Stripes façade variations across the studied perceptual attributes.

	N	$\mu_{irreg.}$	$\sigma_{irreg.}$	$\mu_{reg.}$	$\sigma_{reg.}$	$\mu_{Stripes}$	$\sigma_{Stripes}$
pleasant	30	3.37	0.85	2.40	1.00	2.87	1.01
interesting	30	3.50	0.90	2.87	0.90	2.67	1.03
complex	30	3.17	0.83	2.60	0.86	2.20	0.85
exciting	30	3.47	1.01	2.43	0.94	2.47	0.97
satisfied with amount of view	30	2.17	0.83	1.97	0.85	1.93	0.98

Table 5.5 shows the relevant descriptive statistics (mean μ and standard deviation σ), while Figure 5.3 illustrates the median ratings and median absolute deviations for each perceptual attribute across the three façade variations. In combination with the post-hoc pairwise comparisons, these results illustrate that, when exposed to the Irregular façade geometry, participants rated the presented scene as significantly more interesting, complex, and exciting compared to the Stripes variation, and significantly more pleasant and exciting than the Regular variation.

5.1.2.2 Influence of sky type on subjective responses

In order to investigate the effect of sky type, participant responses for all façade variations were grouped based on the sky type in the virtual environment. The assessments of 21 participants that were immersed in clear sky conditions and 9 that were immersed in overcast sky conditions resulted in two groups of 63 and 27 responses in scenes with clear and overcast sky, respectively. A Wilcoxon Rank-Sum test between the two groups was used to investigate the effect of sky on participant responses. Results showed no significant differences between the two sky types for any of the studied perceptual attributes (all $ps > 0.01$) using the Bonferroni-corrected significance level α'. Table 5.6 presents the mean and standard deviations of responses in the two sky type conditions.

Table 5.6 – Descriptive statistics for the studied perceptual attributes in the clear and overcast sky conditions.

	μ_{clear}	σ_{clear}	$\mu_{overcast}$	$\sigma_{overcast}$
pleasant	2.89	0.97	2.87	0.99
interesting	2.33	1.04	3.06	1.01
complex	1.05	2.22	2.59	0.94
exciting	2.81	0.88	2.98	1.04
satisfied with amount of view	2.89	1.12	1.94	0.80

5.1.2.3 Influence of space function on occupant satisfaction with the lighting

The effect of context scenario on the reported satisfaction with the light composition in the space was investigated by comparing the paired responses from each participant for the two context scenarios of working or socializing in the scene with each façade variation. A total of 18 participants responded to these questions, and were exposed solely to scenes under clear sky. A Wilcoxon Matched-Pairs Signed-Ranks test showed that the reported satisfaction with the light composition differed significantly between the two context scenarios in the case of the Irregular variation ($z = 3.35, p = 0.0008, r = 0.79$), but not in the other two façade variations (all $ps > 0.30$). The effect size r indicates a strong effect of context scenario on the evaluation of the Irregular façade variation.

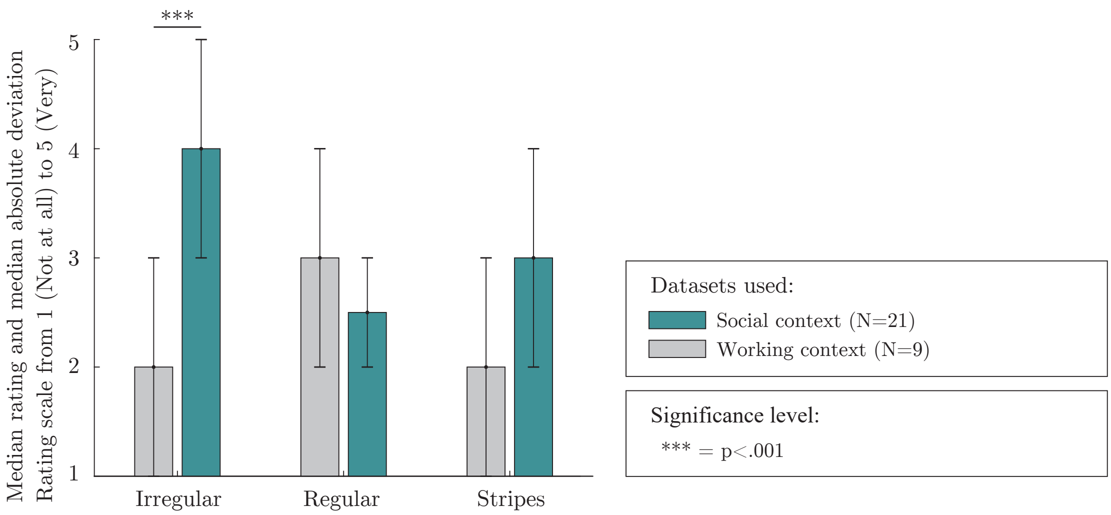


Figure 5.4 – Median ratings and median absolute deviations for evaluations of how pleasant, interesting, and exciting the space was perceived under exposure to each façade geometry variation. In the case of a significant effect of context, the datasets of the two context scenarios are treated separately.

Table 5.7 – Descriptive statistics for the satisfaction with the light composition in the space across context scenarios for the Irregular, Regular, and Stripes façade variations.

	N	$\mu_{irreg.}$	$\sigma_{irreg.}$	$\mu_{regular}$	$\sigma_{regular}$	$\mu_{stripes}$	$\sigma_{stripes}$
satisfaction with light (work)	18	2.39	1.14	2.61	1.24	2.67	1.14
satisfaction with light (social)	18	3.78	1.06	2.78	1.22	2.94	1.00

Table 5.7 provides the mean and standard deviations, and Figure 5.4 illustrates the median rating and median absolute deviation for each combination of façade geometry and context scenario. The participant responses show that the Irregular façade produced particularly contrasting results for the two context scenarios, and specifically, under the Irregular façade condition, participants were more satisfied with the light composition in the room when considering a discussion with friends, compared to conducting their daily office work in the same space.

5.1.3 Discussion

Although the current study is based on a limited number of participants, it presents findings with important implications both for the direction of this thesis and for the fields of lighting and architecture. Specifically, the analysis of participant impressions of an interior space with different façade geometry variations, shown in VR, demonstrated that the façade and the resulting daylight pattern can significantly affect how occupants perceive a space. This finding is in line with recent studies that investigated the effect of façade variations on the perception of working spaces [Omidfar et al., 2015; Abboushi and Elzeyadi, 2018b,a; Abboushi et al., 2019], but the features of the studied façade variations in the present experiment allow us to examine the effects of different façade geometry features on participant impressions. Specifically, the three studied façade variations had the same perforation ratio, and indeed, they did not differ regarding the participants' satisfaction with the amount of view in the scene. The same scene was perceived as more interesting, complex, and exciting in the Irregular façade variation, compared to the Stripes, demonstrating the perceptual effect of the *geometry* of the façade openings. Moreover, the scene with the Irregular façade variation was perceived as more pleasant and exciting compared to the Regular one. As these two variations differ solely in how the rectangular openings are arranged on the façade, this result demonstrates, for the first time, that the *spatial distribution* of façade and daylight patterns in a space can significantly affect how occupants perceive a space.

When immersed in the scene with the irregularly distributed façade openings, participants rated their satisfaction with the light composition in the room significantly higher for a social context scenario (discussion with friends) compared to a working context (conducting their daily office work). Although participants did not perform an actual task, but rather imagined different scenarios, this result illustrates the importance of placing participants in a specific context, and demonstrates that the same lighting condition can be considered satisfactory for one use of the space and unsatisfactory for another. Moreover, as these participants were only exposed to scenes with clear sky, this finding can be linked to the occupants' expectations, and particularly to an expected shift of attention away from the hypothetical task [Boyce, 2003] due to the presence of a distracting sunlight pattern.

Regarding the effect of sky type, no significant differences were found between the participant evaluations of the scenes with clear and overcast sky for any of the studied variables, a finding which could indicate that the effect of the façade dominates over that of the sky type. However, this result could be due to the unbalanced experimental design and limited sample size for this particular factor.

This preliminary study provides important insights for the direction of this thesis, demonstrating that the façade geometry can influence the participants' impressions of a daylit space, and showing that the expected use of space can influence these impressions. Nevertheless, this study was limited both in its sample size and in the equipment that was used, which had a lower resolution, field-of-view, and frame rate than the most recently available VR headset. In order to test the reproducibility of these findings and further investigate this topic, we conducted a second experimental study using the same façade variations and an improved VR headset. The method and findings of this experimental study will be presented in the following section.

5.2 Subjective and physiological responses to façade geometry*

The literature suggests two important challenges in current experimental methods used in lighting research, which might be contributing to the current gap of knowledge on the perceptual effects of the spatial distribution of daylight: the changing lighting conditions in real environments, and the use of rating scales as the sole method of data collection.

This section presents an experimental study which aims to provide substantial evidence on how the façade and the resulting sunlight pattern can jointly affect the individuals' experience of a space, taking into consideration different scenarios of use of space, while employing experimental tools that address the aforementioned limitations of experiments in lighting research. To this end, we investigate the joint impact of the façade and sunlight pattern geometry on occupants through an experimental study that combines the use of VR and the collection of both subjective (self-reported evaluations) and objective (physiological) participant responses.

In particular, we investigate the following hypotheses:

1. The participants' perception of the space is influenced by the joint impact of the façade geometry and corresponding sunlight pattern in the virtual scene.
2. The participants' physiological responses are influenced by the joint impact of façade and sunlight pattern in the virtual scene.
3. A façade with a non-uniform –i.e. irregular– distribution of openings, along with the resulting sunlight pattern, will trigger interest in the virtual scene.
4. The participants' perception of the space is influenced by the type of activity they expect to conduct in the presented virtual scene.

A total of 72 participants were exposed to immersive VR scenes of a daylit interior space with three façade variations of an equal aperture ratio. These façades stem from the preliminary study that was described in the previous section, and consist of a variation with non-uniformly distributed rectangular openings ("Irregular"), a variation with uniformly distributed rectangular openings ("Regular"), and horizontal stripes ("Stripes"). An additional neutral interior scene without access to daylight or view out was used in the beginning of the experiment to record baseline physiological responses in VR. Participants' subjective impressions —how pleasant, interesting, and exciting the

*The content of this section is partly based on a published journal article [Chamilothori et al., 2019a]: K. Chamilothori, G. Chinazzo, J. Rodrigues, E. S. Dan-Glauser, J. Wienold, and M. Andersen, "Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality," *Building and Environment*, vol. 150, pp. 144–155, 2019. The text is reproduced here as a courtesy of the publisher and with the agreement of the co-authors.

space was perceived— and physiological responses —heart rate and skin conductance— were collected during their exposure to each façade variation. Moreover, two different context scenarios of the virtual environment —a working and a social context— were compared to one another to examine the perception of a luminous environment under different scenarios of use.

In this experiment, prior to their immersion in the scenes with the façade variations, participants were immersed in a 180° photograph-based interior scene with colored daylight for a different investigation. The findings resulting from the exposure to this stimulus can be found in [Chinazzo et al., 2017]. Although this prior exposure to an additional stimulus is not expected to influence the outcomes of the present study —as the stimuli were very similar in nature, depicting interior spaces and inanimate objects which are identified as neutral stimuli [Dan-Glauser and Scherer, 2011]—, it is worth noting, as it is not possible to test for a presentation order effect between these two experimental phases. This section will continue by addressing solely the investigation of human responses to façade and daylight patterns.

5.2.1 Experimental method

5.2.1.1 Experimental design

In this study, we used a within-subject experimental design that included the within-subject factor *façade geometry* with three levels (Irregular, Regular, Stripes), and the between-subject factor *context* scenario with two levels (social or working context). The façade geometry, which is the main focus of this study, was selected as a within-subject factor due to its advantage of eliminating the effect of variance between individual participants through the use of repeated measures, since each participant was exposed to all three façade variations. Before administering the verbal questionnaire, the between-subjects variable context was introduced by specifying the use of the presented scene –social or working activities– to the participant. Counterbalancing was used to avoid the introduction of confounding variables. In particular, experimental sessions were designed to counterbalance the order of stimulus presentation, the participants' gender, and the time of day of the experimental sessions (morning or afternoon) to account for possible effects of fatigue.

5.2.1.2 Independent variables

This study aims to investigate the combined effect of façade geometry and of the resulting sunlight pattern on participant responses. The studied façade variations stem from the preliminary study described in the previous section, and are chosen to allow the investigation of both the geometry of the opening and the spatial distribution of the openings on the façade. The combination of the three façade geometry variations and direct sun penetration produce the visual stimuli used in the present study, illustrated in Figure 5.5. As in the current study we only employ scenes with direct sun penetration, the patterns resulting from light entering the room will be referred to as "sunlight patterns". Further information about the selection of these façade geometry variations, as well as the description of the workflow for the creation of the immersive scenes can be found in Section 5.1.1.2.

Although it is not treated as an independent variable, an additional interior scene was used in the beginning of the experiment to establish the participants' baseline physiological responses in virtual reality. As it is necessary to employ a neutral condition to record baseline measurements, this scene was generated from a high dynamic range (HDR) photograph of the experimental room from a participants' viewpoint. The HDR photograph was captured with automatic exposure bracketing with a Canon 70D camera and a 180° Sigma 4.5 mm lens [Inanici, 2006; Reinhard et al., 2010], tone-mapped with the Reinhard02 tone-mapping algorithm [Reinhard et al., 2002] and gamma-corrected with a factor of 2.2. The resulting neutral scene, shown in Figure 5.5, has artificial light and no view access to match the actual visual conditions in the test room during the experimental session. While the lighting conditions and color temperature in the artificially lit photograph-based scene differ greatly from that of the simulated daylit scenes, this limitation does not affect the outcomes of this study, since all analyses are comparing solely the three simulated scenes.

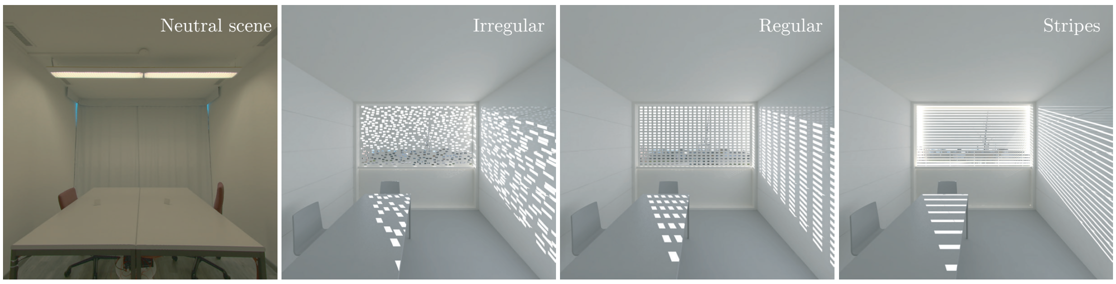


Figure 5.5 – Front view of the neutral scene used for the recording of baseline physiological measures ("Neutral scene") and of the interior scene with the façade variations ("Irregular", "Regular", "Stripes") that were used as independent variables in the study.

5.2.1.3 Dependent variables

Subjective responses
While exposed to each immersive scene, participants were asked to respond to a verbal questionnaire, and evaluated their impressions of how pleasant, interesting, and exciting the space was perceived on a scale from 1 ("Not at all") to 10 ("Very"). These questions, corresponding to the DV.1, DV.2, and DV.4 from Table 5.4, were selected based on the results of the preliminary experimental study described in the previous section, which showed significant perceptual effects of façade and sunlight pattern on these particular attributes. However, the scale range was extended to a 10-point scale, following participants' comments about the limited range of the 5-point scale that was used in preliminary study. The questions were asked in randomized order.

Physiological responses
Heart rate (HR) and skin conductance (SC) were measured throughout each experimental session while the participant was immersed in VR. The mean HR response to each visual stimulus was calculated for the first 28 seconds after stimulus exposure, which was the largest common exposure time across stimuli presentation. This duration encompasses initial orienting responses that have classically been observed when participants were exposed to moving scenes [Lang, 1990; Lang et al., 1993], as well as recovery from orientation and secondary emotional reaction to presented virtual environments [Winton et al., 1984; Ravaja et al., 2006], including when seen in a VR setting [Bekele et al., 2013]. Using the *Ledalab* V.3.4.9 toolbox in *MATLAB*, the raw SC data were separated into phasic and tonic components using the continuous decomposition analysis model [Benedek and Kaernbach, 2010] with default settings and four sets of initial values in the optimization. The skin conductance response (SCR), a measure which has been related to attention and arousal [Dawson et al., 2007], was extracted for a response window from 1 to 4 seconds after each stimulus presentation, using a minimum amplitude threshold of 0.01 μS. Both the response window and the minimum amplitude threshold follow established methodological recommendations [Dawson et al., 2007; Society for Psychophysiological Research Ad Hoc Committee on Electrodermal Measures, 2012]. Table 5.8 provides an overview of the studied experimental variables.

Experimental changes in HR and SCR indices were obtained by subtracting their respective baseline values, to allow for comparison between participants. The baseline was measured during the presentation of the neutral scene in VR, using the response window that corresponded to each physiological indicator. The baseline subtracted indices will henceforth be indicated with "Δ" —ΔHR and ΔSCR for the mean HR and mean SCR, respectively— and will be referred to as "change" to differentiate them from the measured values during the stimulus presentation.

Table 5.8 – Overview of experimental variables.

Independent Variables	
IV1	Façade geometry: Irregular, Regular, Stripes
IV2	Spatial context scenario: Working or socializing
Dependent Variables	
DV.1	How pleasant is this space?*
DV.2	How interesting is this space?*
DV.3	How exciting is this space?*
DV.4	Mean heart rate (HR)**
DV.5	Mean skin conductance response (SCR)**

*A scale from 1 to 10, 1 corresponding to 'Not at all' and 10 to 'Very much', was used for the marked questions.

**Measured for the first 28 seconds of exposure to each stimulus.

5.2.1.4 Equipment

The VR headset used in the study was an Oculus Rift CV1. The maximum luminance of the device measured at the lens was 80 cd/m^2, due to current technical limitations. The field of view of the device is 110°, while the display resolution is 1080×1200 pixels per eye with a 90 Hz refresh rate.

An Empatica E4 wristband [Garbarino et al., 2014; McCarthy et al., 2016], worn on the left hand of the participant, was used to record HR and SC responses. For both SC and HR, physiological responses recorded with the Empatica E4 bracelet showed no significant differences when participants were exposed in physical environments and their 360° representation in virtual reality [Higuera-Trujillo et al., 2017]. The wristband uses a photoplethysmography sensor on the dorsal (outer) wrist that measures blood volume pulse data with a sampling rate of 64 Hz to compute HR. The Empatica E4 been found to adequately measure HR data when tested against traditionally used electrocardiogram-based HR responses [McCarthy et al., 2016], with higher accuracy when the participant's movement is limited [Pietilä et al., 2018], as is the case in the present study. SC was measured through 2 ventral (inner) wrist electrodes of an 8 mm diameter contact area with a sampling rate of 4 Hz. The device uses dry electrodes to measure SC, a method which has been found to be a valid and user-friendly alternative to traditionally used palmar electrodes [Poh et al., 2010] but leads to lower absolute measured values.

5.2.1.5 Participants

A total of 72 participants (36 women and 36 men) took part in the study, and were selected based on eligibility criteria of full color vision, a generally healthy condition, and English language proficiency equal or higher to C1 level. The participant age was limited to a range of 18 to 32 years (μ = 25.9 years, σ = 3 years). This restricted age range was employed to ensure a homogeneous sample and to limit age related differences which have been found in the subjective perception of lighting conditions [Kuijsters et al., 2012; Schweitzer et al., 2016], as well as in cardiac and electrodermal reactivity to affective stimuli [Labouvie-Vief et al., 2003; Smith et al., 2005; Neiss et al., 2009].

5.2.1.6 Experimental protocol

The study was conducted in individual experimental sessions of 30 minutes, over a period of seven non-consecutive days in the summer. Air temperature was measured in each session (mean air temperature = 26.5°C, σ = 3°C). At the beginning of each session, participants were asked to read information about the study and sign a consent form. After consenting to participate in the study, participants wore the Empatica E4 wristband and responded to a series of demographic questions. They were then instructed to wear the VR headset and were guided in adjusting the headset's fit using a training scene. Participants were seated and were asked to limit their hand movements. Following this step, they were shown the experimental room from their viewpoint — a neutral interior scene, with artificial light and no view access— which was used to record baseline measurements. This scene was solely used to measure the participants' physiological responses to a neutral stimulus when wearing the VR headset in a resting state, and was not evaluated by the participants.

The three façade geometry variations were subsequently shown one at a time in randomized order, and exposure to each scene was self-paced in order to minimize participant fatigue. For each condition of façade geometry, participants were instructed to take their time and explore the scene, and to inform the researcher when they were ready to verbally evaluate their perceptual impressions of the presented scene. The resulting mean exposure time to one scene was 68 seconds, while the largest common exposure time to one scene across all three façade variations was 28 seconds. The context scenario of the virtual environment for each experimental session was specified before starting the verbal questionnaire in each scene, by indicating to the participant to "Imagine you have a discussion with friends in this space" or "Imagine this is your office" for the social or working context, respectively.

This research was approved by the EPFL Human Research Ethics Committee and complied with the tenets of the Declaration of Helsinki. All participants provided written informed consent prior to the study and were compensated for their participation.

5.2.1.7 Data analysis

After visual inspection of the raw SC data, 6 problematic cases of non-responders [Dawson et al., 2007] and 5 cases of sudden or intermittent signal breaks were identified and removed. The raw HR data was inspected for cases of values lower than 40 bpm or higher than 200 bpm, or a difference higher than 3 bpm between two consecutive measurements. Even though no such cases were identified, the sessions that were identified as problematic from the inspection of the SC data were also removed from the HR dataset, as a precaution for possible connectivity issues with the wristband. The removal of those cases, together with 3 other sessions where technical problems occurred, result in a dataset of 58 participants for the physiological responses, out of the initial sample of 72. In addition, one of the sessions with technical problems had to be removed also from the dataset of the subjective responses, resulting in a total of 71 participants with valid self-reported data and a sample size of 35 and 36 participants for the social and working context scenario, respectively. Altogether, the resulting sample sizes are 71 participants (36 men, 35 women) for the subjective responses and 58 participants (30 men, 28 women) for the physiological responses.

A one-sample Kolmogorov-Smirnov test revealed that the data for all of the studied variables were not normally distributed, therefore non-parametric statistical tests were used. Main effects for the between-subjects factor of context were investigated with a Wilcoxon Rank-Sum test, while the main effects for the within-subject factor of façade geometry were investigated with a Friedman's one-way ANOVA for dependent samples. In the case of a significant result in the Friedman's ANOVA, post-hoc tests were conducted for all pairwise comparisons using a Wilcoxon Matched-Pairs Signed-Ranks test [Siegel, 1956]. A Bonferroni-corrected significance level α' of .0025 is used for the within-subject factor analyses of subjective responses to account for the 20 comparisons across all studied factors. In the case of statistically significant effects in the pairwise comparisons, effect sizes r [Rosenthal, 1994] are reported, to be interpreted using the recommended thresholds for a minimum (0.20), moderate (0.50), and strong (0.80) effect size [Ferguson, 2009]. Lastly, the between subjective and physiological responses is investigated by calculating the Spearman's correlation coefficient between the variables [Spearman, 1987]. Statistical analyses were performed in *MATLAB R2017a* using the Statistics and Machine Learning Toolbox.

5.2.2 Subjective and physiological responses to façade and sunlight patterns

In the following section, we present the results of the statistical analyses for the main effects on participants' subjective and physiological responses, as well as the correlation between subjective and physiological variables. Possible effects of confounding factors on the findings, such as presentation order, gender, and time of day, are analyzed and presented in the Appendix A.3.

5.2.2.1 Subjective responses to façade and sunlight patterns

A Wilcoxon Rank-Sum test comparing the two context scenarios and considering all three façade variations together revealed a statistically significant effect of context on perceived interest ($z = -3.12, p = 0.002, r = 0.37$), and perceived excitement ($z = 3.39, p = 0.0007, r = .40$), but not on perceived pleasantness ($p = 0.13$). In particular, the space was perceived as less interesting and less exciting in the social context than in the work context (interest: $median_{social} = 4$, $median_{work} = 5$, excitement: $median_{social} = 3$, $median_{work} = 5$), which might reflect the discord between the participants' expectations regarding a space where they would socialize and the presented virtual environment. This finding demonstrates the influence of the use of space on how occupants evaluate a luminous environment, and is conducive to our fourth hypothesis for the evaluations of how interesting and exciting the space is perceived. Following the result of a significant effect of spatial context on participant evaluations of interest and excitement, we investigate the impact of façade and sunlight geometry variation for each context scenario separately for these attributes.

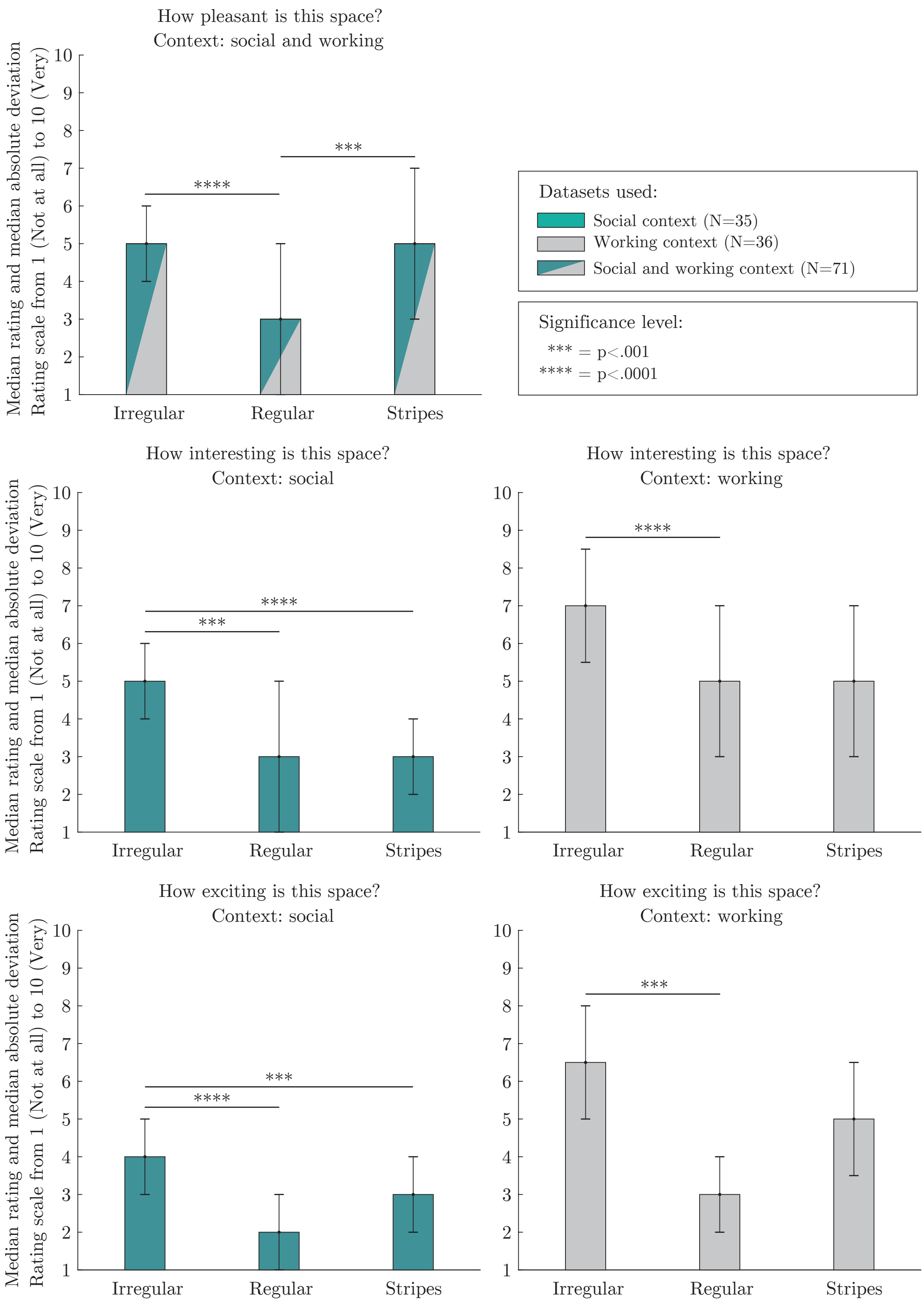


Figure 5.6 – Median ratings and median absolute deviations for evaluations of how pleasant, interesting, and exciting the space was perceived under exposure to each façade geometry variation. In the case of a significant effect of context, the datasets of the two context scenarios are treated separately.

A one-way Friedman's ANOVA for the three façade types showed a statistically significant effect of façade and sunlight pattern geometry on perceived interest and excitement for both the social (interest: $\chi^2(2, N = 35) = 29.34$, $p < 0.00001$, excitement: $\chi^2(2, N = 35) = 21.68$, $p = 0.00002$) and the working context (interest: $\chi^2(2, N = 36) = 22.18$, $p = 0.00002$, excitement: $\chi^2(2, N = 36) = 20.29$, $p = 0.00004$). Perceived pleasantness, where the dataset contained data from both the social and the work context, was also significantly affected by the façade variation ($\chi^2(2, N = 71) = 22.53$, $p = 0.00001$). These results support our first hypothesis, demonstrating that the façade geometry and the associated sunlight pattern jointly influence the participants' evaluations for all three studied attributes of how pleasant, interesting, and exciting the space was perceived. In order to investigate further the differences in the evaluations of the three façade geometry variations, pairwise comparisons were conducted with a Wilcoxon Matched-Pairs Signed-Ranks test for all façade variations, for both the social and the work context, in the case of interest and excitement, and for the two context scenarios treated together, in the case of pleasantness.

The results of the Wilcoxon Matched-Pairs Signed-Ranks test show that the Irregular variation was evaluated as significantly more interesting and exciting than the Regular in both context scenarios (interest: $z_{social} = 3.58, p_{social} = 0.0003, r_{social} = 0.43$, $z_{work} = 4.10, p_{work} = 0.00004, r_{work} = 0.48$, excitement: $z_{social} = 3.89, p_{social} = 0.0001, r_{social} = 0.46$, $z_{work} = 3.93, p_{work} < 0.00001, r_{work} = 0.46$), as well as more pleasant ($z = 4.86, p < 0.00001, r = 0.41$). These findings are in line with the results of the preliminary study in the previous section, where the space was evaluated as significantly more pleasant and exciting in the Irregular façade variation compared to the Regular one. The consistent difference between the Irregular and Regular condition across subjective attributes and context scenarios, shown in Figure 5.6, clearly demonstrates that the spatial distribution of the façade openings and the resulting spatial distribution of the associated sunlight pattern is a defining element in how the space is perceived. The Irregular variation was also evaluated as significantly more interesting and exciting than the Stripes, solely in the case of social context (interest: $z_{social} = 4.73, p_{social} < 0.00001, r_{social} = 0.57$, excitement: $z_{social} = 3.29, p_{social} = 0.001, r_{social} = 0.39$), which supports the argument that this façade variation might be more appropriate than shading systems with horizontal elements for non-working environments. This finding is also in agreement with the outcomes of the preliminary study in the previous section, where the Irregular variation led to the space being evaluated as significantly more interesting and exciting than the Stripes variation. Lastly, in the present study, the Stripes variation was evaluated as more pleasant than the Regular ($z = 4.01, p = 0.00006, r = 0.48$), as shown in Figure 5.6. Although this trend can be seen in the results of the preliminary study as well, no significant differences were found in terms of the pleasantness of these two conditions, a finding which could be explained by the limited sample size of this previous experiment.

5.2.2.2 Physiological responses to façade and sunlight patterns

The analysis of the effect of context on the physiological responses in each presented façade variation with a Wilcoxon Rank-Sum test showed no significant differences between ΔHR responses in the two context scenarios (all $ps > .08$). The context scenario significantly affected the ΔSCR in the Stripes ($z = 2.30, p = 0.02, r = 0.30$) and Regular variations ($z = 4.01, p = 0.006, r = 0.36$). Following these results, ensuing analyses for ΔHR were performed using the data from both contexts, while for ΔSCR, separate analyses were conducted for each context scenario. A one-way Friedman's ANOVA for the three façade variations showed a statistically significant effect of pattern geometry on ΔHR ($\chi^2(2, N = 58) = 7.28$, $p = 0.02$), and no effect on ΔSCR for either context scenario (all $ps > 0.24$). This result confirms our second hypothesis that the joint impact of façade and sunlight pattern can affect the physiological responses of participants, but only in the case of heart rate responses.

Post-hoc analyses on the ΔHR with a Wilcoxon Matched-Pairs Signed-Ranks test showed significant differences between the Irregular and the Stripes variations ($z = 2.49, p = 0.012, r = 0.23$), shown in Figure 5.7, but not for the other pairwise comparisons (all $ps > 0.13$). Following the argument that cardiac deceleration indicates allocation of attentional resources to a perceived stimulus [Lacey and Lacey, 1958], this finding suggests that the participants' attention was higher towards the irregular façade geometry compared to the one with horizontal stripes, and is conducive to our third hypothesis that the non-uniform distribution of openings will result to impressions of interest.

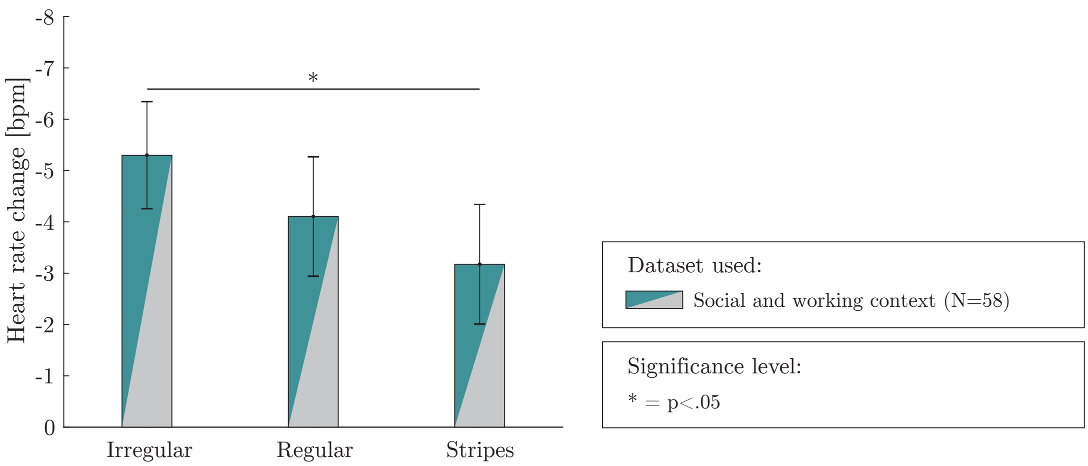


Figure 5.7 – ΔHR (calculated as the difference from the baseline) and standard error of the ΔHR for a 28 s response window after onset of exposure to each façade variation, measured in bpm (beats per minute).

5.2.2.3 Correlation between subjective and physiological responses

It is of interest to investigate the correlation between the participants' subjective and physiological responses. In the following analyses, only a subset of the subjective responses is used, corresponding to the sample size of 58 participants that were used in the analysis of the physiological responses. Due the finding of a significant effect of context on perceived interest and perceived pleasantness, analyses are performed separately both for each context scenario and for each subjective attribute. To account for the multiple comparisons, we use a more conservative threshold for statistical significance with a Bonferroni correction and dividing the conventional significance level α of 0.05 by the number of analyses, $\alpha'' = 0.05/5 = 0.01$.

The calculation of the Spearman's correlation coefficient showed a statistically significant negative correlation between ΔHR and reported interest in the case of social context ($\rho = -0.45, p = 0.00002$), which can interpreted as a small-to-moderate correlation [Ferguson, 2009]. No statistically significant correlation was found between ΔHR and excitement in the social context, between ΔHR and any of the perceptual impressions for the working context, or between ΔHR and pleasantness (all $ps < .04$). The conduction of the same analysis for ΔSCR showed no statistically significant correlation with subjective evaluations (all $ps < .31$).

5.2.3 Discussion

This study employs a novel experimental method that combines physically-based renderings from *Radiance*, shown in virtual reality, with the use of a wearable biometric sensor to investigate the joint impact of façade geometry and associated sunlight pattern on occupants. The findings demonstrate the potential of this method for empirical research on human perception, and highlight its usefulness as a promising experimental tool that can provide control of the visual stimuli and data collection of objective physiological indicators. Furthermore, this work extends our knowledge on the effects of daylight on occupants by showing both the impact of façade and sunlight patterns on subjective impressions and heart rate, and the importance of the use of space on occupant perception of luminous conditions. The presented results demonstrate in a virtual reality setting that architectural façade elements and the spatial distribution of sunlight can be used to impart specific sensations in the built environment. The following sections discuss the limitations of the current research, the findings regarding the joint effect of façade and sunlight pattern (referred to as "façade variation" for brevity) and the context scenario on the dependent variables of the study, as well as directions of future work.

5.2.3.1 Limitations

This experimental study has demonstrated the joint impact of façade and sunlight pattern geometry on participant perception and HR through experiments in VR. These findings have important implications for architectural and lighting design, as they show that short exposure to joint façade and sunlight conditions could trigger specific subjective and physiological responses, and could thus be orchestrated in transition spaces, such as entrance or circulation zones, to achieve specific effects on occupants. Nevertheless, it is important to note the limitations of the conducted experiment.

Due to the use of a VR headset, participants were exposed to each façade variation for a short period —-with a mean exposure time of 68 seconds— which restricts the generalizability of the results. The outcomes of the study could be applied to settings where occupants spend an equivalent amount of time, such as transitional spaces, however further research is needed to investigate their applicability for longer exposure times. In the same vein, the participants' age was limited to avoid age-related effects. Even though the use of a narrow age range ensures a more homogeneous population, it simultaneously requires the repetition of this investigation for other age groups. Regarding the influence of spatial context on the perception of luminous conditions, the use of context scenarios, where the participant is asked to imagine the use of the space, are inferior to actual variations of the furniture in the room, or to the involvement of the participant in different activities. Furthermore, no instructions were given to the participants to remain silent during recording of physiological measures, which might have influenced the recorded responses. Another limitation was the prior exposure of the participants to an additional immersive scene, which, although it is not expected to influence the outcomes of this study, does not allow the testing of any potential effects on the participant responses. Lastly, the use of a VR headset, while it allows identical repetition of the visual stimulus, has the disadvantage of a limited luminance range which cannot induce discomfort. Although in this study we successfully examine the impact of the spatial distribution of light patterns on perception, we are restricted in investigating the threshold between interest and discomfort, which would be possible with luminance ranges close to those of a real environment. Similarly, the representation of daylit scenes through a head mounted display in the present study, even though has been demonstrated to be perceptually similar to real daylit spaces in Chapter 4, cannot replicate exposure to daylight from a physiological standpoint.

One of the main findings of this study is that exposure to the façade variation with an irregular distribution of openings led to participants evaluating the space as more exciting and more interesting, as well as to cardiac deceleration, which has been suggested as a proxy for attention to a stimulus. These results are in alignment with the findings of the previous section, and could relate to existing work in the literature which associates the luminance variation in the occupant's field of view with impressions of interest. However, further studies are encouraged to investigate the replicability of the findings, especially regarding the physiological measures. A wider use of complementary physiological indicators, such as the mean heart rate change, which in this study was shown to be sensitive enough to differentiate between façade and sunlight pattern variations, could help establish these measures as important tools in lighting research studies on perception.

5.2.3.2 Effect of façade and space function on subjective responses

The influence of space use on perception was examined by employing two different context scenarios —socializing and working— of the presented virtual scene. Results showed that the context scenario had a significant effect on participants' evaluations of how interesting and exciting they perceived the space, supporting our fourth hypothesis that the participants' perception of the space will be influenced by the type of activity they expect to conduct in the presented scene. Furthermore, statistical analyses showed that the façade and sunlight pattern geometry significantly influenced the participants' ratings regarding how pleasant, interesting, and exciting the space is perceived for both context scenarios, which confirms our first hypothesis.

Following the aforementioned effects of façade variation on perception, we can use the median ratings to compare the direction of the evaluations, particularly in paired comparisons between the Irregular and Stripes, or the Irregular and Regular variations, which were often found to have statistically significantly differences. From Figure 5.6, we can observe that the Irregular variation was perceived as the most pleasant, interesting, and exciting within each context scenario, with the exception of the evaluations of pleasantness for the working context, where Stripes was the variation rated as most pleasant. The median ratings of excitement and interest for the Stripes in the two context scenarios, shown in Figure 5.6, reveal that this façade variation was rated more negatively in the context of a social space. While these findings are positive for common applications of horizontal blinds —where the prevalent visual attribute is the repetition of horizontal elements [Penacchio and Wilkins, 2015]— in office spaces, they simultaneously bring into question the appropriateness of using such systems in non-working environments where impressions of interest and excitement are desirable.

At the same time, Figure 5.6 shows that the Regular variation was rated as the least pleasant, interesting, and exciting. These observations, along with the significant differences between the evaluations of the Irregular and the Regular variations across all studied perceptual attributes, reveal that the spatial distribution of the apertures —the only feature that differed between these two façade geometry variations— has a direct impact on occupant perception. Furthermore, these findings confirm our third hypothesis that the non-uniformity in the case of the Irregular façade variation and the resulting sunlight pattern is inducive to impressions of interest, enhancing how interesting and exciting the space was perceived compared to the other studied façade geometry variations.

These findings are in line with our results from the preliminary study in the previous section, but differ from the work of Abboushi and Elzeyadi [2018b] where the ratings of visual interest of horizontal stripes and fractal patterns applied to the glazing of a real office environment did not differ significantly between them. This outcome could be explained by the fact that in Abboushi and Elzeyadi [2018b] the shading system covered only a small part of the glazing, while in the present study it covered the whole window, and possibly had a greater effect on participant perception.

In another study by Abboushi and Elzeyadi [2018a], where participants were exposed to pattern variations that fully covered the window of an office space and were seated either perpendicular or parallel to the window, the reported impressions were shown to be influenced by the participants' view direction. In particular, the fractal pattern led to a significant increase of visual interest compared to the variation with the horizontal stripes for participants seated perpendicular to the window, while the opposite effect was found for participants seated parallel to the window. The findings from our own study, where the main view direction is perpendicular to the window, are in agreement with these results, with the high complexity façade variation leading to higher ratings of interest compared to the horizontal stripes.

Further studies by Abboushi et al. [2019], employing fractal patterns with varying degrees of complexity, as defined with the fractal dimension D, showed that the level of complexity is an important factor in occupant perception. Specifically, low complexity fractal patterns were found to be significantly less visually interesting than horizontal stripes, while medium-to-high complexity fractal patterns were found to be significantly more interesting than horizontal stripes. This finding emphasizes the importance of façade features for human perception and motivates further investigation on the perceptual effects of characteristics of façade and sunlight patterns.

5.2.3.3 Effect of façade and space function on physiological responses

Context scenario had a significant effect on mean SCR change, but not on mean HR change. Further analyses revealed a significant effect of façade variation on mean HR change, which supports —only for the case of heart rate response— our second hypothesis that the joint impact of façade and sunlight pattern can influence the participants' physiological responses. In particular, during exposure to the scene with the Irregular variation, participants had a larger decrease in mean HR compared to the Stripes variation, as shown in Figure 5.7, which may suggest a coherent orienting effect [Graham and Clifton, 1966; Laumann et al., 2003] towards this condition. This results suggests that the participants' attention was higher towards the Irregular variation compared to the Stripes, and supports our third hypothesis that the non-uniform distribution of openings will trigger impressions of interest in the scene.

The decrease in mean HR could also be due to a larger parasympathetic nervous system control over the cardiac output [Sztajzel, 2004], which suggests that some conditions lead to improved recovery from what could be a mildly stressful situation in the baseline condition [Ulrich-Lai and Herman, 2009], since participants were uncertain of what was going to happen in the beginning of the experiment. An increased parasympathetic control over the cardiac output can be due to a more relaxed state or to less influence of the sympathetic branch (which activates due to arousing situations, putting the person in a state of alert [Appelhans and Luecken, 2006]), which could also signify that the Irregular condition with the larger decrease in HR was more relaxing compared to the other conditions.

The finding of a statistically significant negative correlation between evaluations of interest and ΔHR in the case of a social context scenario supports the argument that the focus of the participant's attention —which is also reflected in impressions of interest— is accompanied by cardiac deceleration [Lacey and Lacey, 1958]. However, this correlation was found only for the social context, which could be explained by the presence of a similar trend —in opposite direction— of a significant difference between the Irregular and the Stripes variations for both the perceived interest in that context and the mean heart rate response, which is not found in the case of the working context.

The absence of correlation between ΔHR and the evaluations of how exciting the space is perceived indicates that it is not necessarily the same people that show a change in their HR response and evaluate the visual stimulus as exciting. This finding shows that the two measures are quite independent and the conjunction of these two cannot be discussed. A possible interpretation is that the question of "how exciting is the space" (labeled "excitement" for ease) does not necessarily represent the participants' feelings of excitement (i.e. if the participant feels excited). This phrasing of the question was chosen according to the principle of atmosphere perception, which does not represent an affective state, but rather the participant's experience of the environment and is considered a more stable variable [Vogels, 2008].

5.3 Expected perceptual effects of façade geometry according to architects*

The findings of the previous sections confirmed the relevance of the main objective of this thesis, demonstrating that the façade and daylight patterns in a scene can significantly affect human responses. It is thus of particular importance to extend this investigation to a wider range of façade variations. As the stimuli used in the experimental studies of Chapter 5 were chosen intuitively, the present section adopts a systematic approach to identify promising façade variations for further investigation. To this end, a large number of architects were surveyed regarding the expected perceptual effects of façade geometry stemming from contemporary architecture, due to their expertise and training on how design influences occupant perception.

In this section, we introduce a paper-based survey which aimed at examining the expected perceptual effects of façades with different geometry according to architects. To ensure the relevance of the studied façade designs, the façade variations that were used in this survey stem from existing works of contemporary architecture. Consistent with the aim of this section, the findings from this survey were used to identify façade variations that seem promising as stimuli for the extensive experimental study that will be presented in the following chapter.

To this end, this section starts by presenting the initial selection of 40 façade examples from existing contemporary buildings, and the approach that was followed to generate 20 façade variations with equal perforation ratio from this initial set of case studies. Next, we introduce the design and procedure of the paper-based survey that explores the architects' assessment of these 20 façade variations, and present the results of the survey. Lastly, we discuss the relevance of these findings and the limitations of the study.

5.3.1 Expert assessment of façade geometry variations

An initial set of 40 cases of façade designs in existing contemporary buildings was selected from an extensive review of architectural work. Following the methodology for the selection of case studies for contemporary façades by Murray [2009], the selected case studies represent recently constructed buildings that were completed since 2000,

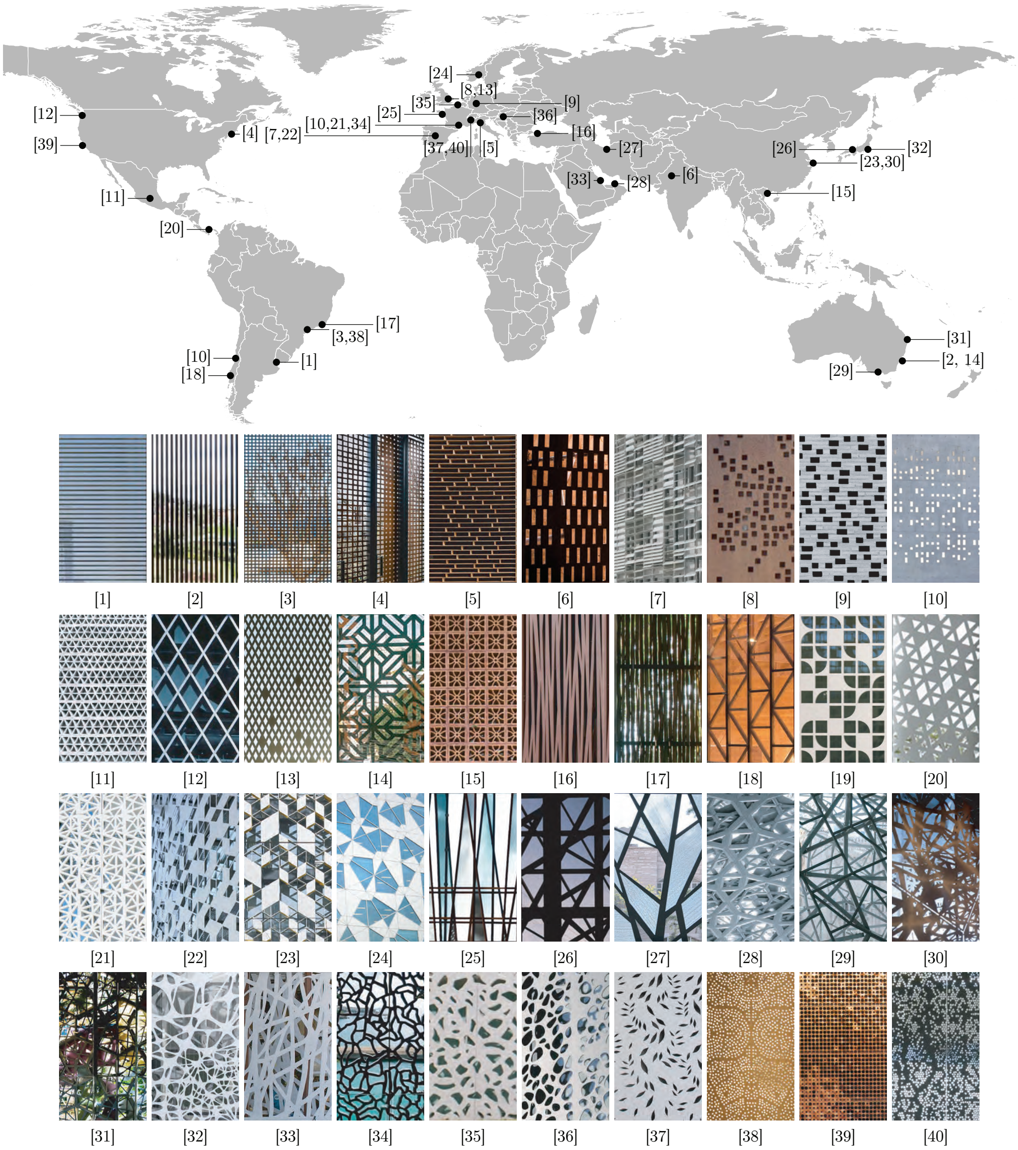
*The content of this section is partly based on a published conference abstract [Chamilothori et al., 2018b]: K. Chamilothori, J. Wienold, and M. Andersen, "Façade design and our experience of space: the joint impact of architecture and daylight on human perception and physiological responses," in *Proceedings of the Light Symposium 2018 Conference*, Stockholm, Sweden, 2018. The text is reproduced here with the agreement of the co-authors.

and span a range of locations, building types, scales, and materials. The focus on contemporary architecture was driven by its relevance for today's practitioners, but also by the global nature of current architectural design, where buildings with similar design features are found across the world [Sánchez Vidiella, 2007; Sklair, 2012]. This globalization of form in contemporary architecture is also present in the European context [Haddad, 2016], and will be investigated in terms of possible regional differences in the appraisal of contemporary façade design across Europe in Chapter 6.

The selected façade examples are geographically diverse, as shown in Figure 5.8 (top). In terms of building function, the selected examples consist of residences, museums, office buildings, educational and cultural institutions, and sports facilities, and range in scale from one to fifteen stories. The selection criteria for these case studies were the presence of geometric patterns on the façade through external shading systems, a curtain wall structure, or openings on the building skin, and this treatment of the façade being central for the design, as indicated from the description of the project. Figure 5.8 illustrates the selected case studies using representative photographs of the building envelope.

As only recently constructed buildings were considered, online sources were preferred over printed ones. Specifically, the architecture websites *ArchDaily* and *Architizer* were used to find internationally acclaimed projects that fulfilled these criteria and to select a total of 40 examples of façade geometry. Moreover, façade patterns that explicitly represented recognizable shapes (such as detailed flowers) were excluded to ensure a focus on the geometrical properties, rather than the representational capabilities of the design. On the contrary, particular effort was made to include schematic representations of natural patterns, which have been suggested to elicit positive responses to built environments [Orians and Heerwagen, 1992; Joye, 2007]. The description of the façade design was used to select such instances, such as "the main visual 'structure' of the façade is created by the trees that run (beyond) each side of the façade" (Figure 5.8, case study 31) and "the façade is [...] textured to represent light filtering through a tree" (Figure 5.8, case study 39).

As discussed in the beginning of this section, the ultimate aim of this process was the selection of façade variations that were expected to elicit strong perceptual responses, and were thus promising to be used as stimuli in the experimental studies described in Chapter 6. To this end, a subset of these 40 façade variations were shown in a survey that investigated the intuition of architects regarding the most and least effective façade designs for creating specific perceptual effects. This survey targeted architects, rather than non-architects, specifically because of their familiarity with design elements and their expertise in extrapolating the effects of architectural design on perception from a single visual representation. Moreover, the choice of architects as the target population for this survey provided important insights on the level of agreement between designers themselves on the perceptual effects of façade design.



[1] Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012 [2] Freshwater House, Chenchow Little, Sydney, Australia, 2008 [3] FT House, Reinach Mendonça Arquitetos Associados, Bragança Paulista, Brazil, 2014 [4] Aperture 538, Luca Andrisani Architect, New York, USA, 2016 [5] Casa Morchiuso, Studio di Architettura Marco Castelletti, Como, Italy, 2012 [6] Raas Jodhpur, The Lotus Praxis Initiative, Rajasthan, India, 2011 [7] Carabanchel 29, Sheppard Robson, Madrid, Spain, 2006 [8] Kew House, Piercy & Company, Richmond, United Kingdom, 2014 [9] Kolumba Museum, Peter Zumthor, Köln, Germany, 2008 [10] San Alberto Hurtado's Memorial, Undurraga Devés Arquitectos, Santiago, Chile, 2010 [11] La Tallera, Frida Escobedo, Cuernavaca, Mexico, 2010 [12] Seattle Central Library, OMA + LMN, Seattle, USA, 2004 [13] Wembley WC Pavilion, Gort Scott, Wembley, United Kindgdom, 2013 [14] Artwall Commercial Building, Dale Jones-Evans Architecture, Syndey Australia, 2003 [15] The Lantern, VTN Architects, Hà Nội, Vietnam, 2016 [16] Selcuk Ecza Headquarters, Tabanlıoğlu Architects, Istanbul, Turkey, 2013 [17] Paraty House, Studio MK27, Suzana Glogowski, Parati, Brazil, 2009 [18] 2Y House, Sebastián Irarrázaval, Colico, Chile, 2013 [19] Moucharabieh New-School, Y.Architectes and Gautier+Conquet, Nimes, France, 2012 [20] Panama Diamond Exchange, Mallol & Mallol Arquitectos, Panamá, Panama, 2014 [21] Nakâra Residential Hotel, Jacques Ferrier Architectures, Cap d'Agde, France, 2015 [22] Edificio Corporativo de Oficinas del Centro Tecnológico de Hispasat, Herreros Arquitectos, Madrid, Spain, 2010 [23] Lane 189, UNStudio, Shanghai, China, 2016 [24] Barcode B.10.1, Snøhetta, Oslo, Norway, 2014 [25] Steel Band, Atelier Arcau, Vannes, France, 2012 [26] Ryotei Kaikatei Annex “So-an”, Kengo Kuma and Associates, Fukui, Japan, 2008 [27] Danial Apartment, Reza Sayadian and Sara Kalantary, Tehran, Iran, 2012 [28] Louvre Abu Dhabi, Jean Nouvel, Abu Dhabi, United Arab Emirates, 2017 [29] Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002 [30] Polish Pavilion, WWAA Architects, Shanghai Expo, Shangai, China, 2010 [31] Wintergarden Façade, Studio 505, Brisbane, Australia, 2012 [32] Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007 [33] Artwall, Legoretta + Legoretta, Doha, Qatar, 2010 [34] MuCEM, Rudy Ricciotti, Marseille, France, 2013 [35] Lille Modern Art Museum, Manuelle Gautrand, Lille, France, 2010 [36] Podčetrtek Sports Hall, Enota, Podčetrtek, Slovenia, 2010 [37] Petit Mont-Riond, CCHE, Lausanne, Switzerland, 2015 [38] K House, Studio Arthur Casas, São Paulo, Brazil, 2012 [39] M.H. de Young Museum, Herzog & de Meuron, California, USA, 2005 [40] Minergie P-EFH Zimmermann, Vomsattel Wagner Architekten, Visp, Switzerland, 2010

Figure 5.8 – Illustration of the initial set of 40 case studies of façade design in contemporary architecture.

From the initial selection of 40 case studies, shown in Figure 5.8, a subset of 20 cases were selected to be used in the survey to minimize participant fatigue. These 20 cases were chosen based on the insights of architects in the Laboratory of Integrated Performance in Design at EPFL with the aim to depict representative typologies of the initial 40 façade design variations. Moreover, the resulting subset of façade variations aimed to create a matrix of designs with increasing complexity as well as a gradual shift from non-curvilinear to curvilinear openings, a feature which has been found as crucial in visual perception [Levin et al., 2001] and has been shown to relate to impressions of naturalness [Berman et al., 2014].

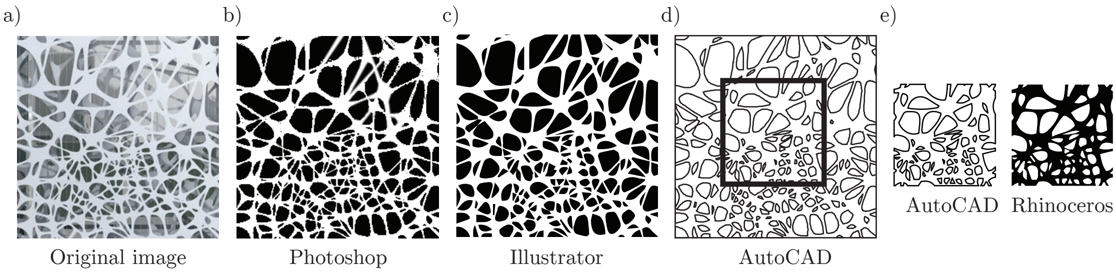
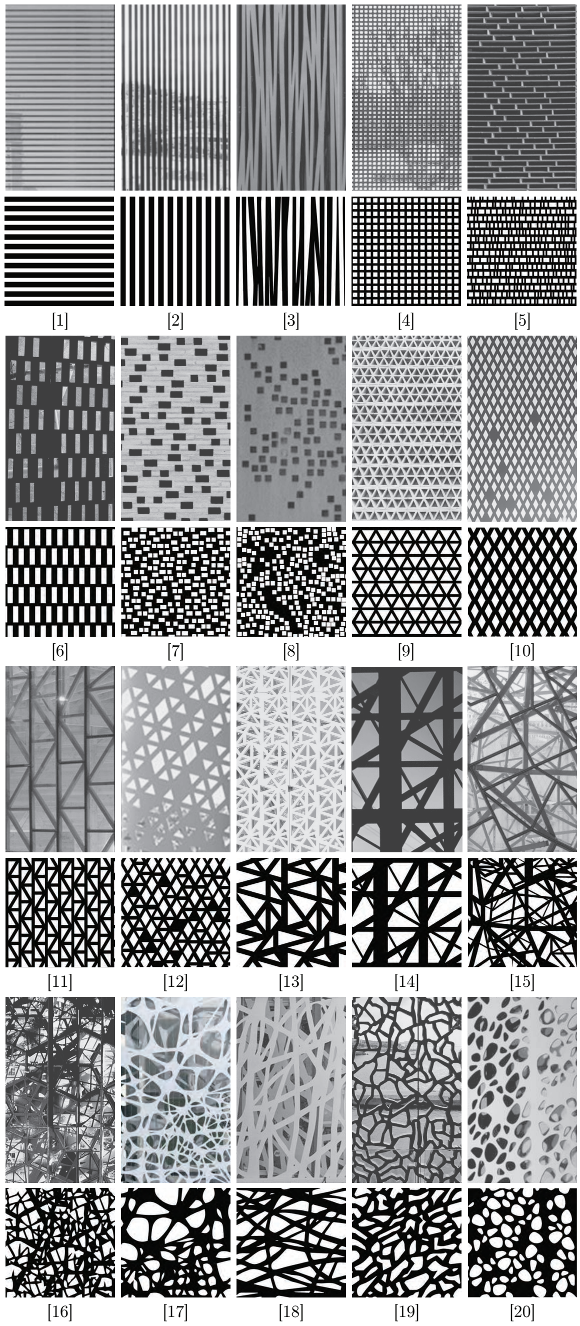


Figure 5.9 – Workflow to create two-dimensional patterns from the selected case studies and adjust their perforation ratio to 40%.

Each of these 20 case studies was used to create a two-dimensional square pattern, adjusted to a 40% perforation ratio (open to total surface area), which has been shown as one of the most preferred in experiments investigating aesthetic preference for different perforation ratios [Friedenberg and Liby, 2016]. To this end, a representative image of the façade, either from photographs or drawings, was used to derive the main pattern of the façade openings as shown in Figure 5.9 (a). With this procedure, the three-dimensional façade structure of each case study was translated to a two-dimensional representation, allowing a uniform treatment of all façade variations. The original image of each façade was edited with the *Black & White* filter in *Photoshop*, resulting in a binary image of black and white pixels, shown in Figure 5.9 (b). The resulting image was used to trace the façade openings, either manually in *AutoCAD* or with the *Image Trace* function of *Illustrator*, illustrated in Figure 5.9 (c). As the automatic form tracing in *Illustrator* cannot produce straight lines, this step was done manually for all façade variations that had straight edges, which is a particularly time consuming process. The resulting line work was examined in *AutoCAD* using the function *Area* to identify square parts of the façade that were closer to a 40% perforation ratio, as shown in Figure 5.9 (d). This section of the façade pattern was then edited by removing or replicating elements as necessary, to achieve a 40% perforation ratio while retaining the façade design as much as possible (Figure 5.9 (e)). The consistency of the perforation ratio is a crucial element in this workflow, as it ensures a common characteristic among the studied façade variations. Lastly, the final pattern was exported as a surface object to the modeling software *Rhinoceros*. The 20 case studies and the corresponding adjusted patterns are shown in Figure 5.10.



[1] Faena Aleph Residences, Foster + Partners, Buenos Aires, Argentina, 2012 [2] Freshwater House, Chenchow Little, Sydney, Australia, 2008 [3] Selcuk Ecza Headquarters, Tabanlıoglu Architects, Istanbul, Turkey, 2013 [4] FT House, Reinach Mendonça Arquitetos Associados, Bragança Paulista, Brazil, 2014 [5] Casa Morchiuso, Studio di Architettura Marco Castelletti, Como, Italy, 2012 [6] Raas Jodhpur, The Lotus Praxis Initiative, Rajasthan, India, 2011 [7] Kolumba Museum, Peter Zumthor, Köln, Germany, 2008 [8] Kew House, Piercy & Company, Richmond, United Kingdom, 2014 [9] La Tallera, Frida Escobedo, Cuernavaca, Mexico, 2010 [10] Wembley WC Pavilion, Gort Scott, Wembley, United Kindgdom, 2013 [11] 2Y House, Sebastián Irarrázaval, Colico, Chile, 2013 [12] Panama Diamond Exchange, Mallol & Mallol Arquitectos, Panamá, Panama, 2014 [13] Nakâra Residential Hotel, Jacques Ferrier Architectures, Cap d'Agde, France, 2015 [14] Ryotei Kaikatei Annex "So-an", Kengo Kuma and Associates, Fukui, Japan, 2008 [15] Federation Square, Lab Architecture Studio, Melbourne, Australia, 2002 [16] Wintergarden Façade, Studio 505, Brisbane, Australia, 2012 [17] Airspace Tokyo, Thom Faulders Architecture + Studio M, Tokyo, Japan, 2007 [18] Artwall, Legoretta + Legoretta, Doha, Qatar, 2010 [19] MuCEM, Rudy Ricciotti, Marseille, France, 2013 [20] Podčetrtek Sports Hall, Enota, Podčetrtek, Slovenia, 2010.

Figure 5.10 – Overview of the 20 selected façade variations, showing the existing façade design and the corresponding simplified patterns used in the survey, adjusted to a 40% perforation ratio.

In *Rhinoceros*, each façade variation was applied on a 2x2 meter window of a sample south-facing space with a width of 6 meters, a length of 5 meters, and a height of 3 meters. This sample space, with no furniture and neutral materials, was preferred over an existing space to ensure that the main point of interest in the scene would be the façade geometry and the resulting daylight pattern. Using the *DIVA-for-Rhino* toolbar, a uniform grey material with 50% reflectance was applied to the ceiling, walls, and façade (the material properties can be found in Appendix A.4). A standard CIE clear sky with sun angle chosen to allow sun patches both on the floor and the walls of the space was generated using the function *gensky* for the latitude and longitude of the Geneva area with the settings "gensky 09 21 09 +s -a 46 -o -6 -m -15".

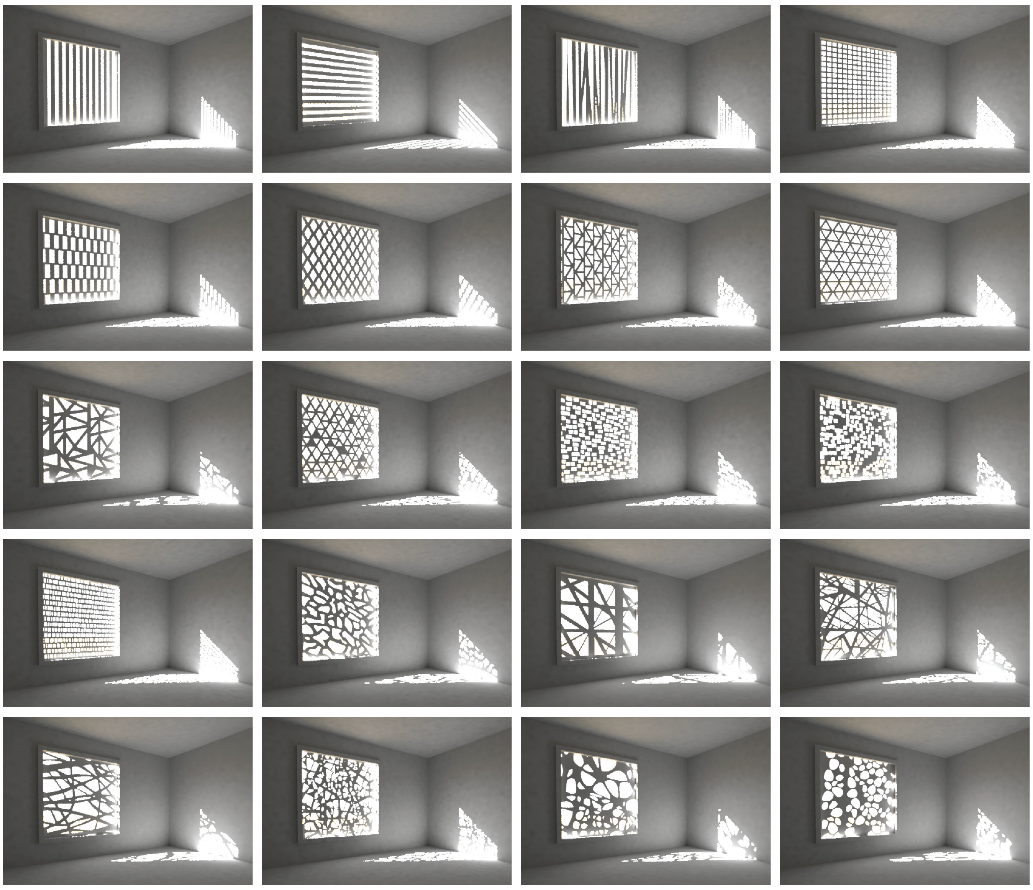


Figure 5.11 – The façade patterns used in the paper-based survey on architects' intuition, based on façades of existing buildings. The patterns have the same perforation ratio of 40% and were shown in a random order.

As neither the orientation, time of day, nor latitude of the sample space were revealed in the survey, the geographic coordinates of the Geneva area were selected solely as a means to create the desired sun patches and are not expected to influence the architects' responses compared to the use of another latitude. Lastly, by keeping the room geometry and materials, view point, and sky type constant, and varying the façade configuration, 20 visualizations were generated in *DIVA-for-Rhino* using the default high image quality parameters, shown in Table A.2, and a 966x648 resolution. The resulting visualizations were automatically tone-mapped with the Ward94 tone-mapping operator and transformed to PNG files in *DIVA-for-Rhino*, and are illustrated in Figure 5.11.

5.3.1.1 Survey design

The resulting images were used in a paper-based survey targeting architects in research and practice in Switzerland with the dual aim to investigate the consensus of experts about the perceptual effects of the studied façade designs and to select the most promising variations for further investigation. In this survey, participants were shown 20 variations of a scene with different façade configurations, arranged in a random order. These variations were printed on a A3 paper, along with instructions about the survey (as shown in Appendix A.4). All survey copies were printed and distributed by the researcher to ensure consistency in the material of the survey.

Participants were asked to rate the three variations that would make the space the most exciting, the least exciting, the most calming, and the least calming. These perceptual attributes were chosen to represent the combinations of the two dimensions in Russel's circumplex model of affect [Russell, 1980] and its interpretation for lighting research by Boubekri et al. [1991], with the dimension of *exciting* representing a condition of high valence (pleasure) and high arousal, and the dimension of *calming* representing a condition of high valence and low arousal.

5.3.1.2 Participants and procedure

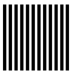
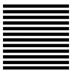
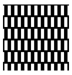
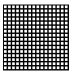
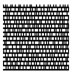
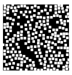
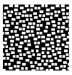
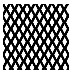
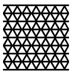
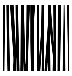
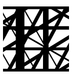
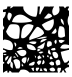
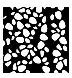
A total of 80 architects (39 women, 41 men) working in Lausanne and Fribourg provided responses in this survey. These two regions were selected because of their accessibility to the researcher, as participants were recruited in person. Specifically, eligible participants were contacted at the EPFL campus or in architecture offices. In each instance, participants were informed that their responses would contribute to a study that investigates the intuition of architects, and that participation was anonymous and voluntary. Eligible participants were required to have a background in architecture.

Participants were given a copy of the printed survey as well as verbal instructions about how to respond, and were asked to inform the researcher when they completed the survey. From the sample size of 80 architects, 35 were working in research and 45 were working in practice. Only three participants reported having expertise in lighting (one working in research and two in practice).

5.3.2 Façade geometry variations with high consensus among architects

Table 5.9 shows the frequency of selection of each façade variation in the categories "most exciting", "least exciting", "most calming", and "least calming".

Table 5.9 – Frequency of placement in each category per façade variation (%).

	Most exciting	Least exciting	Most calming	Least calming
	4	**40**	19	13
	3	**50**	28	6
	11	21	19	8
	5	**43**	20	10
	15	9	30	5
	**38**	1	5	21
	25	3	4	11
	6	23	21	5
	11	19	21	5
	6	10	1	11
	11	8	10	11
	19	6	**43**	1
	6	4	0	29
	8	8	5	19
	30	10	6	**49**
	26	4	5	**38**
	20	10	18	19
	28	11	11	21
	18	14	13	13
	10	9	23	6

These results are shown in percentage of participants (e.g. for the first row, 40% of the 80 participants chose this variation as one of the three least exciting). The variations that were chosen by more than one third of the participants are marked in bold, indicating substantial consensus for the perceptual effect of a particular façade design. As each participant selected three variations for each category, the sum of the values in each column of Table 5.9 equals to 300. The responses show a high agreement between the experts, with cases of specific patterns being chosen by 38-50% of the participants. This finding confirms that there is consensus in architects' evaluations of expected perceptual effects of different façade geometry variations, particularly in the negative range of the effect in the categories "least exciting" and "least calming" with 50% and 49% of participants agreeing, respectively. Another notable observation is that the variations that were selected as the most exciting were not necessary chosen also as the least calming, and vice versa. This finding implies that these two dimensions are not necessarily opposite, and motivates the use of individual unipolar scales to assess separately how calming and how exciting a space is.

This survey was administered to architects working both in research and in practice, allowing to investigate whether there is a difference between the responses of the two populations. In order to examine this effect, we separated the responses of architects in research and in practice, and formed four datasets for each group, corresponding to the façade variations that were selected as those that would make the space the most exciting, least exciting, most calming, and least calming. The names of the façade variations were replaced by numbers from 1 to 20. A one-sample Kolmogorov-Smirnov test revealed that our data is not normally distributed in any of these groups, leading us to apply non-parametric tests. The chosen façade variations of architects in practice were then compared against the equivalent choices of architects in research using a two-tailed Wilcoxon Rank Sum test, which showed no statistically significant differences between the choices of architects working in research and in practice for any of the four categories (all $ps > 0.6$).

Following this finding, we can calculate the difference between the number of times a façade variation was selected as the most and least representative in the dimensions of exciting and calming using the total sample. This approach results in a measure that can be placed on a unipolar scale and shows the consensus towards the direction of the effect for a specific façade variation. This measure is used in Figure 5.12 to illustrate the distribution of the 20 variations in the dimensions of *exciting* and *calming*. The stimuli that were shown to the participants are illustrated with the design of the corresponding façade variation. A façade variation that is located towards the ends of an axis shows that there is a high consensus regarding the direction of the perceptual effect for this variation. On the other hand, a façade variation that is located towards the center of the axes represents either conflicting responses regarding the direction of the effect, or a low frequency of selection of this particular façade variation in the survey. The data in Table 5.9 can be used to complement this figure and examine the participant responses for specific patterns.

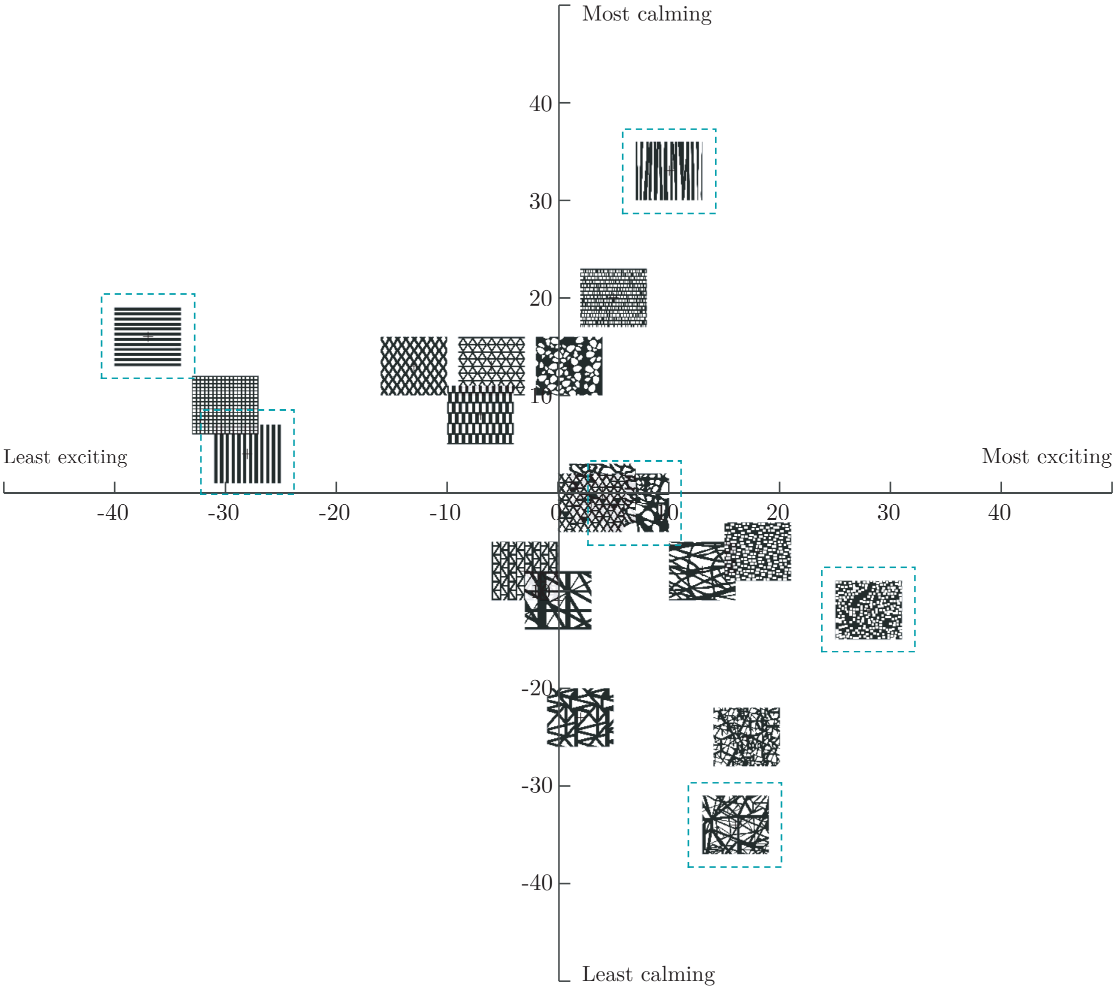


Figure 5.12 – Distribution of the 20 patterns in the dimensions of *calming* and *exciting* based on the survey results, corresponding to the difference between how often a pattern was selected as the most and least representative pattern in each dimension. The highlighted patterns were used in the experimental study that is described in the next chapter.

The distribution of patterns in Figure 5.12 shows a clustering of façade variations. We can intuitively assess that the façade variations in these clusters have common features. Specifically, patterns with low complexity —horizontal stripes, vertical stripes, and square grid— were most often selected in the "least exciting" category and can be found in the second quadrant, while patterns with increasing complexity were most often rated as "least calming" and "most exciting" and can be found in the fourth quadrant. This division is quite striking, as the second quadrant only contains variations with regularly distributed openings, and the fourth quadrant only contains variations with irregularly distributed openings, in alignment with our findings from Chapter 5 which demonstrated the importance of the spatial distribution of façade openings for perceptual impressions.

Moreover, the resulting measure of consensus in Figure 5.12 can be used to identify façade variations that produced strong responses regarding their potential to affect how calming and exciting a space is perceived, consistent with the aim of the study. Four variations that exhibit strong consensus about their potential to render a space the most calming, the least calming, the most exciting, and the least exciting, respectively, can be found in the first, second and fourth quadrant. These variations were selected to be used as stimuli in the experimental study that is introduced in the next chapter. In addition to these four cases, the vertical stripes variation was chosen to provide an additional example of a commonly used system, and one variation located in the center of the graph was selected to cover the design space of the two dimensions. In total, six façade variations, highlighted in Figure 5.12, were selected to be studied further in an extensive experimental study that is presented in Chapter 6.

5.3.3 Discussion

This section presented a paper-based survey that explored the evaluations of architects regarding the expected perceptual effects of façade geometry variations that stem from existing buildings. Specifically, participants were asked to select out of a set of 20 façade designs those would be the most and the least effective in rendering a space exciting, and those that would be the most and the least effective in rendering the same space calming. The survey revealed a high agreement between architects on the perceptual effects of façade geometry, with specific variations being selected by half of the participants. Drawing from the results of this survey, façade variations that seemed promising regarding their potential to affect the appraisal of a space were selected to be further investigated in an extensive experimental study in virtual reality that will be presented in the next chapter.

The agreement between architects is a promising indicator for the robustness of the expected façade-driven perceptual effects. However, it is worth noting that the architects' appraisal of space does not necessarily align with that of laypeople. Studies where experts and non-experts in design and architecture were interviewed regarding their perception of an auditorium under various lighting scenarios reported differences in the scene descriptions between the two groups, which might also reflect differences in their experience of space [Lindh, 2012]. In an experiment that is particularly relevant for the work of this thesis, Omidfar et al. [2015] examined the perceptual impressions of architects and non-architects who were exposed to time-lapse videos of a daylit office with different façade geometries. The assessments of the two groups differed in the case of horizontal stripes, with architects evaluating the lighting in the scene as somewhat appealing, orderly, and non-distracting, and non-architects evaluating the same stimulus as somewhat unappealing, chaotic and distracting. A similar result is found in Imamoglu [2000], where students of architecture rated exterior façades with varying architectural details, such as number and size of windows, as significantly less complex than students of other disciplines. Lastly, the field of neuroaesthetics provides interesting insights on this topic. A study by Kirk et al. [2009] investigated differences in brain activity of architects and non-architects by using functional magnetic resonance imaging (fMRI). Their findings showed that when making aesthetic evaluations of photographs of building exteriors, architects showed a significantly higher activation of brain areas associated with reward compared to non-architects, demonstrating that expertise in architecture modulated brain activity. In light of these possible differences between architects and non-architects, it is even more critical to provide evidence for the occupants' perception of space through empirical studies, which is a central methodological approach in this thesis.

Previous research that investigated how experts in architecture evaluate façade variations have employed stimuli with varying perforation ratio and several variations of façade geometry [Omidfar et al., 2015] or constant perforation ratio and limited variations of façade geometry [Abboushi et al., 2019]. The survey presented in this section extends this work, and is, to our knowledge, the first systematic attempt to examine the intuition of architects about how the façade in a space can influence occupant perception across a wide range of façade geometry variations with a constant perforation ratio. Nevertheless, this survey was conducted using two-dimensional grayscale visualizations of a simple room, and was thus lacking in immersion, realism, and level of detail of the presented scenes. Although architects are familiar with a high level of abstraction in representations of space [Lindh, 2012], these limitations restrict the applicability of the findings to real environments. Moreover, since participants were asked to choose the most representative variations from 20 possible options, their evaluations are relative to the presented items, which introduces a stimulus range bias [Poulton, 1977]. Although the wide range of possible options reduces this effect, the evaluations of the presented items are not absolute, and an additional façade design could have been rated as the most (or least) effective for the studied perceptual attributes. Lastly, in this survey, the function of the presented space was not specified, with the aim to allow the architects the liberty of considering examples from their own experience. In this regard, it would be of interest to repeat this survey for different scenarios of space use, and examine the effect of these scenarios on the architects' responses. In the same vein, future studies could replicate this survey with a target population of non-architects to investigate potential differences in the appraisal of façade design between architects and non-architects. While such differences are not critical for the present thesis —as the main purpose of this survey was to select stimuli that will be tested further in the next chapter—, they would contribute to our understanding of the effects of architectural education on perception, which has been suggested to alter the architects' judgment compared to that of laypeople [Salingaros, 2014a].

The findings of this survey bring important insights for the design practice, considering the façade system is rated as one of the most important aspects in the work of architects, engineers, and energy consultants [Pastore and Andersen, 2019c]. The evaluation of façade variations with irregularly distributed openings as the most effective in creating an exciting space are in line with the findings of Pastore and Andersen, who found that 51% of architects that took part in an on-line survey considered a pattern structure as a desirable or very desirable design option for a shading system [Pastore and Andersen, 2019c]. The same study compared the reported desirability of pattern structures as a design option for an office space between architects, academics, engineers, and energy consultants. The authors report a significant effect of profession on participant responses and emphasize the need for further research to address this point of conflict between building professionals. The next chapter contributes to this effort by presenting an extensive experimental study that investigates the participants' impressions across the façade variations stemming from the findings of the present section.

5.4 Chapter summary

This chapter employed the novel virtual reality-based method that was developed in Chapter 4 to investigate occupant responses to façade and daylight pattern variations through two experimental studies, acting as a proof-of-concept for the aim and the methodological approach in this thesis.

The first section of this chapter presented a preliminary experimental study where 30 participants were exposed to VR scenes of the same interior space under clear or overcast sky with three façade variations of an equal aperture ratio applied to the south wall: an irregular distribution of openings, a regular distribution of openings, and horizontal stripes. The results showed that the façade and daylight pattern significantly influenced how pleasant, interesting, exciting, and complex the space was perceived, demonstrating quantitatively for the first time that the façade geometry and the resulting light distribution can alter how a space appears to occupants. Moreover, the spatial context —whether the space would be used to have a discussion with friends or to conduct daily office work— was shown to have a significant impact on the evaluation of the light composition in the space in the case of irregularly distributed façade openings.

This preliminary study was followed by a larger experimental study, presented in Section 5.2. In this study, we investigated the joint impact of façade and sunlight pattern geometry on occupant perception and physiological responses by exposing 72 participants to the same stimuli as in the preliminary study, this time only showing scenes under a clear sky. Moreover, we examined the effect of the use of space on occupant perception by employing two different scenarios of spatial context —socializing and working— of the presented virtual scene. For each immersive scene, a verbal questionnaire —how pleasant, interesting, and exciting the space was perceived— was coupled with an Empatica E4 wristband, which recorded heart rate and skin conductance response to provide additional objective measures.

Findings showed, once again, a statistically significant effect of the façade geometry and the resulting sunlight pattern on participants' evaluations for all three subjective attributes. In particular, the irregular façade geometry variation was consistently evaluated across context scenarios as more pleasant, more interesting and more exciting than the regular façade variation, demonstrating the influence of the spatial distribution of façade openings. Moreover, the façade and sunlight pattern geometry significantly influenced the participant's mean heart rate, but not their skin conductance response. Specifically, under exposure to the irregular façade and sunlight pattern, participants' mean heart rate was lower compared to the horizontal stripes, which suggest that participants' attention was higher towards the irregular pattern. The two spatial context scenarios —working and socializing in the space— affected subjective evaluations of interest and excitement, but not of pleasantness: the irregular façade variation was perceived as significantly more interesting and exciting than the horizontal stripes for the social context, but not for the working context. This result highlights the relevance of considering the use of space in façade and lighting design, while challenging the use of prevalent shading system designs with repetitive horizontal elements —such as Venetian blinds— in non-working environments. In cases where impressions of interest and excitement are of importance, our findings suggest that a façade with openings that are not regularly distributed, along with the induced sunlight patterns, will be perceived more positively compared to horizontal blinds.

These findings demonstrate that architectural façade elements and their interaction with light have a quantifiable effect on people in a virtual reality setting. In particular, the significant influence of façade and sunlight pattern geometry on mean heart rate change has great implications for architecture, as it shows that a simple change of a shading system —from horizontal stripes to an irregular distribution of openings— can induce physiological changes to the occupant, such as cardiac deceleration. This potential of physiological benefits for the occupant calls for further research with a human-centric perspective, employing knowledge from fields such as psychophysics and neuroscience, traditionally remote from architecture and lighting [Andersen, 2015].

Following these highly positive results and the evidence of differences in the perception of varying levels of façade complexity in the literature, an important research direction that emerged is the investigation of the perceptual effects of a wider range of façade and daylight pattern characteristics. To this end, Section 5.3 introduced a paper-based survey which examined the expected perceptual effects of façade variations according to architects. In this survey, 80 architects working in research and practice selected façade variations that they considered to be the least and most effective in rendering a space exciting or calming, from a total of 20 variations of an equal perforation ratio that were based on case studies of contemporary architecture. Findings showed a high agreement between experts, with specific façade variations being chosen by 38 to 50% of the participants in the survey. Moreover, in agreement with the findings of Sections 5.1 and 5.2, the façade geometry variations that were selected as the most exciting consisted solely of designs with irregularly distributed openings, while variations that were selected as the least exciting consisted solely of designs with regularly distributed openings, confirming the importance of the spatial distribution of façade openings for perception. Having established the relevance of the central research question that drives the present thesis through the findings of the Sections 5.1 and 5.2, the outcomes of this survey were used to select six façade variations that were identified as promising stimuli for further investigation.

One of the central outcomes of this chapter is that horizontal stripes —a stimulus that is considered visually similar to horizontal blinds, one the most prevalent façade variations— led to negative evaluations regarding how interesting the space is perceived in a social context. This finding raises the question: which façade characteristics would be then more appropriate in a social context? How do the characteristics of the façade and daylight pattern geometry affect occupants in different scenarios of space function? Regarding generalizability, are the perceptual effects of façade and daylight patterns consistent across geographical latitudes? In order to address these questions, the next chapter builds on the findings of the present chapter and employs the façade designs stemming from the outcomes of Section 5.3 to investigate the subjective responses to variations of façade geometry, sky type, and spatial context through additional experimental studies conducted in Switzerland and Greece.

Chapter 6

Establishing a relationship between façade characteristics and human perception

The previous chapter demonstrated through experimental studies in virtual reality that the perceptual impressions of an architectural space are significantly affected by the façade composition and the resulting daylight pattern. In particular, we showed that both the geometry and the spatial distribution of the openings on a façade are important factors for these façade- and light-driven perceptual effects. These findings act as a proof-of-concept for the relevance of this thesis and call for further investigation that extends to a wider range of façade and daylight variations, in order to provide architects and lighting designers with a broad matrix of case studies that can be used as a reference.

While the experimental studies in the previous chapter employed façade variations that were chosen intuitively, this chapter will assess the perceptual effects of façade designs that stem from contemporary architecture and were identified as promising for further investigation according to the survey of architects in the previous chapter. Building on the outcomes of Chapter 5, this chapter examines the perceptual responses of participants to these promising façade variations across lighting conditions, context scenarios, and geographical latitudes, providing evidence for the core objectives of the present thesis. Specifically, the façade variations that exhibited the highest consensus among architects in Section 5.3 were used in an extensive virtual reality-based experimental study which was repeated in Switzerland and Greece, allowing the additional investigation of regional differences in the perception of the studied scenes.

This chapter begins by presenting this study, and describing the experimental method, the generation of the immersive scenes, and the findings. Specifically, this study will investigate the effect of façade composition, sky type, and spatial context, as well as the regional differences in the participant responses, and examine trends in the perceptual effects of façade geometry. The chapter ends by summarizing the key outcomes and outlining how they drive the applications presented in the next chapter.

6.1 Subjective responses to façade and daylight patterns across geographical latitudes

While the experimental studies presented in Chapter 5 clearly demonstrated that the façade and its interaction with light can influence how people perceived a space, they were restricted to three variations of façade geometry. In order to broaden our understanding on the perceptual effects of the façade and the resulting daylight composition in a scene, we extend this investigation to a wider range of façade configurations. The paper-based survey in Section 5.3 identified specific façade geometry variations that, according to architects, show great potential in eliciting occupant responses in the dimensions of how calming and exciting the space is perceived. In this section, these façade variations will be evaluated in an extensive experimental study with the aim to investigate the perceptual effects of façade and daylight pattern geometry, as well as the influence of additional factors on space perception. Building on the findings of Chapter 4, this study employs immersive simulated scenes shown in the Oculus CV1 VR headset, and assesses the participants' perception using research instruments that were tested in the previous experimental studies of this thesis.

The experimental study presented in this section was designed to investigate a number of different factors. The central investigation, consistent with the aim of the thesis, is the impact of the façade and daylight pattern on how participants perceive the space. In addition, we will also examine the effect of other factors that are important for this investigation, drawing from the literature and the outcomes of Chapter 5. In particular, we will explore the influence of sky type as well as the influence of space function on participants' perception of the presented scenes. Moreover, we will examine regional effects in the perception of daylit scenes by replicating the experiment in Switzerland and Greece and comparing the responses of participants across geographical latitudes. Lastly, we will test the robustness of the perceptual effects of façade geometry against variations of both the window size and the space type.

Specifically, we investigate the following hypotheses, extending from those examined in Section 5.2:

1. The participants' perception of the space is influenced by the joint impact of the façade geometry and corresponding daylight pattern in the virtual scene.
2. Façade variations with non-uniform —i.e. irregular— distribution of openings, along with the resulting daylight pattern, will trigger interest in the virtual scene.
3. The participants' perception of the space is influenced by the interaction between the sky type and the expected use of the space.
4. The participants' perception of the space is influenced by regional differences.
5. The perceptual effect of changes in the façade geometry and the resulting daylight pattern is robust to variations in the window size and space type.

This section will start by describing the experimental method that was followed in this study. Next, we will present the experimental results, and specifically the influence of the façade and daylight composition, the sky type, the spatial context, and the geographical latitude on participant responses. The section will conclude by discussing the shortcomings of this experimental study, as well as the findings, their relation to relevant results in the literature, and their significance for the fields of architecture and lighting.

6.1.1 Experimental method

The experimental study presented in this section draws from the outcomes of the previous chapters to select both the research instruments and the tested variables. In particular, this experiment will use interior daylit scenes shown in a VR headset as visual stimuli, and employ both verbal questionnaires and physiological measurements to record the participants responses, although the latter will not be reported in this thesis. The purpose of the study is to explore the effect of façade geometry variation on participants' perception of space, consistent with the aim of the thesis. Furthermore, this study aims to also investigate the impact of three additional factors on participant responses: the sky type and the spatial context, relating to the presented stimulus, and the country where the experiment took place, relating to the demographic characteristics of the participants. In addition, the robustness of the perceptual effects of façade geometry were tested in a second experimental phase which examined the impact of window size and space type on participant responses.

Experimental Phase A: Perceptual effects of façade geometry, sky, type, and spatial context

Perceptual impressions of the scene
Visual appearance of the scene

participant responses in virtual reality across combinations of **façade geometry***, **sky type**, and **spatial context** (mixed design)

- ▶ Effect of **façade geometry** on participant responses
- ▶ Effect of **sky type** on participant responses
- ▶ Effect of **spatial context** on participant responses

Experimental Phase B: Perceptual effects of window size and space type

Perceptual impressions of the scene
Visual appearance of the scene

participant responses in virtual reality across combinations of **window size***, **façade geometry**, **sky type**, **spatial context**, and **space type** (mixed design)

- ▶ Robustness of façade-driven perceptual effects to changes in the window size
- ▶ Robustness of façade-driven perceptual effects to changes in the space type

Experiments repeated in **Switzerland** and **Greece**

- ▶ Regional differences in participant responses

▶ Objective of the investigation
∗ Within-subject experimental factor

Figure 6.1 – Outline of the experimental phases in the present study.

Specifically, this study is divided in two experimental phases that were conducted in random order, and will be referred to as experimental phase A and B. Figure 6.1 summarizes these phases and their objectives.

The experimental phase A is designed to test the perceptual effects of façade geometry, spatial context, and sky type, as well as the interactions between spatial context and sky type, relevant to the first three studied hypotheses. The effect of spatial context is examined by comparing scenarios of using the space for working or socializing, implied through the type of furniture in the presented scenes. The effect of sky type on participant responses is investigated with the use of three different conditions: a clear sky with a high sun angle, a clear sky with a low sun angle, and an overcast sky. The two variations of clear sky are used to examine the acceptance of different levels of sunlight penetration, particularly in combination with the spatial context for the third studied hypothesis. To this end, we employ a condition with a high sun angle where there is no direct light on the furniture of the room, and another with a low sun angle which allows direct light deeper in the room, creating sun patches on the furniture. In addition, the clear and overcast sky conditions are used to investigate differences between the presence of direct and diffuse light in the scene, which affects the daylight patterns in the scene.

The experimental phase B examines the robustness of façade and daylight-driven perceptual effects in the context of our fifth hypothesis. Specifically, participants were exposed to a subset of the studied façade variations under the same sky type and spatial context, but with varying window size and space type, in order to test whether these factors have an influence on the perception of the façade and daylight composition.

Lastly, in order to identify possible regional differences in the participant responses, relevant to our fourth hypothesis, we take advantage of the mobility offered by the VR headset and replicate the experiment in Switzerland and Greece, and specifically in the cities of Lausanne, with a latitude of 46.53° and Chania, with a latitude of 35.51°. These latitudes represent the central and southernmost regions of Europe, respectively. This experiment was also repeated in Trondheim, Norway, corresponding to the northernmost region in Europe, in a study conducted in collaboration with the Light and Colour Group at the Norwegian University of Science and Technology (NTNU). As the comparison between these three latitudes exceeds the scope of the present thesis, this analysis can be found in Chamilothori et al. [2019b].

6.1.1.1 Experimental design

The experimental phase A followed a mixed 6x3x2x2 full factorial design. Specifically, the design consisted of the within-subject factor *façade geometry* (with six levels, corresponding to the façade variations stemming from the Section 5.3) and the between-subject factors *sky type* (clear sky with high sun angle, clear sky with low sun angle, and overcast sky), *spatial context* (with two levels, social and working context), and *country* (with two levels, Switzerland and Greece). An overview of the factors and their levels can be found in Table 6.1. The *façade geometry* was employed as a within-subject factor to remove the variance due to differences between subjects through the use of repeated measures. Each participant was shown all six façade variations in random order, in one out of the six possible combinations of the factors *spatial context* and *sky type*.

Table 6.1 – Overview: independent variables of the experimental phase A.

Factor	Level
IV.1	Façade geometry*: 6 variations
IV.2	Sky type: clear with high sun angle, clear with low sun angle, overcast
IV.3	Spatial context: socializing or working
IV.4	Country: Switzerland and Greece

* Within-subject factor.

The experimental phase B, designed in collaboration with the Light and Colour Group in NTNU, followed a mixed 3x2x3x2x2x2 full factorial design. This experimental design consists of the within-subject factor *window size* (with three levels, small, medium, and large window) and the between-subject factors *façade geometry* (with two levels, corresponding to a subset of façade variations used in experimental phase A, with expected opposite perceptual effects), *sky type* (with three levels, clear sky with high sun angle, clear sky with low sun angle, and overcast sky), *spatial context* (with two levels, social and working context), *space type* (with two levels, large space and small space), and *country* (with two levels, Switzerland and Greece). Table 6.2 presents an overview of these factors.

Table 6.2 – Overview: independent variables of the experimental phase B.

Factor	Level
IV.1	Window size*: small, medium, and large window
IV.2	Façade geometry: 2 variations (subset of those in experimental phase A)
IV.3	Sky type: clear with high sun angle, clear with low sun angle, overcast
IV.4	Spatial context: socializing or working
IV.5	Space type: large space and small space
IV.6	Country: Switzerland and Greece

* Within-subject factor.

In the context of this thesis, the outcomes of this second experimental phase will be limited to testing the robustness of façade- and daylight- driven perceptual effects across variations of the factors *window size* and *space type*, according to the fifth studied hypothesis. Since in experimental phase B participants were exposed to scenes with the same façade variations and lighting conditions as in experimental phase A, but with different spatial configurations, we can examine whether the findings regarding the joint impact of façade and daylight patterns are generalizable to other architectural spaces. Specifically, we will test whether the façade-induced differences in the perception of a scene —between the two studied façade variations in experimental phase B— are influenced by the window size and the space type. Further investigation of the effect of window size and space type on space perception can be found in Moscoso et al. [2019b;

2019a].

6.1.1.2 Independent variables

A multi-use room in the EPFL campus was selected to be represented in the immersive scenes of the experimental phase A to test the effect of façade and daylight variations on space perception. This space was chosen because its volume, materials, and actual use allowed realistic scenarios of working and socializing in the scene, and it was accessible for on-site measurements. This room has a fully glazed east-facing façade along its length, a two-level ceiling, delineated with a row of concrete columns, and wooden floor. A photograph of the interior, as well as the shading system that is currently installed in the space, is shown in Figure 6.2. The dimensions of the room were measured and used in combination with drawings provided by the Domaine Immobilier et Infrastructures of EPFL to recreate a three-dimensional model of the room in the modeling software *Rhinoceros*. Although the length of the real space is 43.22 meters, it is often divided with movable partition walls to host different functions, and this length was chosen for the digital model. The resulting dimensions were 10.88x21.19 meters, with a height of 3.43 meters and 5.72 meters at the low and high part of the ceiling, respectively. As the level of detail was shown to be an important factor from the experiments in Chapter 4, all fixed objects that were present in the room, such as luminaires, door and window handles, columns, and wall plugs, were measured and modeled as well.

Figure 6.2 – The multi-use room represented in the immersive scenes (left) and the shading system used in the real environment (right). Photographed by the author in 2018.

Similarly, the materials of the main surfaces in the space were measured under daylight conditions with a Konica Minolta CM-600d spectrophotometer, specifying a CIE 2° standard colorimetric observer and a CIE D65 standard illuminant [International

Organization for Standardization (ISO), 2007a]. The XYZ values were translated to *Radiance* RGB material properties, shown in Table 6.3. A texture was used for floor and columns in the room, to better represent their materials —wood and concrete, respectively— and increase the realism of the scene. Specifically, the materials were photographed and applied as textures using the *Radiance* scripts *wood_pat.cal* and *picture.cal* for the wooden floor and *picture.cal* for the concrete column. In the same vein, the visual transmittance of the glazing in the space was determined by calculating the average ratio of multiple vertical illuminance measurements with and without the glazing using an LMT POCKET LUX 2 illuminance meter. The resulting visual transmittance was converted to transmissivity and was used to create the corresponding *glass* material. As an additional measure to enhance the realism of the scenes, the view out of the window in the room was photographed using a Canon EOS 70D camera, a 180° SIGMA 4.5mm F2.8 EX DC HSM lens and automatic exposure bracketing during an overcast day, and the resulting HDR image was mapped to the *Radiance* sky.

Table 6.3 – *Radiance* material properties for the main surfaces.

Surface	Type	R	G	B	Reflectance	Specularity	TVis
Ceiling	plastic	0.95	0.94	0.92	94%	0	
Floor	plastic	0.31	0.31	0.31	31%	0	
Columns	plastic	0.54	0.52	0.46	52%	0	
Walls	plastic	0.94	0.93	0.90	93%	0	
Façade	plastic	0.25	0.25	0.25	25%	0	
Furniture (social)	plastic	0.70	0.70	0.70	70%	0	
Furniture (work)	plastic	0.75	0.75	0.75	75%	0	
Doors	plastic	0.09	0.09	0.09	9%	0	
Window	glass	0.654	0.654	0.654			60%

Lastly, six façade variations were modeled in Rhinoceros based on the selected patterns from the Section 5.3. Each façade variation was applied across the whole glazing, and was modified accordingly to ensure both a 40% (±1) perforation ratio of open to total window surface and no visible seams or repetitions in the pattern. Whenever possible, the dimensions of the individual openings were kept in a comparable range*. The resulting scenes were exported to *Radiance* using DIVA-for-Rhino. Different sets of furniture were placed in each scene, corresponding to either a social or a working context. Specifically, a lounge setting with couches, low tables and chairs was used for the social context, and an office setting with desks, office chairs, and computers was used for the working context.

In order to test the effect of sky in combination with the façade geometry, three sky types were created using the *Radiance gensky* script through *DIVA-for-Rhino*. Two variations of a clear sky type with sun were generated for the geographical coordinates

*Specifically, the vertical and horizontal stripes have an aperture length and width, respectively, of 4 cm, the variations with the rectangular openings and the skewed vertical elements have apertures with a width of roughly 4 to 8 cm, while the last two complex variations have apertures with a width from 4 up to 45 cm due to their design.

of the Geneva area, with the same date and varying time of day, using the settings "gensky 03 15 10.6 +s -a 46 -o -6 -m -15" and "gensky 03 15 9 +s -a 46 -o -6 -m -15". These two clear sky types were designed to correspond to a high sun angle that does not allow direct sun on the furniture of the space and a low sun angle that allows sunlight penetration on the furniture and towards the depth of the room, with a solar altitude of 33.5° and 20.5°, respectively. In addition, an overcast sky type was generated with the setting "-c" in *gensky* to provide diffuse daylight conditions.

A point close to the center of the room was selected as a suitable viewpoint for the simulations. Using this point as a reference, four viewpoints with varying height were generated to account for differences in the height of the participants. This additional step in the procedure was based on feedback from previous experiments, where participants mentioned that they could perceive that their eye height in VR differed from their actual one. Moreover, experimental studies have shown that the eye height in immersive virtual environments influences the perceived dimensions of the scene [Leyrer et al., 2011, 2015], which is an important factor for the present study where the perception of spaciousness is one of the studied variables, as discussed in Section 6.1.1.3.

These four viewpoints were based on anthropometric data for the eye height of the 5th, 50th, and 95th percentile of standing men and women [Huston, 2013]. Due to the similarity between the 5th percentile of men's eye height and the 50th percentile of women's eye height, as well as between the 50th percentile of men's eye height and the 95th percentile of women's eye height, with a difference of 1.4 cm and 2.5 cm respectively, the average values of the equivalent pairs were used to represent these categories. This approach allowed the identification of four categories of expected eye height level of participants. These categories were used to create four variations of the same viewpoint, with a height that corresponded to each eye height level shown in Table 6.4.

Table 6.4 – Categories of stature, eye height, and corresponding participant height.

Stature [m]	Eye height [m]	Shown to participants with height [m]
1.5308	1.427	$\leq$ 1.58
1.6363	1.5325	> 1.58 and up to 1.69
1.7408	1.637	> 1.69 and up to 1.80
1.8518	1.748	> 1.80

In addition, the average difference between stature (natural height) and eye height across all percentile ranks for men and women, equal to 10.3 cm, was used to calculate the corresponding stature for each eye height category. The difference between the stature values in each category was divided by two to identify a range of possible heights that can be represented by each stature level. Based on this range, the actual height of participants was used to select the viewpoint that was closest to their eye height, as shown in Table 6.4. The differences across the four viewpoints are illustrated in Figure 6.3.

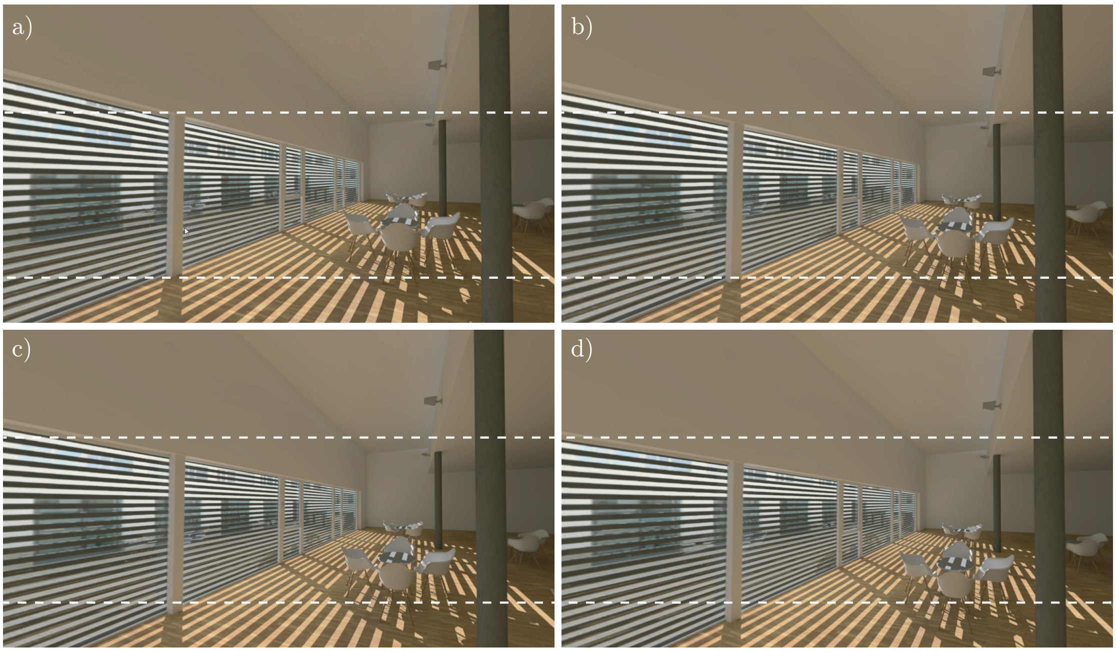


Figure 6.3 – Illustration of the view point differences for the four levels of eye height, from the lowest (a) to the highest (d), using the distance between the dotted lines as a reference.

The combination of the six façade variations, the three sky types, and the two types of furniture produced 36 unique scenes that were exported to *Radiance*. Each of these scenes was rendered from the four viewpoints described in Table 6.4, resulting to a total of 144 simulations. In the time of this study, it was possible to create a full 360° over-under stereo equirectangular projection using the *Radiance* script *view360stereo.cal* [Stock, 2017]. This projection method allows the creation of scenes that are fully stereoscopic, which presents a substantial advantage over the cubemap projection that was used in the previous chapters. The simulations were created for the default interpupillary distance in the script, equal to 60mm, using the *Radiance* parameters shown in Table 6.5 and a resolution of 12960x12960 pixels. A common ambient file was used between the four variations of viewpoint height in the same scene to store indirect illuminance values as a means to reduce computation time. Due to the high accuracy simulation settings, each scene required between 48 and 72 hours of computation time. As the output is an over-under stereo projection, it comprises of two images stacked vertically, with the top one corresponding to the right eye view and the bottom one corresponding to the left eye view, as shown in Figure 6.4 (left).

Table 6.5 – *Radiance* rpict parameters for the equirectangular projection renderings.

-dj	-ds	-dt	-dc	-dp	-st	-ab	-aa	-ar	-ad	-as	-lr	-lw
0.02	0.05	0.05	0.5	256	0.5	4	0.02	32	50000	25000	4	0.000003

Resolution: 12960x12960 pixels.

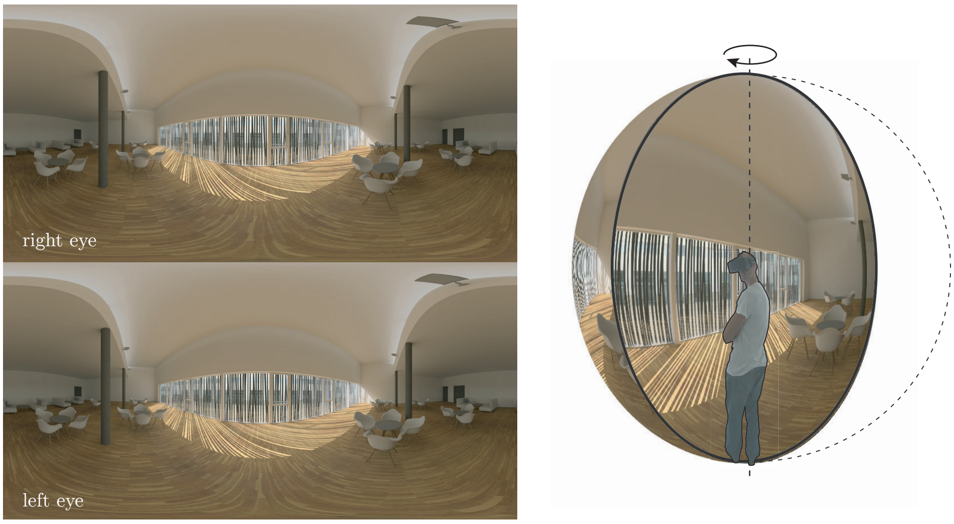


Figure 6.4 – Example of the 360° over-under stereo equirectangular projection (left) and illustration of the participants' immersion in the scene (right).

To increase the quality of the resulting HDR images, anti-aliasing was performed by scaling each image to 1/3 of its original size with the function *pfilt* and the setting "–1" to specify a single pass. The resolution of the resulting anti-aliased images is 4320x2160 pixels. Following the findings of the perceptual comparison of tone-mapping operators in Section 4.2, the anti-aliased HDR images were tone-mapped with the Reinhard02 TMO using the *pfstools* package and the function *pfstmo_reinhard02* with the setting "–s" to enable local adaptation. Then, the tone-mapped output image was cropped with the function *pcompos* to separate the two parts and create two different files. Lastly, the images were gamma-corrected with a factor of 2.0 with the function *pfsgamma* and transformed to PNG files with the function *pfsout*.

The resulting equirectangular projections were used to create immersive scenes in Unity 2017.3.0f3. Each set of images were applied as textures to two spheres as shown in Figure 6.4 (right), using an *Unlit* two-sided material that is unaffected by light sources in the Unity environment. In addition, both the type of imported textures and the color space used in the Unity Project were specified as gamma color space, ensuring that the rendering pipeline uses the textures in the gamma color space in which they are originally stored. One sphere was used for each eye, with the corresponding image applied as texture, to create full stereoscopic content from the participant's viewpoint. A virtual *OVRCameraRig* camera from *OculusUtilities* was placed in the center of the spheres, allowing the control of the view direction through the VR headset.

Lastly, a separate Unity Project was created for each eye height, sky type, and spatial context combination, resulting to 24 unique files. Each Unity Project contained all six façade variations for the corresponding combination, illustrated in Figures 6.5, 6.6, and 6.7. Although the scene might seem slightly distorted in these figures, as the projection is not the same as in the VR headset, this distortion does not appear from the participants' point of view in VR. The presented scene in VR was controlled through custom C# scripts in Unity, which enabled the projection of a specific stimulus by linking specific keyboard combinations to each scene.

The vertical illuminance of each scene was measured in the VR headset to ensure similarity between the scenes. For these measurements, we used the scenes corresponding to the second lowest eye height and measured the vertical illuminance with a LMT POCKET LUX 2 illuminance meter placed at the center of each lens. The façade variations within the same combination of sky type and spatial context differ between them with a maximum factor of 1.05, while all 36 combinations of façade variations, sky type, and context differ between them with a maximum factor of 1.40, both below the threshold of 1.50 which constitutes the smallest difference for a just noticeable variation in illuminance [European Committee for Standardization (CEN), 2011].

Similarly, the average RGB values of the equirectangular projections were calculated for each scene, using the images corresponding to the second lowest eye height and shown to the right eye. These values were transformed to the L*a*b color space and used to calculate the color difference ΔE^*ab [International Organization for Standardization (ISO), 2007b] between all image combinations. The maximum ΔE^*ab between all combinations of façade variations, sky type, and context was found to be 5.88, above the threshold of 2.3 for color differences that are noticeable by the human eye [Mahy et al., 1994]. The maximum ΔE^*ab within the same context is 4.52, also above the threshold, and indicates that these color differences stem from the variations in the lighting conditions between sky types. This is an expected effect when the incident sunlight changes, which can also be seen when visually comparing the scenes such as in Figures 6.6 and 6.7. However, the maximum ΔE^*ab within the same sky type is 2.22, while the maximum ΔE^*ab of the façade variations within the same combination of sky type and spatial context is 0.90, both below the threshold for noticeable color differences.

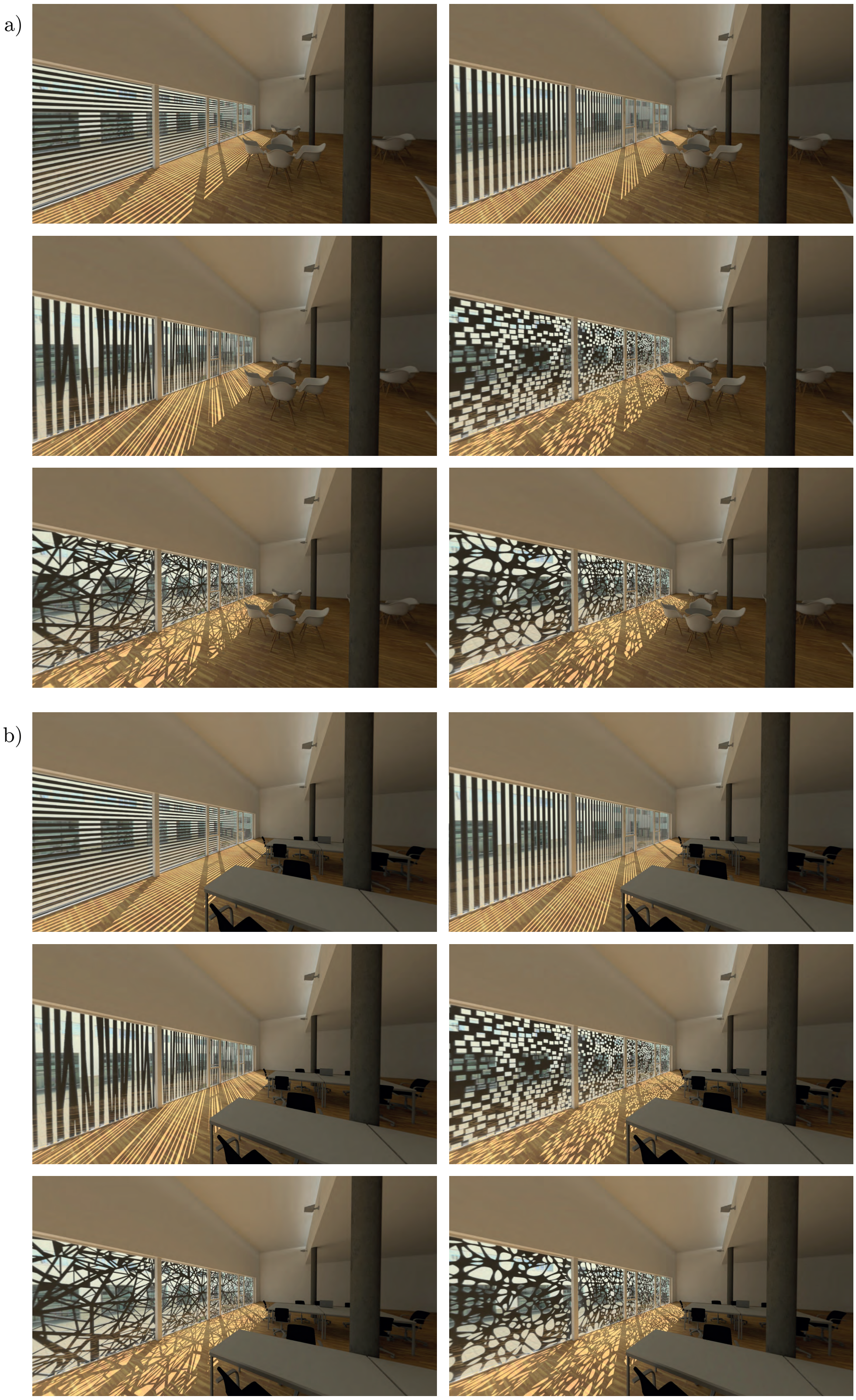
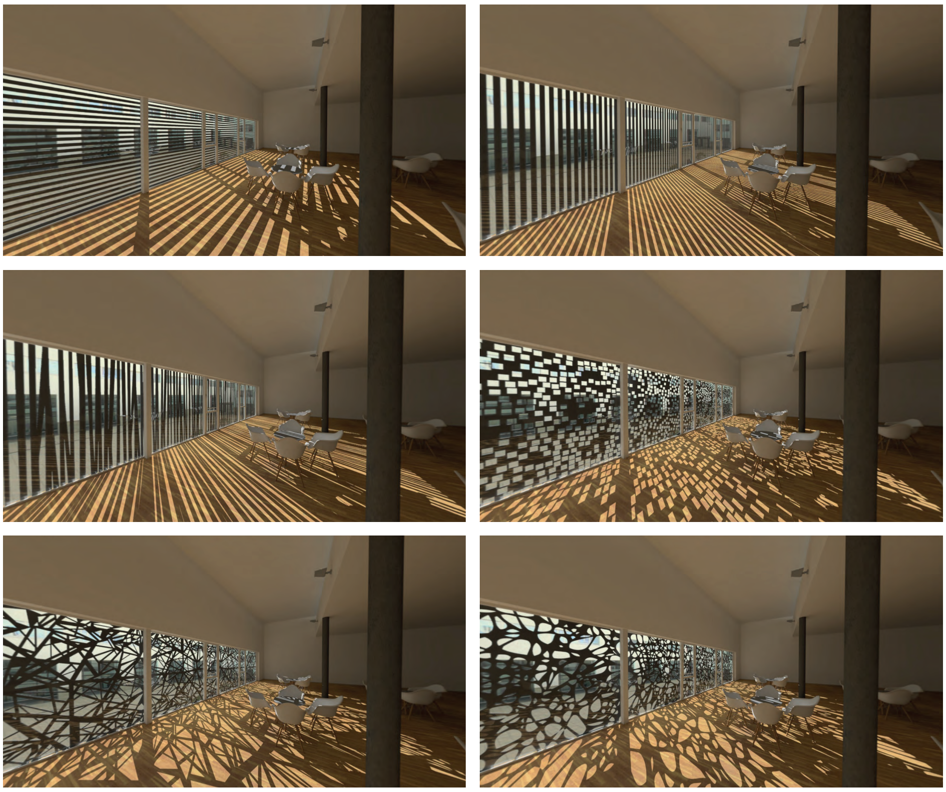


Figure 6.5 – Illustration of the six façade variations for the combination of (a) clear sky with high sun angle and social context and (b) clear sky with high sun angle and working context.

a)



b)

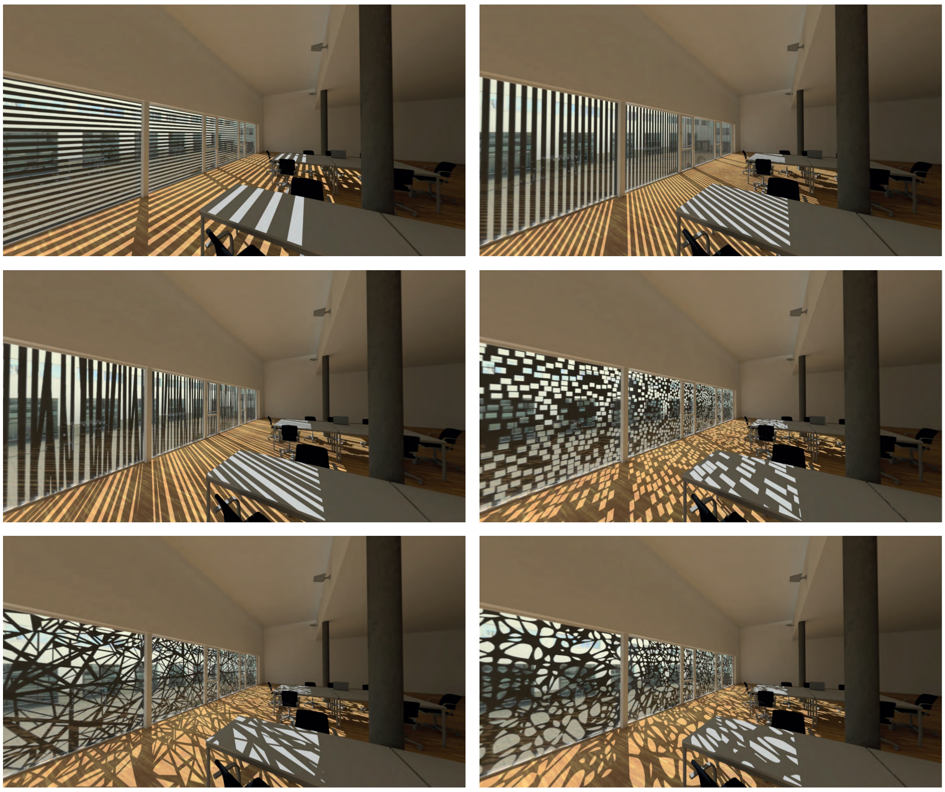


Figure 6.6 – Illustration of the six façade variations for the combination of (a) clear sky with low sun angle and social context and (b) clear sky with low sun angle and working context.

Figure 6.7 – Illustration of the six façade variations for the combination of (a) overcast sky and social context and (b) overcast sky and working context.

These results indicate that possible perceptual effects of sky type could be influenced by the color difference between the scenes. However, within the same sky type, variations of spatial context, as well as of façade geometry —the latter being the main focus of the thesis— are perceptually similar both in terms of color and of vertical illuminance.

The same procedure and simulation parameters were used to generate the stimuli that were used in the experimental phase B. For brevity, we will describe here the stimuli that are relevant for the analyses presented in this chapter, namely the three window size variations for the multi-use room, and the second variation of space type with a large window size. By comparing the responses of participants between the window size variations in the same space, we can examine the robustness of façade-induced perceptual effects to changes in the window size, while by comparing the responses across two variations of space with a large window we can examine the robustness of these effects to changes in the type of space where the façade is applied.

Regarding window size, two additional variations were produced for the multi-use room, using the existing window in the real environment as a reference for the large window size. These variations corresponded to a small and a medium window size. The small window size was designed to allow a daylight factor of 2% in each space, following the minimum recommended values in Norwegian regulations [Direktoratet for byggkvalitet, 2017], while the medium window size was designed to cover an area that was the average between the small and the large window sizes. Following the procedure that was discussed earlier in this section, immersive scenes based on equirectangular renderings were produced for all combinations of window size, sky type, spatial context, and façade geometry, the latter being limited to two conditions only for this experimental phase. As the window size was the within-subject factor in this experimental phase, an example of all window size variations seen by a participant for a combination of one façade variation, a clear sky with low sun angle, and social context can be seen in Figure 6.8 (a),(b), and (c). For brevity, the scenes resulting from the remaining combinations of the studied factors can be found in the Appendix A.5.2.

Regarding the variations in the type of space where the façade is applied, an additional three-dimensional scene model was employed to test the robustness of the façade-driven perceptual effects to changes in the architectural space. In order to use a contrasting stimulus, we employed a space with widely different characteristics in terms of the volume and design of the virtual scene. For this purpose, we used a single person office space with a width of 4.29 meters, length of 4.70 meters, and height of 3.45 meters, located at the NTNU campus in Norway. The height of this office space is the same as the lowest level of the two-level ceiling in the multi-use space and smaller by a factor of 1.65 compared to the highest level of the two-level ceiling, while its width and length are smaller by a factor of 2.5 and 4.5, respectively. The 3D model of the space and its fixed furniture, as well as the material properties of the main surfaces, were provided by the Light and Colour group in NTNU and were based on measurements of the real environment. To ensure that the factor under examination would be the design of the space, the model of the office was oriented towards the same direction as the multi-use space, and the same view out and floor material were used in the *Radiance* simulations. The two façade geometry variations of the experimental phase B were applied to the model of the space, and were used to create immersive scenes for all combinations of the factors façade geometry, sky type, and spatial context. A subset of these scenes, corresponding to the two space variations under a clear sky with low sun angle and social context are shown in Figure 6.8 (a) and (d), while the remaining scenes can be found in the Appendix A.5.1.

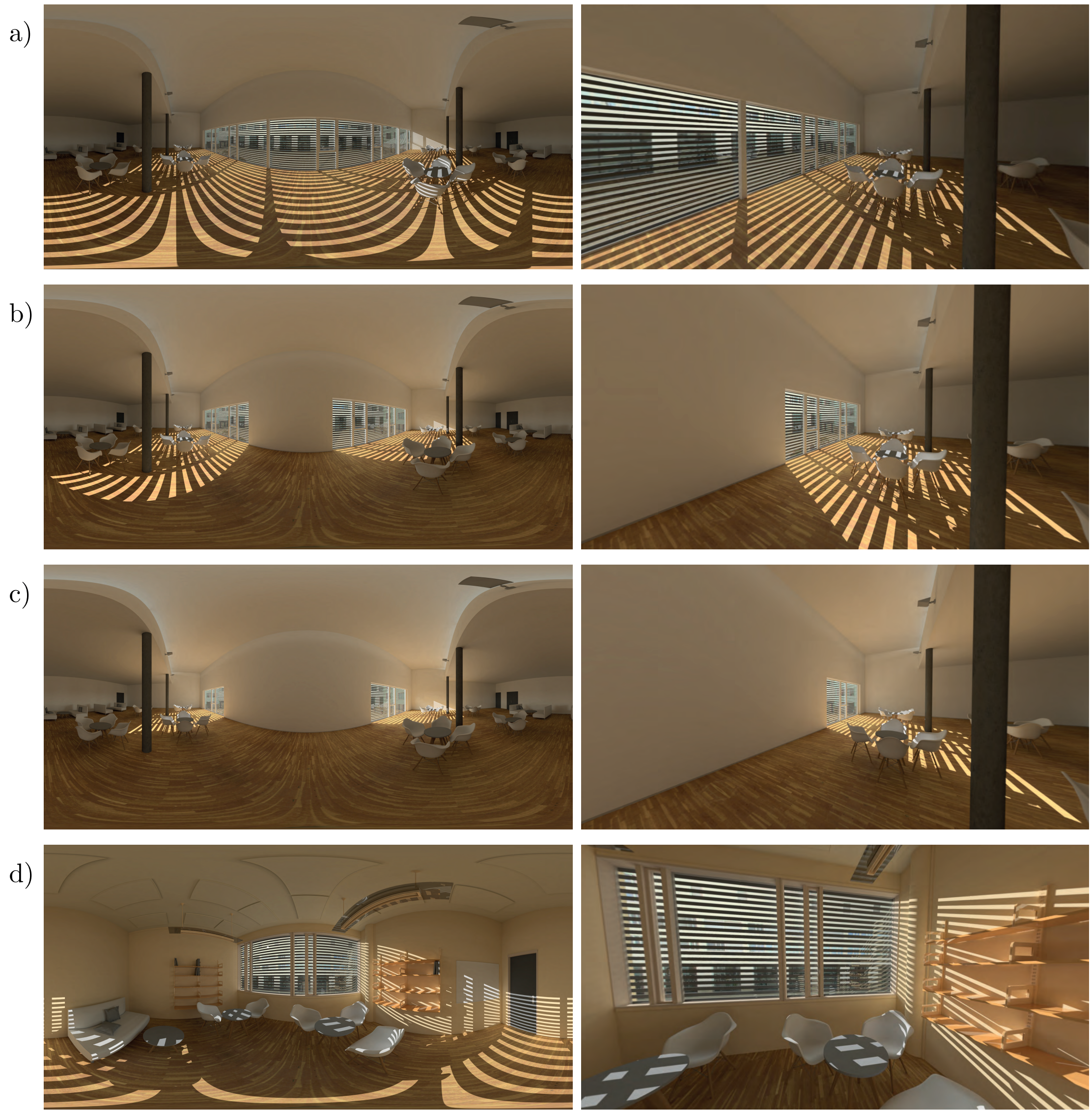


Figure 6.8 – Equirectangular projections of the 360° scene (left) and illustrations of a perspective view in the scene (right) for the multi-use space with (a) large, (b) medium, and (c) small window size, and (d) the office space with a large window size, for a clear sky with low sun angle and social context.

6.1.1.3 Dependent variables

In alignment with the design of previously presented experimental studies in this thesis, the dependent variables examine both the emotional response and the visual appearance of the scene. Regarding the emotional response induced by the presented scene, participants were asked how pleasant, interesting, exciting, and calming they find the space. These perceptual attributes are in line with previous studies in the literature that investigate subjective responses to lighting conditions [Cauwerts, 2013; Rockcastle et al., 2017a,b; Rockcastle, 2017], and cover the emotion space of Russell's circumplex model of affect [Russell, 1980]. Following the results of the survey that was presented in the Section 5.3, which showed that the dimensions of calming and exciting are not necessarily antithetical, we employ two separate questions for the impressions of how *calming* and how *exciting* the space is perceived.

As the central investigation of this study is the perceptual effect of façade and daylight patterns with varying complexity, the measured perceptual attributes are complemented with the question "How complex is this space?" to provide an indicator of perceived complexity of the stimuli. In addition, we examine the effect of the presented scenes on the satisfaction with the amount of view in the space, as well as the perceived brightness and spaciousness of the scene. Since the studied façade variations have the same perforation ratio, these questions aim to quantify the influence of the spatial distribution of façade openings on these visual attributes of the scene. Although the studies in Chapter 5 did not reveal an effect of façade geometry on the reported satisfaction with the amount of view in the space, the current experiment extends to a wider range of façade characteristics which warrant further study of this attribute. In the same vein, a façade-driven effect on the satisfaction with the view out is also expected to influence the perceived brightness of the scene, as the relation between view access and perceived brightness is well established [Franz et al., 2005; Stamps, 2010; Ozdemir, 2010]. Similarly, studies in the literature have shown that the shape and size of the window can affect both the perceived dimensions of the space [Matusiak, 2006] and the reported spaciousness [Franz et al., 2005; Stamps, 2010; Bokharaei and Nasar, 2016], and it is thus of interest to investigate this effect further in the context of façade design.

All attributes, with the exception of how spacious and how calming the scene is perceived, have been shown to be perceptually accurate in virtual reality through the studies of Chapter 4. Even though the findings of Chapter 4 showed that the perceptual accuracy of the immersive scenes tone-mapped with the Reinhard02 operator did not meet the set threshold, no significant difference was found between the responses in the real and virtual environments, and we thus chose to employ this attribute in the present study. However, we note that a small-to-moderate, —rather than small— effect of the virtual environment was found on the impressions of calm in Section 4.2, and encourage future research to investigate further the impact of this discrepancy in accuracy.

An overview of the dependent variables is presented in Table 6.6. All questions were asked in random order, using a verbal 11-point scale from 0 to 10 with anchors at the end points ("Not at all" to "Very"). This extension of the scale from the previously used 10-point scale in Section 5.2 was chosen to offer a neutral response and to provide a range which approaches an interval scale. Specifically, 11-point scales from 0 to 10 have been shown in simulation studies to be closer to normality and to interval scales, and are suggested both because of this attribute and their ease of use [Wu and Leung, 2017].

Table 6.6 – Overview: studied dependent variables.

Perceptual impressions	
PI.1	How pleasant is this space?*
PI.2	How interesting is this space?*
PI.3	How exciting is this space?*
PI.4	How calming is this space?*
Visual appearance	
VA.1	How complex is this space?*
VA.2	How bright is this space?*
VA.3	How spacious is this space?*
VA.4	How satisfied are you with the amount of view in this space?

*A scale from 0 to 10, with 0 corresponding to 'Not at all' and 10 to 'Very', was used for all marked questions.

In addition to the verbal questionnaire, the participants' physiological responses to the presented stimuli were recorded using an Empatica E4 bracelet, repeating the experimental setup of the study presented in Section 5.2. The analysis of the physiological responses, which is outside the scope of the thesis, will be addressed in future publications. A description of the relevant equipment, measures and experimental setup for physiological measures can be found in Section 5.2.1.

6.1.1.4 Participants

A call for participants, advertised via e-mail and posters, was used to recruit subjects in both countries. Participation was voluntary and eligible participants were selected based on the criteria of normal or corrected-to-normal vision, age between 18 and 50 years old, English language proficiency of C1 or higher, and a minimum duration of stay of 18 months in the country where the experiment took place. These criteria follow those set for the previous experiments presented in this thesis, with the age restriction applied to avoid the occurrence of presbyopia [Brückner, 1967] which is problematic for the use of head-mounted displays. The additional criterion of a minimum duration of stay stems from the work of Lysgaard on cultural adaptation, which suggests that a satisfactory adjustment to the foreign country occurs after 18 months of stay in the host country [Lysgaand, 1955]. Although the three stages of cultural adaptation proposed by Lysgaard have been criticized in recent studies, the threshold of 18 months is still shown to be a sufficient duration for cultural adjustment to a foreign country [Ward et al., 1998; Ying, 2005; Markovizky and Samid, 2008].

From an initial sample size of 265 participants, 7 were excluded as it was found out after the experiments that they were not fulfilling the criterion for cultural adaptation*. The resulting sample size corresponds to 258 participants: 120 in Switzerland (60 women and 60 men) and 138 in Greece (64 women and 74 men). The mean and standard deviation of participant's age were μ = 27.8 years, σ = 8 years in Switzerland and μ = 24.2. years, σ = 4.7 in Greece. These age ranges are close to age brackets employed in studies investigating age-related effects on lighting perception [Kuijsters et al., 2012; Schweitzer et al., 2016], and thus the population samples in the two countries can be considered sufficiently similar in terms of age.

Following the discussion regarding potential differences in the perception of experts and non-experts in Section 5.3.3, the expertise of participants in architecture and lighting design was collected as a demographic characteristic but was not balanced across population samples in the two countries due to the difficulty of finding eligible participants. From the total sample, 57 participants in Greece and 10 participants in Switzerland reported that they were trained in architecture, while 6 participants in Greece and none in Switzerland reported that they were trained in lighting design.

Participants in each country were randomly assigned to one of six groups, corresponding to the combination of the factors sky type and spatial context of the presented immersive scenes. Table 6.7 presents an overview of the distribution of participants for each combination of factors across the two countries. This experimental study was approved by the EPFL Human Research Ethics Committee (applications HREC 008-2016 and 025-2017) and complied with the tenets of the Declaration of Helsinki. Participants provided written informed consent prior to the beginning of the experiment and were compensated for taking part in the study with 10 Swiss Francs or Euros, depending on the country.

Table 6.7 – Sample size per country, spatial context, and sky type.

	Switzerland		Greece	
Sky type	Social context	Work context	Social context	Work context
Clear, high sun angle	20	22	21	23
Clear, low sun angle	20	20	27	23
Overcast sky	18	20	22	22
Sum	58	62	70	68

6.1.1.5 Experimental protocol

Experiments in Greece were conducted in May 2018, and in Switzerland in June 2018. Sessions took place in an office room at the EPFL campus in Switzerland, and in an office room at the campus of the Technical University of Crete in Greece. Both rooms had a window, and were selected to ensure a quiet experimental space with commonly

*While two participants in Switzerland were found after the experimental sessions to be 52 and 53 years old, they had spectacle-corrected vision and thus they were not removed from the dataset. To ensure that these two participants do not influence the outcomes of the study, the statistical analyses were repeated without their responses and confirmed that the findings are consistent.

found indoor environmental conditions. Shading devices (in both countries) and air-conditioning systems (in Greece) were used to ensure that uncomfortable lighting and thermal conditions were avoided. An Onset U12 HOBO Logger was used to record air temperature and humidity. Measurements showed a mean temperature of 25.2°C (σ = 1.1°C) in Switzerland and 24.6°C (σ = 0.4°C) in Greece, and a mean relative humidity of 55.8% (σ = 2.9%) in Switzerland and 54% (σ = 0.4%) in Greece, indicating conditions within the comfortable range for warm months [SIA, 2007].

Individual experimental sessions were scheduled with each participant and lasted 25 minutes on average. Each participant was first welcomed by the researcher and presented with a document containing information about the experiment and indicating that the study investigated "how different parameters influence your perception of the interior of a daylit space in virtual reality". This description was intentionally vague to ensure a single-blind procedure. If they agreed to take part in the study, participants were asked to provide written informed consent before starting the experiment. After consenting to participate, participants were provided with the written definitions of the perceptual attributes that would be used in the verbal questionnaire, shown in Appendix A.6, and were informed that they could ask the researcher to repeat a definition at any moment during the experiment. Following this step, participants were introduced to the equipment that was used in this study, which comprised of the Oculus CV1 VR headset used in combination with an Acer Predator 17-X laptop, and the Empatica E4 bracelet. As the equipment used in this study was identical to that employed in the experiment described in Section 5.2, for brevity, we refer the reader to the detailed description of the equipment that can be found in Section 5.2.1.4.

Participants were first asked to answer a demographic questionnaire regarding information such as their age, gender, and length of stay in the country where the experiment took place, using a tablet. When they were ready to proceed, they were requested to provide their height, which was used by the researcher to select the equivalent view point height to be shown in VR from Table 6.4. Participants were then provided with a disposable sanitary mask for head-mounted displays and they were instructed in how to wear it. After this step, they were guided to the center of the experimental room and they were shown how to wear and adjust the headset in a training VR scene with black background and white letters. Participants were instructed that they could freely turn and look around them, and were asked to remain in the same spot and to avoid looking at their body to ensure a sense of presence in the virtual scene.

Each participant was randomly assigned to one of six possible groups, corresponding to the presented stimulus and specifically the combination of the factors*sky type* and *spatial context*. In order to specify the spatial context, when presented with the first experimental scene, the participant was told "You can see from the furniture that this is a [working/social] space. I would like you to imagine that you are here and you are [working/socializing], both for this scene and for all the scenes you will see today. Please take this into account when answering." Both the order of the experimental phases and the stimuli within each experimental phase were randomized. Before the presentation of each immersive scene, a single color was shown in VR for 15 seconds to ensure chromatic adaptation [Rinner and Gegenfurtner, 2000]. This color corresponded to the average RGB value of all scenes that would be shown to the participant within the relevant experimental phase. Similarly to the procedure used in other lighting studies [Newsham et al., 2010; Cauwerts, 2013], participants were asked to remain silent for the first 30 seconds of presentation of each new immersive scene and freely explore the virtual environment during that time. When this time period had passed, participants were informed by the researcher and were then asked to indicate when they were ready to evaluate the scene. After the presentation of all stimuli within one experimental phase, participants were asked to remove the headset and take a small break. In the following experimental phase, the training scene was shown again in VR to ensure that the headset was correctly adjusted, and the same procedure with the single color scene preceding each stimulus and the silent period during the first 30 seconds of immersion to each scene was followed until the end of the experiment.

6.1.1.6 Data analysis

In this section, we focus on the results of the experimental phase A, which employed the *façade geometry* as a within-subject factor, and the *sky type* and *spatial context* as between-subject factors. Specifically, we investigate the effects of façade geometry, sky type, spatial context, and latitude on the participants' responses. Moreover, we are examining possible interactions between the sky type and the spatial context, in alignment with the fourth hypothesis of this study. In the mixed experimental design that was used, shown in Table 6.1, repeated measures from the same participant were collected for each level of the factor *façade geometry*. To avoid the violation of the assumption of independence between observations, we employed Linear Mixed Models (LMM), which address the issue by taking into account the correlated structure of the data. In particular, LMM allow the specification of fixed factors, that were controlled during the study, and random factors —in our case, the participants of the study— which were not controlled but rather chosen randomly from a larger population [McCulloch and Searle, 2001].

Linear mixed model analyses were conducted with the statistical software *R v.3.5.2* [R Core Team, 2018] and the R packages *lme4 v.1.1.20* [Bates et al., 2015] and *lmerTest v3.0.1* [Kuznetsova et al., 2017]. Separate linear mixed model analyses were conducted for each dependent variable. The façade geometry, sky type, spatial context, country, and the interaction between sky type and spatial context were used as fixed effects. The unique number of each participant was specified as a random factor to account for the possible correlation between responses of the same subject, as well as for the inter-subject variance in responses. Analyses were controlled for the potential confounding factors of the participants' gender, first presented façade variation*, and experimental phase order by specifying them as covariates in the model. Lastly, whenever the interaction term did not have a significant effect, it was excluded from the final model.

The R package *car v.3.0.2* [Fox and Weisberg, 2011] and the function *vif* was used

*The first presented façade variation was added as a covariate, rather than the total presentation order of the façade variations in each experimental phase, due to the high VIF of the factor presentation order.

to calculate Variance Inflation Factors (VIF) and identify potential collinearity between the independent factors. Results showed VIF below 1.5 for all factors, with the exception of the interaction term with a VIF of 9, which are below the commonly used threshold of 10 [Belsley, 2004]. The visual inspection of residual plots showed that the linear mixed model assumptions of homoscedasticity and normality were respected, with the exception of the model for perceived spaciousness which deviated from normality. However, simulation studies in the literature show that LMM are robust when this assumption is not followed [Maas and Hox, 2004], especially with a high number of groups as is the case in our study. For the analysis of ordinal data in mixed experimental designs, Cumulative Link Mixed Models (CLMM) have been suggested as an alternative [Agresti, 2012]. Nevertheless, these models are still in their infancy and their application in empirical studies, particularly in the field of lighting research, has been limited. In addition, simulation studies have shown that CLMM led to a considerably higher Type I (a false positive finding) error rate compared to LMM, and recommend using LMM to analyze ordinal data [Kizah, 2014]. In order to further verify the robustness of LMM with our ordinal data, the analysis of the main fixed and random effects was repeated with both LMM and the equivalent CLMM models using the *ordinal* package in R and the *clmm* function [Christensen, 2019]. The findings were consistent between these two approaches for all our dependent variables, which confirms the reliability of using LMM with our data. Following these outcomes and the wide use of LMM with ordinal data in lighting research [Murdoch and Stokkermans, 2014; de Kort and Smolders, 2010; Smolders et al., 2012; Smolders and de Kort, 2017], we proceed with LMM analyses for the present study.

The statistical significance of the effect of each term was calculated using type III Wald F tests with the Kenward-Roger method using the *Anova* function in the R package *car v.3.0.2* [Fox and Weisberg, 2011]. This method was selected because of its robustness to data with low skewness and high kurtosis, especially for total sample sizes of 45 or higher [Arnau et al., 2013], which is the case of our dataset with a total sample size of 258 and maximum skewness and kurtosis of -0.46 and 3.3, respectively, for the perceived spaciousness. All analyses were conducted at a 0.05 significance level. For these planned analyses, the results are interpreted using a Bonferroni-corrected significance α' of $0.05/64 = 0.0008$ to account for the multiple comparisons of 8 models with 8 terms each. In the case of a significant effect of the main factors, post-hoc pairwise comparisons of estimated marginal means were conducted using the R package *emmeans* v.1.3.2 [Lenth, 2019] and applying the Šidák adjustment for multiple comparisons [Šidák, 1967]. Marginal and conditional R^2 are reported for each LMM, and were estimated using the R function *r.squaredGLMM* [Nakagawa et al., 2017] of the R package *MuMIn v.1.43.6* [Bartoń, 2019]. The marginal R^2 is proportion of the total variance that is explained solely by fixed effets, while the conditional R^2 is the proportion explained by the full model, including both fixed and random effects [Nakagawa et al., 2017].

Lastly, the robustness of the significant effects of façade geometry was tested against variations in the window size and type of the scene. To this end, we use the data from the experimental phase B, where participants were exposed to scenes with varying window size and space type. Specifically, we employ the differences in the evaluations of the scene when participants were exposed to two contrasting façade geometry conditions. If the difference in the evaluations of the same scene between these two façade geometry conditions is not influenced by changes in the window size or the type of space, we can infer that the relative effect of façade geometry is robust to such variations of space configuration. As in the experimental phase B the façade geometry was a between-subject factor, we will use the distribution of participants' responses across the whole range of the 11-point rating scale as a indicator of the perceptual effect of the façade. By calculating the difference in the distribution of participants' responses between the two studied façade variations, we produce a measure of the perceptual effect of the change in façade geometry across different configurations of the scene. This measure consists of 11 data points —corresponding to the difference in the percentage of responses for each unit of the rating scale between the two façade variations—, and can be compared across window size levels and space type configurations to investigate its robustness. Specifically, a Wilcoxon Rank-Sum test was used to investigate the effect of space between the two space types, and a Kruskal-Wallis test was used to investigate the effect of window size between the three window variations in the multi-use space. As each group is limited to only 11 data points, an a priori analysis for the Wilcoxon Rank-Sum test was conducted with the G*Power software [Faul et al., 2007] and showed that for the commonly used statistical power of 0.80 and a significance level of 0.05, this sample size is sufficient to distinguish moderate effects ($d = 1.3$) [Ferguson, 2009], which is adequate for the purpose of this analysis.

6.1.2 Perceptual effects of façade geometry, sky type, and spatial context across geographical latitudes

As discussed in the section 6.1.1.6, each dependent variable was analyzed with a separate LMM model. In this section we will discuss the findings regarding the significance of the terms in each model. Analyses showed that the interaction term *sky type*spatial context* did not have a significant effect on any of the dependent variables (all $ps > 0.013$), and as a result, this term was excluded from the final models. It is worth noting that the same outcome would hold true if the multiple comparison analysis was applied solely to the four main factors (α'=0.05/40 = 0.0016).

A highly significant effect was found for the factor *façade geometry* for all dependent variables. Specifically, the façade significantly influenced how *pleasant* ($F(5, 1285) = 15.50$, $p < 0.0001$), interesting ($F(5, 1285) = 63.88, p < 0.0001$), *exciting* ($F(5, 1285) = 51.59$, $p < 0.0001$), and *calming* ($F(5, 1285) = 18.78$, $p < 0.0001$) the space was evaluated. Regarding the visual appearance of the space, the façade geometry significantly affected how *complex* ($F(5, 1285) = 128.74$, $p < 0.0001$), *bright* ($F(5, 1285) = 41.81$, $p < 0.0001$), and *spacious* the scene was perceived. Lastly, the *satisfaction with the amount of view* in the space was also influenced by the façade geometry ($F(5, 1285) = 7.89$, $p < 0.0001$). Due to the number of pairwise comparisons and the complexity of these results, the outcomes of the post-hoc tests for each dependent variable and the detailed analysis of the effects of each studied façade configuration are presented in the section 6.1.2.1 below.

Neither the factor *sky type* nor the *spatial context* affected the participant responses in the studied variables (all $ps > 0.20$ for both factors), indicating that the façade variation was the predominant factor. Regarding cultural differences in the participant responses, solely the evaluation of how *exciting* the space was perceived approached significance ($F(1, 257) = 7.30$, $p = 0.007$) but failed to meet our adjusted threshold. These results reject our third and fourth hypothesis, demonstrating that neither the interaction between the sky type and the spatial context nor the regional differences had a significant influence on participants' responses. Although such effects were anticipated based on indications from the literature, and are thus an unexpected result, these two outcomes greatly increase the generalizability of the main findings regarding the perceptual effects of façade geometry. The first —and central for this thesis— hypothesis in this study, which argued that the participants' perception of the space will be influenced by the façade geometry, is confirmed for all the dependent variables. This finding, in combination with the lack of an effect from the sky type, the spatial context, or their interaction, shows that the façade design can be used to shape the perception of a space across variations in the lighting conditions or the function of the space. Moroever, as the responses of participants in central and southern Europe did not differ significantly between them, these design-driven perceptual effects can be expected to apply across these latitudes, at least within Europe.

Similarly, no statistically significant effects were found for the covariates of the model. Specifically, the presentation order of the experimental phases did not influence the participant responses for any of the dependent variables (all $ps > 0.024$). The effect of the first façade variation that was presented approached significance for the perceived *complexity* ($F(5, 252) = 3.39$, $p = 0.006$, all other $ps > 0.036$). Lastly, the participants' gender approached significance solely for the reported *satisfaction with the amount of view* ($F(1, 257) = 8.26$, $p = 0.004$, all other $ps > 0.036$). These findings are very positive, as they suggest that the perceptual effects of façade geometry are robust to both characteristics of the scene (such as the sky type and spatial context), characteristics of the occupants (such as gender), as well as effects of sequential experience (such as the first façade shown).

Table 6.8 presents the marginal and conditional R^2 for the LMM of each dependent variable. We can observe that the proportion of explained variance in the model is greatly increased for the conditional R^2, where the random effects are considered. Moreover, we find that the façade geometry, sky type, and spatial context in the presented scene, as well as the latitude where the experiment took place, explain in combination up to 65% of the variance of the participant responses —in the case of how *spacious* the scene is perceived— when controlling for repeated measures. According to the relevant thresholds suggested by Ferguson [2009], these conditional R^2 values can be interpreted as moderate to strong, the latter in the case of perceived spaciousness.

Table 6.8 – Marginal and conditional R^2 of the LMM for each dependent variable.

Dependent variable	$R^2_{marginal}$	$R^2_{conditional}$
Pleasantness	0.05	0.38
Interest	0.14	0.53
Excitement	0.13	0.52
Calmness	0.06	0.38
Complexity	0.22	0.56
Brightness	0.10	0.59
Spaciousness	0.06	0.65
Satisfaction with the amount of view	0.15	0.53

6.1.2.1 Perceptual differences between façade characteristics

Following the significant main effects of the factor *façade geometry* on all studied variables, further analyses were conducted to identify the effects of individual variations of façade design. Figure 6.9 shows the median ratings and median standard deviations for the evaluations of how *pleasant*, *interesting*, *exciting*, and *calming* the space was perceived for each façade geometry, across all participants and variations of sky type and spatial context. For ease, the façade variations are represented with the corresponding pattern from the survey of Section 5.3 and in text they will be referred to as "Pattern [X]" with numbers from one to six, one being the leftmost and six being the rightmost. To complement this figure, the means and standard deviations for each façade variation across all sky types and averaged over all other factors are provided in the Appendix A.7 for all dependent variables.

In Figure 6.9, we can observe that each façade variation might induce responses with different directions according to the perceptual attribute. For example, Pattern 4 is shown to be one of the most interesting variations, but it is simultaneously one of the least pleasant, while Pattern 3 is evaluated both as one of the most interesting, and one of the most pleasant variations. Generally, the variations with higher complexity led to higher evaluations of how interesting or exciting the space is perceived, in accordance with the previous findings in this thesis. Moreover, we can observe similarities between the perceptual effects of specific variations for certain attributes, such as Patterns 1 and 2 or Patterns 5 and 6 in how exciting the space is perceived. Similarly, this figure suggests consistent differences between specific pairs of patterns, such as the Pattern 2 and 3, in how pleasant, interesting, or exciting the space is perceived.

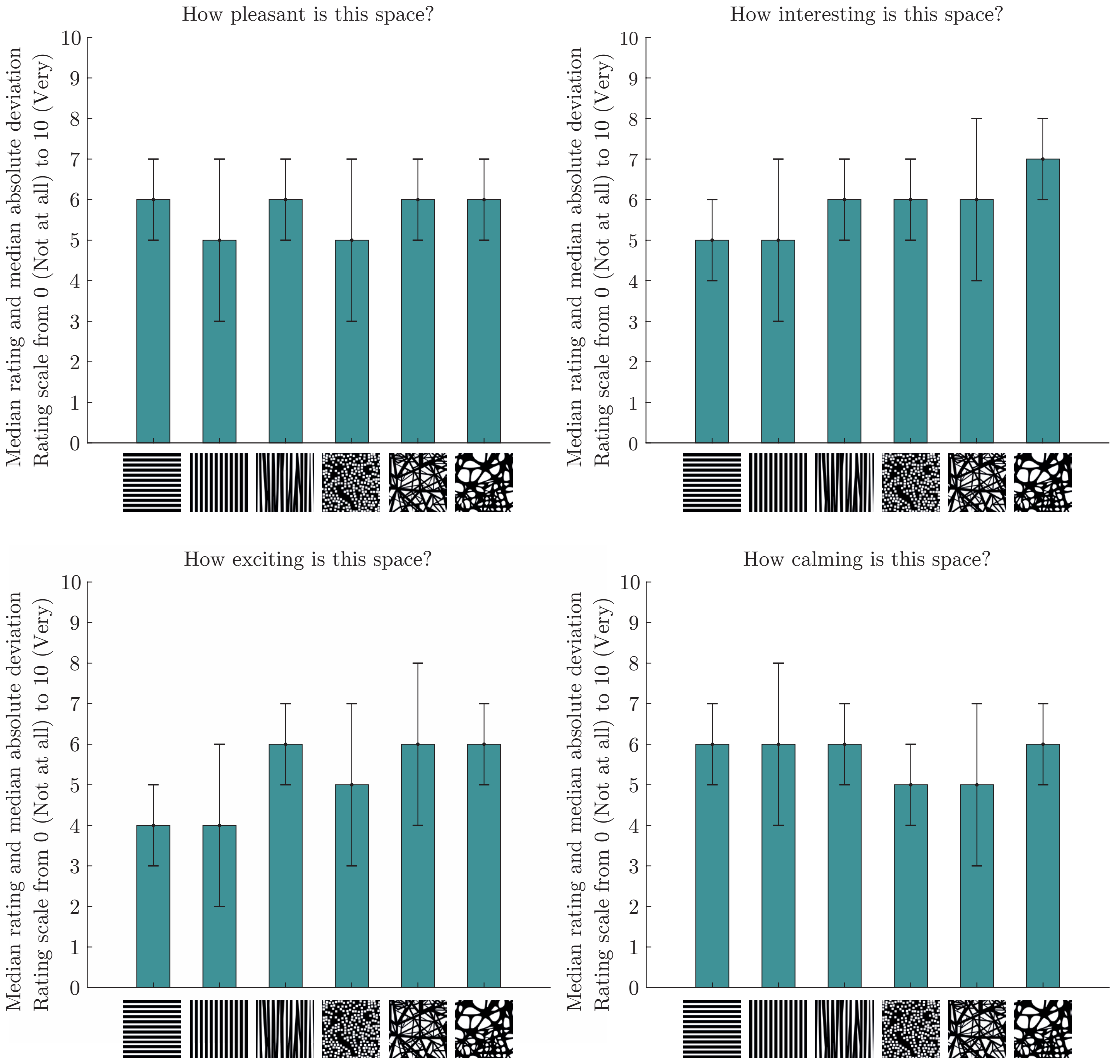


Figure 6.9 – Median ratings and median absolute deviations for evaluations of how pleasant, interesting, exciting, and calming the space was perceived under exposure to each façade geometry variation.

Figure 6.10 presents the same descriptive statistics for the evaluations of how *complex*, *bright*, and *spacious* the space was perceived, as well as how satisfied were the participants with the amount of view in the space. The evaluations of perceived complexity in this figure suggest a similar trend with how interesting and exciting the space is perceived, with the leftmost variations rated more negatively than the rightmost ones. This observation is confirmed with the results of a Spearman's rank correlation*, which shows a small-to-moderate significant positive correlation between the evaluations of complexity and interest, as well as of complexity and excitement (with a ρ of 0.49 and

*The analysis of correlation between the dependent variables is limited to testing specific observations to avoid multiple comparisons and limit the family-wise error rate.

0.47, respectively, and $p < 0.0001$ for both). Moreover, regarding the brightness, spaciousness, and satisfaction with the amount of view in the space, Pattern 4 is shown to lead to more negative evaluations. This is particularly interesting in the case of the reported brightness and the satisfaction with the amount of view in the space, as this experiment was designed to control both for the actual brightness of the scenes and the perforation ratio of the façade, which shows that this effect is due solely to the façade design.

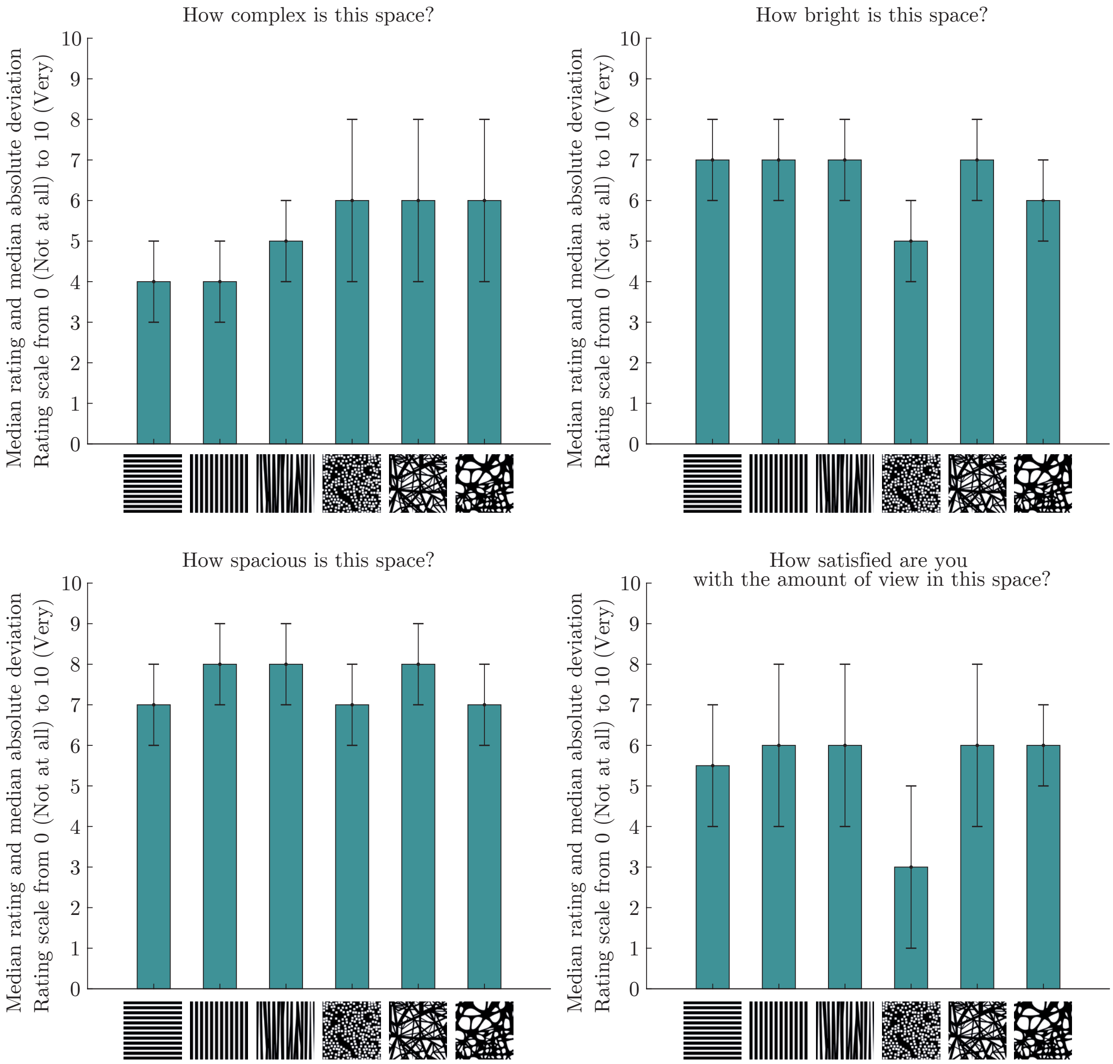
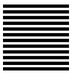
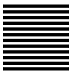
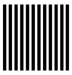
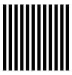
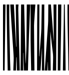
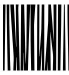
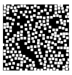
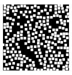
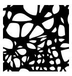
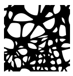
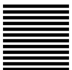
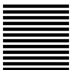
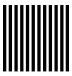
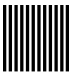
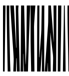
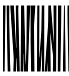
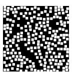
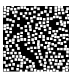
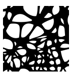
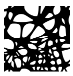


Figure 6.10 – Median ratings and median absolute deviations for evaluations of how bright, complex, and spacious the space was perceived, and how satisfied the participant was with the amount of view in the space under exposure to each façade geometry variation.

In order to verify these initial observations, post-hoc pairwise analyses were conducted for all combinations of façade geometry variations for each dependent variable. As the pairwise comparisons are too many to be depicted in these figures, Tables 6.9-6.12 below present the results in a matrix for each dependent variable. These tables are conceptually similar to a correlation matrix, and allow the reader to observe clusters and trends in the results of the pairwise comparison. Pairs with significant differences between them are reported with the relevant estimates (corresponding to the estimated marginal means of the façade variation in the equivalent column minus the equivalent row) and significance levels. For brevity, estimates and significance levels will be described in text only when discussing a particularly notable finding.

Table 6.9 – Pairwise comparisons of all façade variations for the evaluations of how pleasant and interesting the space was perceived. Estimates β (comparison: column minus row) and adjusted significance levels are shown for pairs with significant differences.

How pleasant is this space?							
Pattern 1							
Pattern 2							
Pattern 3		-0.55**	-0.81****				
Pattern 4		0.46*		1.02****			
Pattern 5				0.46*	-0.55**		
Pattern 6		-0.53**	-0.78****		-0.99****	-0.44*	

How interesting is this space?							
Pattern 1							
Pattern 2							
Pattern 3		-1.19****	-1.09****				
Pattern 4		-1.04****	-0.93****				
Pattern 5		-1.65****	-1.54****	-0.45*	-0.61****		
Pattern 6		-1.79****	-1.68****	-0.60****	-0.75****		

Significance levels are marked as follows:
* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$.

Table 6.10 – Pairwise comparisons of all façade variations for the evaluations of how exciting and calming the space was perceived. Estimates β (comparison: column minus row) and adjusted significance levels are shown for pairs with significant differences.

How exciting is this space?						
Pattern 1						
Pattern 2						
Pattern 3	-1.12****	-1.05****				
Pattern 4	-0.80****	-0.73****				
Pattern 5	-1.50****	-1.43****		-0.70****		
Pattern 6	-1.57****	-1.49****	-0.45****	-0.77****		

How calming is this space?						
Pattern 1						
Pattern 2						
Pattern 3		-0.49*				
Pattern 4	0.89****	0.58**	1.07****			
Pattern 5	0.93****	0.62***	1.11****			
Pattern 6			0.62***	-0.46*	-0.49*	

Significance levels are marked as follows:
* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$.

Table 6.9 shows the outcome of the pairwise analyses for the perceived pleasantness in the scene. These results show that Patterns 3 and 6 were similar in terms of how pleasant the space was evaluated, as they led to significantly higher ratings compared to the Patterns 1, 2, 4, and 5, while they did not differ between them. Specifically, the exposure of participants to Pattern 3 led to an estimated increase of 1.02 units ($\beta = 1.02$, $p < 0.00001$) in the 11-point rating scale regarding how pleasant the space was evaluated compared to Pattern 4. Lastly, scenes with Pattern 4 were evaluated as significantly less pleasant compared to those with Pattern 1 or 5.

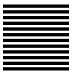
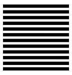
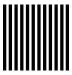
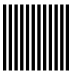
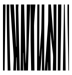
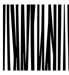
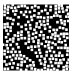
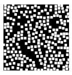
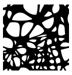
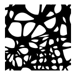
Regarding the perceived interest in the space, Table 6.9 shows that Patterns 1 and 2 induced very similar responses, as both led to significantly lower evaluations compared to Patterns 3, 4, 5, and 6. In particular, these variations induced a maximum estimated decrease of 1.79 units of perceived interest ($\beta = -1.79$, $p < 0.00001$) in the case of Pattern 1 and 1.68 units in the case of Pattern 2 ($\beta = -1.68$, $p < 0.00001$), both when compared to Pattern 6. In the same vein, Patterns 5 and 6 have analogous results, with both variations being evaluated as significantly more interesting than Patterns 1, 2, 3, and 4. These findings, in combination with the lack of significant differences within the three pairs of Patterns 1 and 2, 3 and 4, and 5 and 6, suggest three clusters of façade variations grouped according to their perceptual effects: Patterns 1 and 2, Patterns 3 and 4, and Patterns 5 and 6, inducing responses of low, moderate, and high interest, respectively. This outcome agrees with the findings of the two experimental studies in Chapter 5 and confirms the second hypothesis of the current study that façade variations with irregularly distributed openings will trigger interest in the virtual scene.

The pairwise comparisons of all façade variations regarding how exciting the space was perceived in Table 6.10 show two clusters of variations that support our initial observations from Figure 6.9 as well as those for the perceived interest in the space. Specifically, neither the pair of Patterns 1 and 2 nor that of Patterns 5 and 6 differ between them, indicating similarity within these two pairs in the evaluations of how exciting the space was perceived. Moreover, Patterns 1 and 2 both differ significantly from all other façade variations and led to the same scene being perceived as significantly less exciting, with a maximum decrease of 1.57 units of perceived excitement ($\beta = -1.57$, $p < 0.00001$) between Patterns 1 and 6. Patterns 3 and 4 emerge as outliers compared to these two clusters. In particular, Pattern 4 led to significantly higher evaluations of perceived excitement compared to Patterns 1 and 2, and significantly lower evaluations compared to Patterns 5 and 6. In the same vein, Pattern 3 led to the space being evaluates as significantly more exciting compared to Patterns 1 and 2, and significantly less exciting compared to Pattern 6.

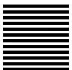
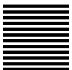
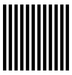
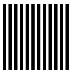
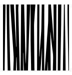
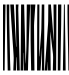
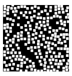
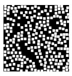
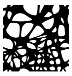
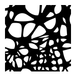
The results concerning how calming the space was perceived in Table 6.10 suggest the existence of different clusters of façade variations compared to how exciting the space was perceived. While Patterns 1 and 2 do not differ significantly between them, this is not the case for Patterns 5 and 6, contrary to the grouping suggested from the findings of how exciting the space was perceived. Specifically, Pattern 6 led to the space being evaluated as significantly more calming compared to Pattern 4 and 5, and as significantly less calming compared to Pattern 3. Pattern 3 is shown to be the most calming variation, being evaluated significantly higher than Patterns 2, 4, 5, and 6, but showing no significant difference from Pattern 1. In particular, Pattern 3 induced a maximum estimated increase of 1.11 units ($\beta = 1.11$, $p < 0.00001$) in how calming the space was perceived when compared to Pattern 5. Lastly, Patterns 1 and 2 both led to the space being evaluated as significantly more calming compared to Patterns 4 and 5, confirming the difference between these pairs of façade variations.

Table 6.11 – Pairwise comparisons of all façade variations for the evaluations of how complex and bright the space was perceived. Estimates β (comparison: column minus row) and adjusted significance levels are shown for pairs with significant differences.

How complex is this space?

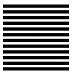
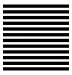
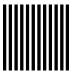
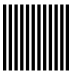
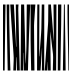
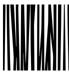
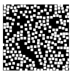
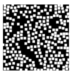
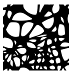
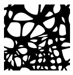
Pattern 1							
Pattern 2							
Pattern 3		-1.12****	-1.10****				
Pattern 4		-2.05****	-2.03****	-0.93****			
Pattern 5		-2.32****	-2.30****	-1.21****			
Pattern 6		-2.28****	-2.26****	-1.16****			

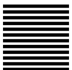
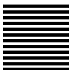
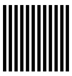
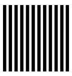
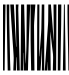
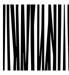
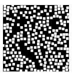
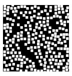
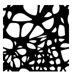
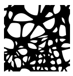
How bright is this space?

Pattern 1							
Pattern 2							
Pattern 3							
Pattern 4		1.08****	1.30****	1.15****			
Pattern 5					-1.06****		
Pattern 6			0.41***		-0.89****		

Significance levels are marked as follows:
* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$.

Table 6.12 – Pairwise comparisons of all façade variations for the evaluations of spaciousness and satisfaction with the amount of view in the space. Estimates β (comparison: column minus row) and adjusted significance levels are shown for pairs with significant differences.

How spacious is this space?							
Pattern 1							
Pattern 2							
Pattern 3							
Pattern 4		0.28^{*}	0.47^{****}	0.46^{****}			
Pattern 5					-0.32^{**}		
Pattern 6					-0.29^{**}		

How satisfied are you with the amount of view in this space?							
Pattern 1							
Pattern 2							
Pattern 3							
Pattern 4		1.96^{****}	2.21^{****}	2.26^{****}			
Pattern 5		-0.55^{**}			-2.52^{****}		
Pattern 6		-0.45^{*}			-2.42^{****}		

Significance levels are marked as follows:
* $= p < 0.05$, ** $= p < 0.01$, *** $= p < 0.001$, **** $= p < 0.0001$.

The analysis of how complex the space was perceived in Table 6.10 shows an interesting cluster of responses. Specifically, the absence of significant differences in the pairs between Patterns 1 and 2, as well as between Patterns 4, 5, and 6, suggests two groups of façade designs with similar perceived complexity. According to the median ratings, Pattern 1 and 2 are shown to form a group of low complexity, and Patterns 4, 5, and 6 are shown to form a group of high complexity façade variations. Moreover, Patterns

1 and 2 are evaluated as significantly less complex than Patterns 3, 4, 5, and 6, with a maximum estimated decrease in perceived complexity equal to 2.32 units ($\beta = 2.32$, $p < 0.0001$) between Patterns 1 and 5. However, Pattern 3, which leads to significantly higher ratings of complexity compared to Patterns 1 and 2, led also to significantly lower ratings compared to Patterns 4, 5, and 6, as shown by the sign of the estimates. This finding suggests that Pattern 3 does not belong to either of the two identified clusters of low and high complexity façade variations, and should be considered separately in terms of perceived complexity.

Lastly, regarding the reported brightness in the space, the results of Table 6.10 show that Pattern 4 led to significantly lower evaluations compared to all other patterns, in alignment with our observations from Figure 6.10. Specifically, Pattern 4 led to a minimum estimated decrease of 0.89 units of reported complexity when compared to Pattern 6 ($\beta = -8.09$, $p < 0.0001$) and a maximum estimated decrease of 1.30 units ($\beta = 1.30$, $p < 0.0001$) when compared to Pattern 2, the latter corresponding to a decrease of 11.8% in reported brightness. Pattern 2 led also to significantly higher evaluations of reported brightness compared to Pattern 6 ($\beta = 0.41$, $p < 0.001$).

Table 6.12 shows that Pattern 4 was the main driver of the significant effect of façade geometry on the perceived spaciousness of the space. Specifically, Pattern 4 led to significantly lower evaluations of how spacious the space was perceived compared to all other variations, with a maximum estimated decrease of 0.47 units in perceived spaciousness ($\beta = 1.30$, $p < 0.0001$) when compared to Pattern 2. Similarly, when immersed in the scenes with Pattern 4, participants rated their satisfaction with the amount of view in the scene significantly lower compared to all other variations. This effect ranged from 1.96 units in the 11-point scale used in the study when compared to Pattern 1 ($\beta = 1.96$, $p < 0.0001$) to 2.52 units when compared to Pattern 5 ($\beta = -2.52$, $p < 0.0001$), demonstrating a maximum of decrease of 22.9% in the satisfaction with the amount of view in the space. This outcome is similar to the findings for perceived spaciousness and brightness, and shows that Pattern 4 had a unique effect in rendering the space seemingly darker, smaller, and less satisfactory in terms of the amount of view. Interestingly, Pattern 1 led to significantly lower evaluations of satisfaction with the amount of view in the space compared to Patterns 5 and 6, with a maximum estimated decrease of 0.55 units ($\beta = -0.55$, $p < 0.0001$) when compared to Pattern 5. This result could be due to the size of the openings in Patterns 5 and 6, which allow larger sections of unobstructed view to the outside.

These findings reveal consistent similarities and differences between specific variations across a number of perceptual attributes of the space. We have identified that Patterns 1 and 2 did not differ significantly between them for any of the dependent variables, while Patterns 5 and 6 only differed in the evaluations of how pleasant and how calming the space was perceived. Moreover, these two groups of façade variations often differed significantly between them in the attributes relating to the emotional aspects of the space. As Pattern 1 and 2 induced identical responses in terms of their differences with the Patterns 5 and 6, we can use Pattern 1 as a reference to outline these differences. Specifically, Patterns 1 and 6 differed in how pleasant, interesting, and exciting the space was perceived, while Patterns 1 and 5 —evaluated as the least exciting and the least calming, respectively, in the survey of architects in Section 5.3.2— differed in how interesting, exciting, and calming the space was perceived.

6.1.2.2 Robustness of the perceptual effects of façade and daylight pattern geometry across variations in window size and space type

In order to test the robustness of the significant effects of façade pattern geometry on participant perception that were demonstrated the previous section, we examine whether the perceptual differences between Patterns 1 and 5 are influenced by changes in the window size or the type of space used in the presented scene. For this purpose, we used the results of the experimental phase B, which employed scenes with varying window size and space type. Specifically, as discussed in Section 6.1.1.6, we calculated the difference in the distribution of participant responses across the range of the 11-point scale between the two faccade variations as a measure of the perceptual effect of the change in façade geometry from Pattern 1 to Pattern 5. We will refer to this difference in the distribution of responses between the two façade variations in the same scene configuration as Δ.

By grouping the responses of participants across sky type and context variations, we computed three Δ for the changes in the responses of participants in the multi-use room with the large, medium, and small window, named $\Delta_{large\,window}$, $\Delta_{medium\,window}$, and $\Delta_{small\,window}$, respectively. An example of these window size variations for Pattern 1 can be seen in Figure 6.8 (a),(b), and (c). Following the same procedure, we calculated the equivalent change in the distribution of responses in the small space with the large window size, $\Delta_{small\,space}$, which can be seen in Figure 6.8 (d) with Pattern 1 applied to the façade. The equivalent Δ were calculated for all studied attributes.

A Kruskal-Wallis test was used to investigate an effect of window size on the Δ by comparing the $\Delta_{large\,window}$, $\Delta_{medium\,window}$, and $\Delta_{small\,window}$. The results showed that the window size did not affect the changes in the distribution of participant responses between the two façade variations for any of the studied attributes (all $ps > 0.59$). In addition, a Wilcoxon Rank-Sum test was conducted to examine the effect of space type on the Δ by comparing the $\Delta_{largewindow}$ and the $\Delta_{small\,space}$, which refer to the scenes with the multi-use room and small office space with the large (existing) window variation applied in both cases. The results show that the type of space did not influence the change in the distribution of participant responses between the two façade variations for any of the studied attributes (all $ps > 0.26$). These findings confirm the robustness of the perceptual effects of façade geometry, in alignment with our fifth hypothesis, and show that the façade-induced changes in the participant evaluations of a scene are not affected by the size of the windows or the type of space where the façade is applied. This outcome is particularly promising, as it demonstrates the generalizability of the findings of this study across variations in the size of the windows in a space, as well as the design features of the space.

6.1.3 Discussion

6.1.3.1 Limitations

The current study is, to our knowledge, the first to systematically investigate the perceptual effects of a wide range of façade variations that stem from existing buildings and differ solely in the shape and spatial distribution of their openings. Although the outcomes of this study bring important insights on the influence of façade geometry on the spatial experience and have been shown to be robust to a number of factors, they are still limited by the methodological approach in this study. Specifically, even though the similarity between real and virtual reality environments in the perception of daylit scenes has been demonstrated in Chapter 4, the use of virtual reality limits both the realism and the luminance range of the stimulus. As it is not possible to induce visual discomfort in the immersive scene, the presented stimuli were evaluated in comfortable visual conditions, which might not correspond to the equivalent real situation. In the same vein, we cannot investigate the relation between visual interest and discomfort, a research direction which is particularly promising due to possible effects of glare tolerance in conditions of high visual interest [Tuaycharoen and Tregenza, 2005; Abboushi and Elzeyadi, 2018a].

Another important limitation is the limited exposure time to the experimental stimuli. Although a minimum exposure of 30 seconds was ensured for all presented stimuli, the remaining exposure time after this period was dictated by the participants. While this particular shortcoming is more critical in the context of physiological measures, such as those described in Section 5.2, it raises the question of the generalizability of the façade-driven effects on perception in situations where occupants are exposed for a longer time period —such as hours, or days— to the same environment. This issue is particularly relevant for effects related to visual interest, which is linked to novelty [Silvia, 2008], an attribute that is expected to diminish with prolonged exposure time. Future studies are encouraged to investigate the effect of exposure time on subjective responses, a research direction which is relevant not only in the context of façade design, but in the general field of light- and space-induced effects on perception. In the same vein, the matter of novelty is also related to the stimulus itself: while the horizontal and vertical stripes in our stimuli were used specifically due to the prevalence of visually similar blind systems in existing buildings, all other studied façade designs are still a rare (although increasingly less so) occurrence. This observation suggests that the perceptual effects of façade design might be driven not only by the geometric characteristics of the façade openings, but also by the lack of familiarity with the particular design.

Moreover, the workflow that was developed in this thesis to generate immersive scenes from physically-based renderings does not allow free movement and interaction with the scene due to current technical limitations. These features could increase the sense of presence in the scene and allow further investigation of the behavior of occupants in daylit spaces.

Regarding the limitations of the experimental design in the experimental phase A, even though the use of façade geometry as a within-subject factor eliminates the inter-subject variance for that factor, it simultaneously places the focus of the participant on the sole changing feature of the scene. Although LMM analyses were employed to explicitly account for the use of repeated measures, this experimental design introduces a possible stimulus range bias, which might have contributed to the lack of a significant influence of sky type or spatial context on participant responses. In the context of sky type, for example, one might have expected the scenes with direct sun to lead to higher overall ratings of interest, with the low complexity façade variations under clear sky conditions being rated as more interesting than the high complexity variations under overcast sky conditions. This was not the case in the present study, as seen in the statistical analysis and the descriptive statistics in Appendix A.7, where the perceptual effects of the façade design overshadow those of the sky type. Future studies are encouraged to employ experimental designs where sky type is a between-subject factor to examine further the relative effect of sky type and façade design.

Furthermore, a fixed viewing distance was used in all presented stimuli. Even though the visual interest and preference of projected light patterns has been shown to not be affected by the viewing distance [Abboushi et al., 2019], it is a factor that could affect the perceptual effects of façade geometry, particularly regarding the satisfaction with the amount of view. In the same vein, the two studied conditions of spatial context (socializing and working in the space) were represented by different types of furniture placed in the scene. Although this approach is an improvement compared to the verbal instructions (without a change in the visual stimulus) that were employed in the previous studies in this thesis, it is still inferior to the actual conduction of activities in the scene. Future work could address this limitation through experiments in real spaces where participants can perform different types of activities. Such studies which would allow further investigation of the effect of spatial context on space perception, and particularly of possible conflicts between the visual attention to the background and the task in the case of façade variations of high visual interest.

Lastly, the methodological approach of keeping a number of factors constant in the studied façade variations —such as the perforation ratio, depth, and material of the façade— led to unavoidable limitations in the generalizability of the research findings to other façade designs. Even though these façade variations stem from existing buildings, they were originally designed for applications of different scales and were modified to ensure an identical perforation ratio. Consequently, the resulting façade variations might not be applicable as shading systems in their current form. Similarly, the employed façade variations had a limited thickness and were kept in the same geometric plane, which restricts the representation of façade designs with additional degrees of freedom, such as rotating elements. Although this aspect does not diminish the relevance of the perceptual effects of façade geometry that were demonstrated in the current study, it brings forth the subject of the applicability of these façade variations in a shading system and its daylight performance, which will be examined in the next chapter.

6.1.3.2 Overview of key findings and comparison with the literature

This study, conducted with 258 participants in Greece and Switzerland, showed that the perception of interior immersive scenes was significantly influenced by the façade design that was applied in the space. Specifically, participants were exposed to variations in the façade geometry, in the sky type, and the spatial context of the scene. Findings revealed the façade geometry as the driving factor in the participants' experience of the space. While the presented façade variation significantly influenced the evaluations for all studied attributes, neither the sky type, the spatial context, or the country where the experiment took place influenced the participants' responses. This result is particularly relevant for the application of the findings in the built environment, as it places the focus on the design of the façade as a tool to shape the experience of the space. Moreover, these façade-driven perceptual effects were shown to be robust both to changes in window size and to the type of space were the façade variations were applied. Specifically, the shape and distribution of the façade openings are shown to be the primary factor, from those studied, that can affect the experience of the space. As a result, the findings of this thesis regarding the perceptual effects of façade variations emerge as powerful index of case studies that can complement the architect's intuition and contribute to the design of spaces that can induce specific subjective impressions to their occupants.

Further analyses of the participants' responses across the six variations of façade geometry revealed important insights on the individual effects of the studied façade characteristics. Across all dependent variables, we observed that the horizontal and vertical stripes (Patterns 1 and 2) do not differ significantly between them, and often they showed identical behavior in terms of their differences with the other façade variations. This is an expected outcome, considering the simple geometric design of these façade variations. These findings are also in alignment with the work by Omidfar et al. [2015], where the evaluations of non-experts regarding the appeal of the lighting resulting from both horizontal and vertical stripes agreed between the two façade variations. However, in [Omidfar et al., 2015], the evaluations of the complexity of the lighting seem to differ between the two façade variations, with the lighting resulting from the horizontal stripes being evaluated as complex, and that from the vertical stripes being evaluated as relatively simple. A possible explanation for this discrepancy is the nature of the question, as in the present study participants evaluated the perception of the space, rather than the lighting in the scene.

When comparing another pair of geometrically similar façade variations, Pattern 2 and Pattern 3, findings showed that Pattern 3 was evaluated as significantly more pleasant, interesting, exciting, calming, and complex compared to Pattern 2. As Pattern 3 differs from Pattern 2 only in having slightly skewed —rather than straight— vertical elements, these results indicate a defining difference between these seemingly similar designs. This difference is translated to an estimated increase of up to 1.09 units ($\beta = -1.09$, $p < 0.0001$) —in the case of how interesting the space is perceived— in the 11-point scale that was used in this study. This simple shift of predominantly vertical elements from straight to slightly skewed results in a significant increase in the dimensions of pleasantness, interest, excitement and calmness of the space, and reveal a design feature that can be used to induce desired responses to occupants. This research direction will be further explored in Chapter 7 through a proof-of-concept study which builds on these findings to develop an alternative shading system to commonly used vertical blinds.

The analysis of the responses to Pattern 4, a façade design with irregularly distributed rectangular openings, revealed that this variation led to a significant decrease in how spacious and bright the space was perceived, as well as in the satisfaction with the amount of view in the space. As all façade variations were designed to have the same perforation ratio, and the openings of Patterns 3, 5 and 6 were also irregularly distributed, this perceptual effect can be considered a result of the shape and the size of the openings. This effect was not found in the previous study in Section 5.1 that employed façade variations which included both horizontal stripes and irregularly distributed rectangular openings. Although the size of the openings was very similar in the two studies, the perforation ratio differed greatly, with 25% of open to total window surface used in the previous study and 40% used in the current study. The limited view access in the previous study led to generally low ratings of satisfaction with the amount of view for all studied façade variations, which was not the case in the present study. As a result, the dissatisfaction with the amount of view might have overshadowed the effects of this façade configuration. Although recent work by Konstantzos et al. [2015] has greatly contributed to our understanding of view clarity through fabrics, little is known regarding the view-related effects of the shape and size of openings of a shading system. The results of our study suggest that the fragmented view through Pattern 4 —compared to the continuous access to view out through Patterns 1, 2 and 3, or the existence of openings with larger dimensions in Patterns 5 and 6— led to a significant dissatisfaction with the amount of view to the outside, which, as expected, influenced the perception of brightness and spaciousness in the scene.

In alignment with the second hypothesis in this study, façade variations of higher complexity led to higher evaluations of interest. Specifically, scenes with Patterns 5 and 6 were evaluated as significantly more interesting than all other variations. Similarly, these two façade variations led to significantly higher evaluations of how exciting is the space compared to all variations except for Pattern 3. These findings are in alignment with the results of our previous studies on the perception of façade characteristics in Chapter 5, as well as the work of Abboushi et al. [2019] where patterns of medium to high complexity —as quantified by the fractal dimension D— were evaluated as more visually interesting. The results of the pairwise analyses in our study suggest three clusters of façade variations, namely Pattern 1 and 2, 3 and 4, and 5 and 6, corresponding to low, medium, and high levels of perceived interest and excitement in the scene. However, the analysis of the reported complexity shows a different distribution of the façade variations in the three groups of low, medium, and high levels of perceived complexity. In particular, Patterns 1 and 2 form a group of low complexity, Patterns 4, 5, and 6 form a group of high complexity, and Pattern 3 is shown to be in between, evaluated as significantly more complex than Patterns 1 and 2, and significantly less complex than Patterns 5 and 6. This outcome demonstrates the need for further work in identifying the characteristics of the façade geometry that induce specific perceptual effects, which will be discussed further in Chapter 7.

The façade-driven perceptual effects that were found in this study are in alignment with the expected effects resulting from the survey of architects that was presented in Section 5.3. As predicted, scenes with Pattern 1 and 2 were evaluated as the least exciting, while scenes with Pattern 3 were evaluated as significantly more calming compared to all variations except Pattern 1. However, Pattern 6, which did not exhibit strong consensus in the survey, emerged along with Pattern 5 as the façade variations that led to the scene being evaluated as the most exciting. Moreover, Pattern 4, which was expected to be the most effective in rendering a space exciting, was shown to be the least calming façade variation. These results show that the direction of participants' evaluations is in agreement with the architects' intuition in the case of patterns of low complexity, and differs in cases of high complexity patterns. Although the results of these two studies cannot be directly compared due to the differences in their method, this outcome indicates potential cases of discord between the perception of experts and non-experts and motivates further systematic study. To this end, we used the responses of the 138 participants in Greece —out of which 57 were trained in architecture— to conduct additional LMM analyses, specifying the expertise in architecture (rather than the country where the experiment took place) as a fixed effect. The results showed no significant effect of expertise in architecture for any of the studied attributes (all $ps > 0.21$, with the exception of reported pleasantness which approached significance with $p = 0.02$). Although this outcome is positive for the robustness of our findings, showing that the façade-driven perceptual effects are applicable to occupants irrespective of their expertise in architecture, it could be influenced by the unbalanced groups sizes, and merits further investigation with dedicated studies. Moreover, this result suggests that the discrepancy in the appraisal of high complexity patterns between the findings of the present study and those of Section 5.3 could be due to the use of different research methods —such as the use of rating rather than ranking questions—, rather than the perception of architects and non-architects.

6.2 Chapter summary

The current chapter built upon the outcomes of Chapters 4 and 5 and investigated the perceptual effects of a wide range of façade configurations that stem from existing buildings, with the aim to provide architects and lighting designers with an empirically-based reference for the occupants' perception of different façade geometry characteristics.

This chapter presented a virtual reality-based experimental study where a total of 258 participants were immersed in interior scenes with varying façade geometry, sky type and spatial context. Moreover, the same study was repeated in Switzerland and Greece to investigate possible regional differences in the participants' perception. Participants were asked to evaluate how pleasant, interesting, exciting, and calming the space was perceived in a verbal questionnaire. In addition, they were asked to assess how complex, bright, and spacious they found the scene, and how satisfied they were with the amount of view in the space. Results demonstrated that the façade geometry significantly influenced the participants' evaluations for all studied attributes, while the spatial context, sky type, and country where the experiment took place did not show a significant effect.

This finding reveals that the façade geometry is the predominant factor, among those studied, in the participants' experience of the space. The absence of a significant effect of sky type, in combination with the use of façade geometry as a within-subject factor, indicate that façade variations influenced the participants' responses under the same sky type, a finding which was consistent across the studied sky conditions.

In addition, further analysis of the perceptual effects of individual façade variations revealed consistent similarities and differences in the perception of certain variations, as well as cases of façade designs that significantly differed from all others regarding the responses they induced. Moreover, the robustness of the perceptual effects of façade geometry was tested against variations in the window size and the type of space in the presented scene. The analysis showed that neither the window size nor the space type influenced these façade-driven perceptual effects, demonstrating the generalizability of the findings of this study across different architectural spaces.

The findings of this chapter provide strong evidence for the importance of the façade design not only as a crucial factor in the building energy consumption and the comfort of occupants, but also as driver of the occupants' experience of the space. In alignment with the outcomes of Chapter 5, this chapter demonstrates that simply changing the design of the façade openings induces significant differences in how the space is perceived. In one of the most striking outcomes, the change of the façade geometry from straight to slightly skewed vertical elements can make the same space appear as significantly more pleasant, interesting, exciting, and calming. Similarly, the façade design is shown to affect traditionally objective* attributes, such as the reported brightness, spaciousness, and satisfaction with the amount of view in the scene.

These outcomes bring forth two main research directions, both relating to the application of the findings of this thesis in the built environment. The first direction regards the identification —and prediction— of the façade characteristics that induce specific perceptual responses. In this chapter, the perceived complexity of the scene is shown to be positively correlated with impressions of interest and excitement. Which features of the façade contribute to this perceived complexity? Could we predict the occupants' impressions from the features of the façade, and thus orchestrate specific responses to an interior space? The second direction relates to the applicability of this new knowledge of façade-driven perceptual effects in the design of a shading system. How can these findings drive the design process? Can we utilize these perceptual effects alongside daylight performance metrics? The next chapter investigates these questions in two parts, the first investigating the potential of existing image-based measures for the prediction of façade-driven perceptual effects, and the second presenting a proof-of-concept study for a novel kinetic shading system that changes states to induce different subjective responses to occupants.

*Here we use the word "objective" to refer to scalable attributes of the environment, following the categorization by Tiller and Rea [Tiller and Rea, 1992] and Hyvärinen [Hyvärinen and others, 2015] for commonly studied attributes in lighting research.

Chapter 7

Extensions of research findings

The findings of Chapter 5 and Chapter 6 provided consistent evidence that the façade design can dramatically alter the way occupants perceive a space, affecting aspects relating to both the emotional effects and the visual appearance of the environment, such as the perceived *interest* and *brightness* of the space. In addition, the façade geometry was shown to be the main driver of the occupants' spatial experience among the studied factors, inducing perceptual effects that are robust to cultural differences, as well as to changes in the sky type, space features, and function of the space. As a result, the façade design emerges as a powerful way to shape the occupants' experience, and the façade variations studied in this thesis can be directly used as a reference to support the exploration of façade design, with a conscious intent regarding space perception. To complement this approach, two additional research directions are discussed in the present chapter to extend the application of these findings in the built environment.

The first research direction pertains to identifying the underlying features of façade designs that can be directly linked to the perceptual effects revealed in this thesis. In other words, this chapter will examine the potential of image-based computational measures of contrast and complexity for anticipating what the occupants' responses to a façade variation will be. The second research direction integrates the expected perceptual effects induced by a given façade pattern (provided by the findings of Chapter 6) to the design of a façade component that would act as a shading system.

This chapter is composed of three sections. The first section begins by introducing existing metrics from the fields of aesthetics, visual perception, and environmental psychology, and continues by evaluating their potential to predict the responses of participants to the façade variations from Chapter 6. Through this analysis, the first section identifies promising image-based metrics which relate to different perceptual effects that are elicited by the façade design. The next section addresses the applicability of these façade-driven effects in a real-world setting. Specifically, it presents a novel kinetic shading system which employs flexible elements to shift between façade design variations with contrasting perceptual effects. By examining the daylight performance of this kinetic shading system, this section illustrates the potential of employing perceptual effects of façade geometry alongside established metrics for visual comfort and energy efficiency in façade design. Lastly, the third section provides a summary of the chapter and outlines the implications of these research directions for the built environment.

7.1 Towards the prediction of façade-driven perceptual effects

Following the consistent evidence for façade-driven perceptual effects from the experimental findings in Chapter 6, the emerging question is whether these effects can be anticipated and related to the visual characteristics of the façade design. To this end, the currents section investigates the capability of computational measures of contrast and complexity as predictors of these façade-driven effects.

The present section starts with an overview of relevant metrics in the field of environmental psychology, aesthetics, and perception, to select an initial set of promising image-based measures. The potential of these measures as predictors of subjective responses is then investigated using a set of testing scenes that depict the same façade variations as those used in Chapter 6. The most promising of these measures are applied to the experimental scenes and compared with the appraisal of these scenes by the participants with the aim to examine the predictive capabilities of the selected measures. Lastly, the results from this analysis are discussed and related to relevant findings from the literature, as well as to promising future research directions.

7.1.1 Overview of computational measures of contrast and complexity

While in Rockcastle et al. [2015; 2017a; 2017b] both the architectural composition and the lighting conditions in the scene were shown to affect occupant impressions of the space, the current work —through its focus on a particular architectural element— shows that the façade design predominates over the lighting conditions in terms of perceptual effects. This finding can be explained by theories of environmental psychology, applied in the context of architectural design elements. As discussed in Chapter 2, the built environment has been suggested as a potential source of fascination, provided that it contains objects that attract the occupants' attention [Kaplan et al., 1993]. Van den Berg et al. [2016] showed that this effect can be achieved with higher levels of ornamentation and detail in building façade. In the subject of façade detail, Stamps [1999] showed that the area covered by small façade elements correlates with ratings of the amount of detail on the drawing of an elevation, and indicated that architectural elements such as balconies and ornaments contributed to impressions of detail more than the material of the façade. In the same vein, the presence of ornamentation and natural patterns —and the lack thereof—, particularly in the building façade, has been suggested as an essential design feature that affects occupants [Salingaros, 1999]. The findings of the previous chapter support this stance, revealing that the geometric features of the façade can significantly alter how an occupant experiences the same space.

The question that emerges is whether these effects of the façade design on occupant perception can be anticipated, and thus possibly extended to additional façade variations than those studied in the present thesis. Consequently, it is of particular interest to investigate the potential of computational measures of image characteristics as correlates of the façade-driven perceptual effects that were found in Chapter 6. Although previous studies aiming to quantify the impressions of occupant in daylit environments have focused primarily on contrast measures [Demers, 1998; Parpairi et al., 2002; Rockcastle and Andersen, 2013a; Rockcastle, 2017], the experimental findings of the present thesis, in combination with the literature, suggest that the complexity of the visual stimulus is an equally important feature. To this end, for this analysis, we will employ not only contrast measures, which focus on differences in pixel intensity, but also complexity measures, which aim to quantify the diversity of elements in an image.

7.1.1.1 Contrast measures

Algorithms that aim to measure contrast perception in images can be broadly classified into global and local methods. Global contrast measures, such as the Michelson [Michelson, 1927] or Root Mean Square (RMS) [Pavel et al., 1987] metrics, evaluate the contrast across an image without considering the spatial distribution of pixel intensities. On the other hand, local contrast measures evaluate contrast by considering pixel neighborhoods or localized features of the image.

The metric Modified Spatial Contrast, mSC, is a local measure developed by Rockcastle et al. [2017a] that evaluates the contrast distribution in the occupant's field-of-view by considering neighboring pixels and dividing the resolution of the image at multiple levels (sub-sampling). In experimental studies by Rockcastle et al. that compared the evaluation of simulated daylit architectural interiors with the corresponding contrast measure, this metric has been shown to predict the judgment of a space as *calming* or *exciting* [Rockcastle et al., 2017a; Rockcastle, 2017; Rockcastle et al., 2017b]. This groundbreaking work demonstrated for the first time that the perceptual impressions of occupants in a space can be predicted. This metric has been demonstrated to successfully distinguish the perceptual differences between distinct spaces and lighting conditions [Rockcastle, 2017], but its sensitivity has not been tested for small changes in architectural elements —such as the façade openings— within the same space. The metric RAMMG, another local contrast measure that was developed by Rizzi et al. [2004], has also been related to impressions of excitement in the studies by Rockcastle et al. [2015; 2017a; 2017; 2017b]. Both mSC and RAMMG have also been found to correlate significantly with impressions of complexity [Rockcastle et al., 2017a]. In addition, the global metric RMS [Pavel et al., 1987] has been related to the perceived complexity of simulated architectural interiors [Rockcastle et al., 2017a] as well as photographs of natural and urban scenes [Kacha et al., 2013; Marin and Leder, 2013; Cavalcante et al., 2014; Marin and Leder, 2016].

7.1.1.2 Complexity measures

The complexity of a visual stimulus has been revealed to relate to other perceptual impressions. Specifically, ratings of subjective complexity have been shown to correlate to impressions of arousal —such as how calming, exciting, or fascinating is a stimulus— in studies using diverse visual stimuli [Marin and Leder, 2013, 2016; Rockcastle, 2017]. Moreover, Berlyle [Berlyne, 1971] suggested a relationship of an inverted U curve between a complex and a pleasing stimulus, with stimuli of low and high complexity being evaluated as less pleasant compared to stimuli of medium complexity.

This inverted U-shape between pleasantness and complexity has been confirmed in experimental studies investigating the appraisal of abstract patterns [Friedenberg and Liby, 2016], paintings [Forsythe et al., 2011; Saklofske, 1975], and images of nature [Spehar et al., 2003; Taylor et al., 2005]. Such a relationship has also been demonstrated in studies that investigated the perception of building façades, a result that is particularly relevant for this thesis. Specifically, Akalin et al. [2009] compared evaluations of preference and impressiveness using photographs of exterior façades with varying complexity, defined as the number of alterations from the original design, such as the addition of decorative architectural elements. Results showed a higher preference for envelopes of intermediate complexity, even though those of higher complexity were evaluated as more impressive. Similarly, Imamoglu [2000] examined ratings of preference and pleasantness for drawings of exterior façades with increasing complexity, interpreted as the number of architectural elements and level of detail shown in the elevation, and found that drawings representing intermediate levels of complexity were more positively evaluated. Lastly, in the context of façade patterns, the findings of Abboushi et al. [2019] showed the same trend between visual preference and perceived complexity for façade and daylight patterns with varying fractal complexity.

Research on quantifying the visual complexity has revealed a number of computational image-based measures that correlate successfully with complexity ratings. A family of such measures are image compression methods, and their association with perceived complexity relates to the field of information theory. Following the definition of Kolmogorov complexity, which is the length of the shortest program that can describe an output [Solomonoff, 1986], the size of a compressed image can be used as a proxy for complexity. According to this principle, the higher the file size of the compressed image, the higher the complexity of that image. This relation has been confirmed in multiple studies using a number of different image formats (such as GIF, JPEG, PNG, and TIFF) [Forsythe et al., 2008; Marin and Leder, 2013; Cavalcante et al., 2014; Machado et al., 2015; Marin and Leder, 2016].

Another family of promising measures are edge detection algorithms, which detect differences in intensity to identify the edges of the elements in an image. The level of perceived complexity is expected to increase with the number of edges present in an image [Forsythe et al., 2003]. As edge detection methods rely on differences in intensity to detect edges in an image, it could be argued that they are also contrast measures; however, as they aim to evaluate the *complexity* of differences in intensity, they are considered as complexity measures in this thesis. Various edge detection algorithms, such as the Sobel [Sobel, 1990] and Canny [Canny, 1986] methods, as well as the contour-based measure Perimeter Detection [Forsythe et al., 2003], have been demonstrated to correlate with impressions of complexity in photographs of natural and urban environments [Marin and Leder, 2013, 2016; Cavalcante et al., 2014]. One of the most common measures is the total number of pixels that correspond to the detected edges in an image (often referred to as "RAW"). Edge detection methods are often combined with image compression, resulting to a measure equal to the file size of the perimeter image [Marin and Leder, 2013; Machado et al., 2015]. Two other notable measures that have related to both impressions of complexity and affective responses are the entropy of the histogram of image intensity values and the fractal dimension of the image. Specifically, the image entropy has been found to correlate moderately with the reported complexity and fascination of simulated urban scenes [Lindal and Hartig, 2013], as well as with ratings of complexity of photographs of natural scenes [Marin and Leder, 2013]. The fractal dimension D quantifies the presence of self-similar patterns across a range of magnification levels of an image, which characterizes fractal objects [Mandelbrot and Wheeler, 1983]. This measure has been shown to have a linear relationship both with impressions of complexity in different visual stimuli [Hoeger, 1997; Kacha et al., 2013] as well as with ratings of visual interest towards light patterns [Abboushi et al., 2019].

7.1.1.3 Promising measures from the literature

The overview of relevant studies in the previous section highlighted a number of metrics which have been identified as promising regarding their relation with impressions of complexity, calm, interest, excitement, or fascination with the scene. Table 7.1 presents a synopsis of these findings, grouped by computational measure and perceptual attribute.

Table 7.1 shows that the majority of promising metrics have been related to perceived complexity. Measures based on the file size of different image formats (GIF, JPEG, PNG, TIFF file size) seem particularly promising as predictors of perceived complexity. Similarly, the sum of white pixels of binary images after edge detection (RAW-CANNY1986, RAW-PERIM4), as well as the file size of these binary images (PNG-PERIM4, JPEG-SOBEL) have been shown to correlate significantly with the evaluations of complexity in studies using photographs of nature, objects, and urban scenes as stimuli. Following these observations, as well as the identification of certain variations in the edge detection methods used by different studies that will be explained further in the Section 7.1.2.2, we will employ five edge detection methods.

Table 7.1 – Overview of promising image-based metrics. Metrics using the sum of white pixels in a binary image are noted with "RAW-", while metrics using the file size of a particular image format are noted with "IMAGEFORMAT-", followed by the edge detection method.

Image-based metric	Complexity	Arousal**
GIF (file size)	Forsythe et al. (2011)* Marin and Leder (2013)*	
JPEG (file size)	Forsythe et al. (2008) Forsythe et al. (2011)* Cavalcante et al. (2014)* Machado et al. (2015)* Marin and Leder (2016)*	
PNG (file size)	Marin and Leder (2016)*	
TIFF (file size)	Marin and Leder (2016)*	
RAW-CANNY1986	Forsythe et al. (2008) Marin and Leder (2013)* Marin and Leder (2016)*	
RAW-PERIM4	Forsythe et al. (2008) Forsythe et al. (2011)* Marin and Leder (2013)* Cavalcante et al. (2014)* Marin and Leder (2016)*	
PNG-PERIM4	Marin and Leder (2013)*	
JPEG-SOBEL	Machado et al. (2015)	
Entropy	Marin and Leder (2013)* Lindal and Hartig (2013)*	Lindal and Hartig (2013)*
Fractal D	Hoeger (1997) Kacha et al. (2013)*	Abboushi et al. (2019)*
RMS	Kacha et al. (2013)* Marin and Leder (2013)* Cavalcante et al. (2014)* Marin and Leder (2016)* Rockcastle et al. (2016)*	Rockcastle et al. (2016)*
RAMMG	Rockcastle et al. (2016)*	Rockcastle et al. (2015)* Rockcastle et al. (2016)* Rockcastle et al. (2017)
mSC5	Rockcastle et al. (2016)*	Rockcastle et al. (2016)* Rockcastle et al. (2017)*

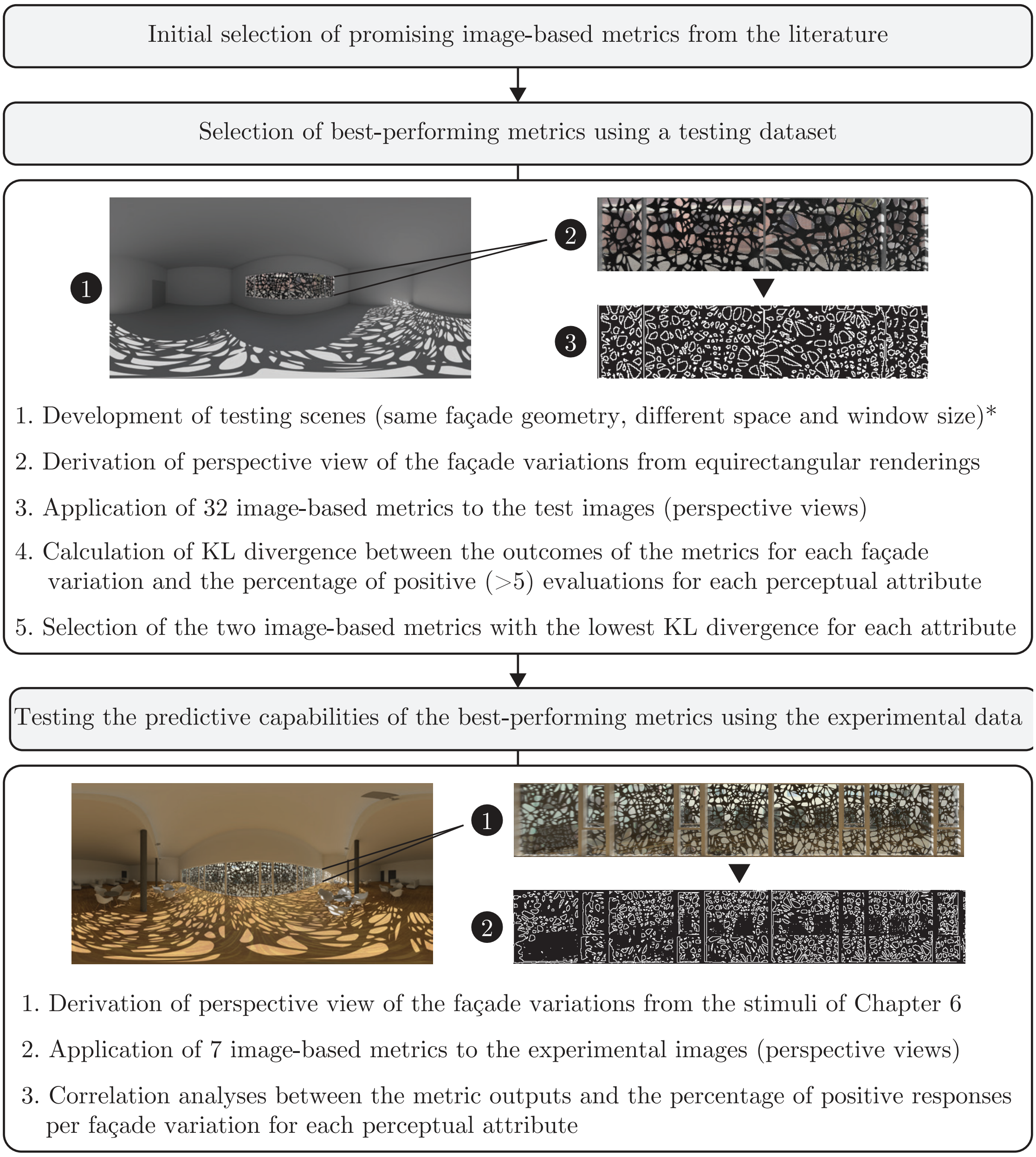
* Studies that used stimuli depicting natural, urban, or interior scenes in daytime are marked with an asterisk.
** The category "Arousal" contains studies that investigated impressions of excitement, calm, or fascination.

Specifically, we will use two variations of both the Canny edge detection method, which was shown to correlate consistently with subjective evaluations of complexity [Forsythe et al., 2008; Marin and Leder, 2013, 2016] and the perimeter detection introduced in Forsythe et al. [2003; 2008] and reported as being successful in predicting subjective complexity in multiple studies [Forsythe et al., 2008, 2011; Marin and Leder, 2013; Cavalcante et al., 2014; Marin and Leder, 2016]. In addition, we will employ the Sobel method [Sobel, 1990], which was found to be promising in combination with JPEG compression across multiple types of image content in Machado et al. [2015]. Lastly, we will follow the methodology in Marin and Leder [2013] to generate four measures for each edge detection method, corresponding to the sum of white pixels in the resulting binary images, as well as their file size when converted into JPEG, PNG, and TIFF image formats.

A number of metrics —namely entropy [Marin and Leder, 2013; Lindal and Hartig, 2013], fractal dimension [Kacha et al., 2013; Abboushi et al., 2019], as well as the contrast measures RMS [Kacha et al., 2013; Cavalcante et al., 2014; Marin and Leder, 2013, 2016], RAMMG [Rockcastle and Andersen, 2015; Rockcastle et al., 2017a,b] and mSC5 [Rockcastle et al., 2017a,b]— have been shown, either within the same study or in different investigations, to relate both to impressions of complexity and to attributes linked with emotional arousal, such as excitement and fascination. In addition, these findings were demonstrated with photographs of natural or urban scenes [Kacha et al., 2013; Cavalcante et al., 2014; Marin and Leder, 2013, 2016] or simulated architectural interiors [Rockcastle and Andersen, 2015; Rockcastle et al., 2017a,b], and are thus particularly promising for the present study. As the metrics mSC5 and RAMMG have been suggested to be interchangeable due to the high correlation (r = 0.96) between them [Rockcastle et al., 2017b], in this study we will employ only mSC, and analyze separately the results for five sub-sampling levels. Moreover, we will investigate the potential of the measures of entropy, fractal dimension, and RMS contrast. Lastly, the global contrast measure Michelson [Michelson, 1927] will be also employed as a reference, resulting to a total of 32 variations of studied image-based metrics.

7.1.2 Using computational measures to predict subjective responses to façade geometry

Following the initial selection of image-based metrics from the literature, this section presents further work in testing the potential of these metrics as predictors of façade-driven perceptual responses. In order to investigate the predictive capabilities of the image-based measures identified in Section 7.1.1.3, this section begins with the development of a testing dataset, containing scenes with the same façade variations as those employed in the experiments of the previous chapter and differing in terms of space, window size, and furniture. The equirectangular renderings depicting these scenes are then used to derive perspective views of the façade, and the studied image-based metrics are applied to these perspective views. The outputs of this analysis are used to identify the best-performing metrics using a similarity measure between the distributions of the metrics and the percentage of positive responses for each perceptual attribute from the experimental data of Chapter 6. The selected metrics are then applied to the perspective views of stimuli employed in the previous chapter, and correlation analyses are conducted to determine the predictive capabilities of these metrics. Figure 7.1 provides an outline of this workflow, which is described in detail in the following sections.



* Compared to the scenes from the experimental phase A in Chapter 6.

Figure 7.1 – Illustration of the workflow to investigate the predictive capabilities of image-based metrics.

7.1.2.1 Development of a testing dataset

The aim of this section is to investigate the potential of the aforementioned computational metrics —which were identified as promising from the literature— for anticipating occupant responses to façade design variations. To this end, the experimental stimuli and participant responses from the experimental phase A described in Chapter 6 will be used to examine the relationship between the studied metrics and the collected subjective ratings across façade variations. In order to retain the reliability of this dataset, which will be referred to as “experimental dataset” in the current section, a new set of scenes was created to test the initial set of metrics and select the most promising ones for further analysis.

These new scenes depict the same façade and sky type conditions as those used in the experimental dataset, but differ in the window size, dimensions, furniture, and materials of the space, in order to provide a sufficiently different image. To this end, a space with a smaller volume, a smaller window, and no furniture, shown in Figure 7.2, was modeled using the software *Rhinoceros*. The dimensions of the space (a width of 6.5 meters, length of 10 meters, and height of 3.5 meters) were chosen to be approximately half of those of the multi-use space used in the experiments of the previous chapter, to ensure a sufficiently different scene.

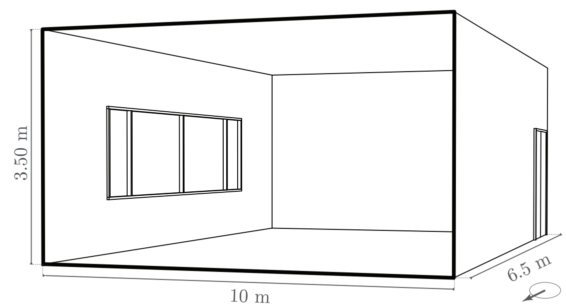


Figure 7.2 – Illustration of the space used for the generation of the testing image dataset.

The six façade geometry variations from Section 6.1.1.2 were applied to the new space and modified accordingly to ensure a 40% (± 2) perforation ratio (open to total window area), in correspondence with the stimuli in the experimental dataset. *DIVA-for-Rhino* was used to apply a combination of default DIVA materials for the ceiling and interior walls and the façade and glazing material that was used in the experimental dataset. An overview of the *Radiance* materials can be found in Table 7.2. The three *Radiance* sky descriptions that were used in Section 6.1.1.2 were employed to create a total of 18 combinations of façade geometry and sky type. Each scene was exported to *Radiance*, and a viewpoint corresponding to the middle of the room and the second lowest eye height from Table 6.4 was specified for the simulations. In order to further differentiate the test scenes from in the experimental dataset, a new HDR photograph of view out under overcast conditions —courtesy of Clotilde Pierson, captured in field studies described in [Pierson et al., 2018]— was mapped to the *Radiance* sky. Lastly, to reduce simulation time, the parameter -aa was increased by a factor corresponding to the ratio between the volume of the previous space in Section 6.1.1.2 and the new smaller scene. The volume (bounding box) of the two scenes was calculated with the *Radiance* function *getbox*. With the exception of -aa, all other *Radiance* rendering parameters were kept the same as in Section 6.1.1.2 to ensure high accuracy and image quality, and are shown in Table 7.3.

Table 7.2 – *Radiance* material properties for the main surfaces.

Surface	Type	R	G	B	Reflectance	Specularity	TVis
Ceiling	plastic	0.70	0.70	0.70	94%	0	
Floor	plastic	0.52	0.52	0.52	52%	0	
Walls	plastic	0.50	0.50	0.50	50%	0	
Façade	plastic	0.25	0.25	0.25	25%	0	
Window	glass	0.654	0.654	0.654			60%

Table 7.3 – *Radiance* rpict parameters for the equirectangular projection renderings.

-dj	-ds	-dt	-dc	-dp	-st	-ab	-aa	-ar	-ad	-as	-lr	-lw
0.02	0.05	0.05	0.5	256	0.5	4	0.05	32	50000	25000	4	0.000003

Resolution: 12960x12960 pixels.

The same procedure as in Section 6.1.1.2 was followed to generate 360° over-under stereo equirectangular projection PNG images, tone-mapped with the Reinhard02 algorithm, for each of the 18 test scenes. An example of the resulting simulations can be found in 7.3 (top), showing two combinations of the façade and sky type variations, while the total set of images can be seen in Appendix A.8. An initial testing of the different metrics showed that they are all —as expected— particularly sensitive to changes in the lighting conditions and the presence of sun patches in the scene. However, the findings from Section 6.1.1.2 demonstrated that the façade geometry, rather than the sky type, was the predominant factor influencing the participant responses. To address this issue, the metrics in all upcoming analyses are applied solely to the area of the window, utilizing a section of the original images. This approach greatly increases the sensitivity of the applied metrics to the object of interest, i.e. the geometry of the façade openings. At the same time, it permits to retain differences between images resulting from scenes with the same façade geometry and varying lighting conditions, view out, or furniture, through reflections or direct changes in the content of the image. This is an advantage, since the resulting representation of the scene is closer to the image seen by occupants, which is not the case when analyzing the complexity of façade configurations through purely geometric representations.

As, to the author's knowledge, there is currently no widely available automated procedure to separate the window from the rest of the scene, this procedure was conducted by using custom scripts and manually specifying the area corresponding to the window. Specifically, the equirectangular renderings for the left eye were used to extract a 160°x160° perspective image of 2304x2304 pixels* of the view facing the window of the space using the *Equi2Persp* script in *Python*. The resulting images were cropped using *ImageMagick* to contain only the façade, resulting to a perspective view image with a resolution of 395x88 pixels. These perspective view images of the façade are illustrated in Figure 7.3 (bottom).

*This resolution was chosen to provide comparable images with the studies in [Rockcastle and Andersen, 2015; Rockcastle et al., 2017a] in terms of the angle of view that is represented in each pixel, for the resolution-sensitive metric mSC.

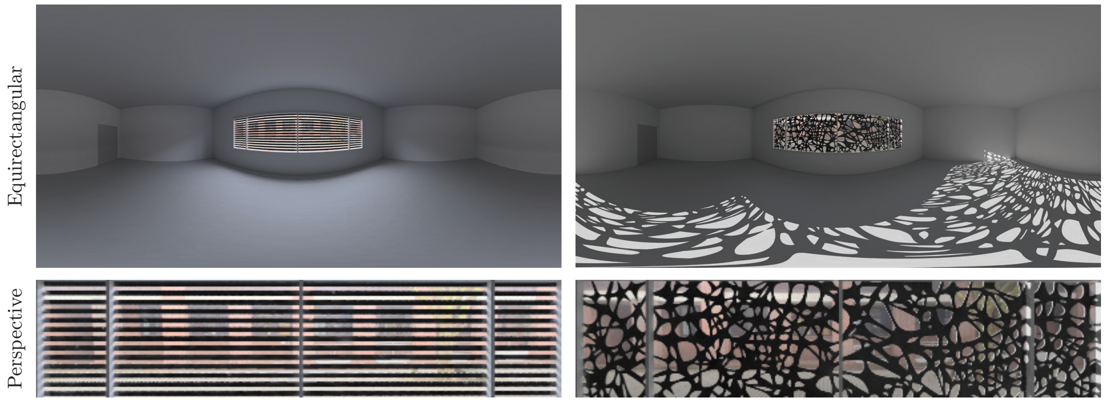


Figure 7.3 – Example of the renderings of the testing scenes with Pattern 1 and overcast sky (left) and Pattern 6 and clear sky with low sun angle (right). The equirectangular projection images are shown in the top row, and the perspective view images, cropped to show only the façade, are shown in the bottom row. The pictured projections correspond to the left eye view.

7.1.2.2 Calculation of image-based measures

This section will present a short overview of the workflow for the calculation of the studied metrics. For all metrics that use file size as a measure, we employ both lossy and lossless compression formats following the approach in previous studies [Forsythe et al., 2011; Marin and Leder, 2013, 2016]. The JPEG and TIFF image formats were generated using the function *imwrite* in *MATLAB* using default settings, which ensure that the JPEG file is compressed with a lossy compression method, while the TIFF file is compressed with a lossless compression method. As *MATLAB* supports only 8-bits images as outputs for the GIF format, the conversion from PNG to GIF was conducted in the software *ImageMagick*, using default settings. The file size for all image formats was calculated by using the *MATLAB* structure property "*.bytes*".

Moreover, the original PNG image files were converted into lossless BMP format images, to ensure compatibility with the metric mSC [Rockcastle and Andersen, 2015; Rockcastle et al., 2017a,b]. For consistency, all image-based metrics (with the exception of the four file size-based measures) were applied on grayscale BMP format images, with additional steps to create binary images and detect edges when necessary. All image-based analyses were conducted in *MATLAB* R2017b using the Image Processing Toolbox. Figure 7.4 provides a schematic outline of the main processes for the calculation of the image-based metrics.

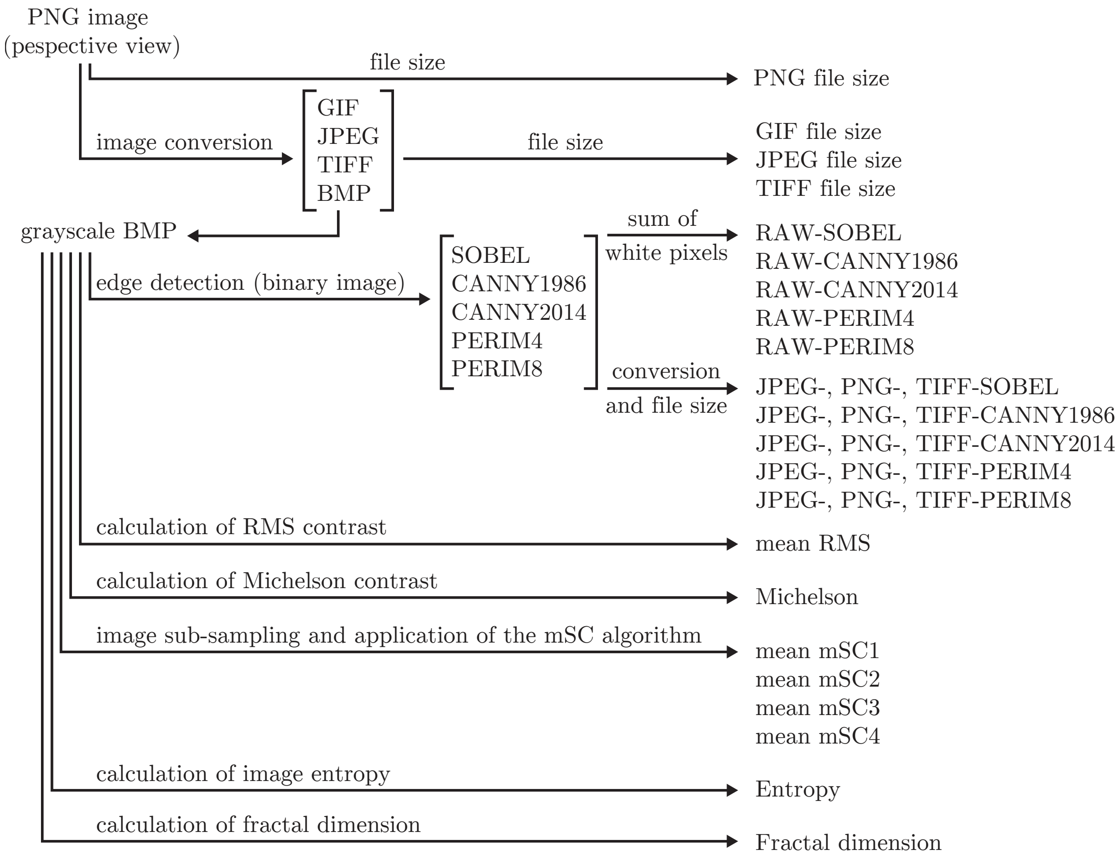


Figure 7.4 – Schematic illustration of the workflow for the application of the 32 image-based metrics.

The SOBEL edge detection method [Sobel, 1990] was applied using the function *edge* and specifying "Sobel" as the preferred method. In order to conduct perimeter detection for the PERIM4 and PERIM8 methods, a different procedure was followed according to Marin and Leder [2013]. The grayscale input image was first used to calculate a global image threshold using Otsu's method [Otsu, 1979] with the function *graythresh*. This threshold was then specified in the function *imbinarize* to create a binary image with values of one corresponding to white, and values of zero corresponding to black. Lastly, the function *bwperim* was used to detect the perimeter of objects in that image. In order for a pixel to be considered as belonging to the perimeter of an object, it should have a value of one (corresponding to white) and be connected to at least one pixel with a value of zero (corresponding to black). The number of connected black pixels is called pixel connectivity, and the default value, which is used in several studies [Marin and Leder, 2013, 2016], is four. However, Forsythe et al. [2003] showed differences in the images resulting from a pixel connectivity of four or eight, and motivated the use of both settings to create two versions of perimeter edge detection, referred to as PERIM4 and PERIM8 in this chapter. An example of the output of the PERIM8 perimeter detection method can be seen in Figure 7.5.

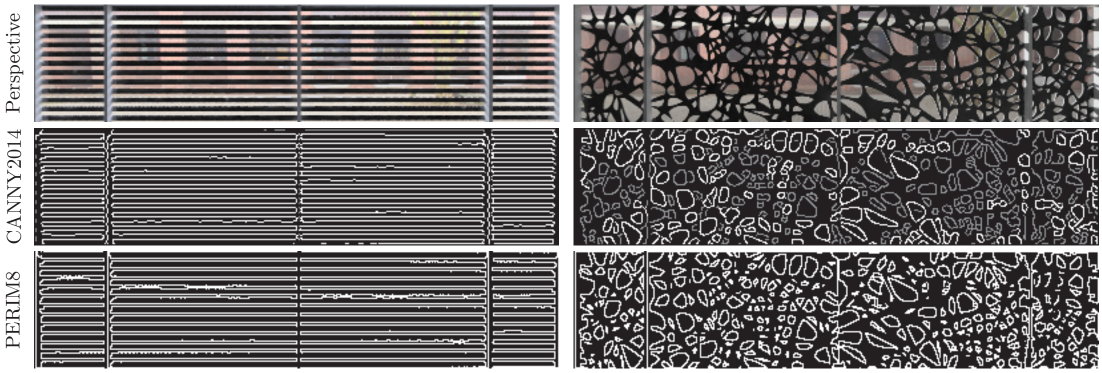


Figure 7.5 – Example of two test conditions, showing Pattern 1 with overcast sky (left) and Pattern 6 with clear sky and low sun angle (right). The top row shows the retrieved perspective images of the façade from the corresponding equirectangular renderings shown in Figure 7.3, while the two bottom rows show the binary images resulting from the CANNY2014 and PERIM8 methods.

Two variations were also used for the application of the Canny edge detection [Canny, 1986], resulting to the methods CANNY1986 and CANNY2014. Using the grayscale image as input, the function *edge* was used to produce binary images with CANNY1986, using default settings and specifying the edge detection method "Canny". A variation of this method that differentiates between weak and strong edges, suggested in Berman et al. [2014], was shown to be an important predictor in the perception of naturalness in photographs of natural and urban scenes [Kardan et al., 2015]. This method was replicated in the current study following the procedure described in Kardan et al. [2015]. Specifically, the function *edge* (with the "Canny" setting) was used to extract the automatically computed lower and upper thresholds for edge detection. These thresholds were multiplied by 1.6 and 0.8, respectively, to detect strong and weak edges in the image. The same function was repeated twice, using as input the grayscale image and specifying as thresholds either the high or low sensitivity threshold. The resulting matrices were added and divided by two, creating a matrix with values of 0 where the pixel was not identified as an edge in either the high or low sensitivity threshold, values of 0.5 where the pixel was detected as an edge solely in the high sensitivity threshold (indicating a faint edge), and values of 1, indicating a salient edge that is detected also with the low sensitivity threshold. These three levels of edge detection sensitivity, corresponding to black, gray, and white pixels, can be seen in Figure 7.5.

Lastly, the five aforementioned edge detection methods (SOBEL, PERIM4, PERIM8, CANNY1986, CANNY2014) were used to generate four metrics per method, according to the procedure followed in Marin and Leder [2013]. Specifically, the binary images resulting from the application of studied edge detection methods, were used to calculate the sum of white pixels in the image (referred to as "RAW-"), and were saved as JPEG, PNG, and TIFF image formats to calculate the corresponding file sizes (referred to as "JPEG-","PNG-", and "TIFF-").

In addition to these metrics, two global contrast measures, Michelson [Michelson, 1927] and RMS [Pavel et al., 1987], were calculated. While the metric RMS is used differently in Rockcastle et al. [2017a] and Marin and Leder [2013; 2016], applied to the whole image in the former and in pixel neighborhoods of 15x15 pixels in the latter, in this study we chose the former method, as it has been shown to correlate both with impressions of complexity and excitement [Rockcastle et al., 2017a]. To this end, a custom script was employed to calculate the root mean squared (RMS) difference of individual pixel intensities from the mean on the grayscale images, according to Pavel et al. [1987]. Similarly, the Michelson contrast was calculated using the ratio of the maximum minus the minimum pixel intensity, divided by the sum of the maximum and the minimum pixel intensity [Michelson, 1927]. The metric mSC, which was shown to relate to both impressions of complexity and excitement, was calculated across five sub-sampling levels using *MATLAB* functions provided by the author of the metric [Rockcastle, 2017]. In addition, the entropy of the intensity histogram of the grayscale images was calculated using the function *entropy*. Lastly, the binary file of the grayscale image (generated with *imbinarize* and a threshold of 0.5) was used to compute the fractal dimension D with Moisy's [2008] *MATLAB* implementation of the boxcounting method, described in [Taylor et al., 2005].

7.1.2.3 Selection of the best-performing measures using the testing dataset

Following the method in Rockcastle et al. [2015; 2017a], the percentage of positive responses for each perceptual attribute was used as the reference for the assessment of the studied metrics. In light of recent studies that have emphasized the importance of individual differences in the preference for complexity [Güçlütürk et al., 2016], percentage of positive responses is particularly relevant for design applications, as it allows the identification of consensus towards a specific direction of the attribute.

In order to specify the reference for the tested image-based metrics, we calculated the percentage of ratings higher than 5 (the middle point in the rating scale from 0 to 10) for each façade variation, grouping scenes with the same façade geometry and varying sky type and spatial context. The resulting mean and standard deviation of the percentage of positive ratings across all façade variations for the evaluations of how *pleasant*, *interesting*, *exciting*, and *complex* is the space are shown in Figures 7.6 and 7.7. As can be seen from these figures, the distribution of the percentage of positive ratings is very similar to that of the median ratings shown in Figure 6.9.

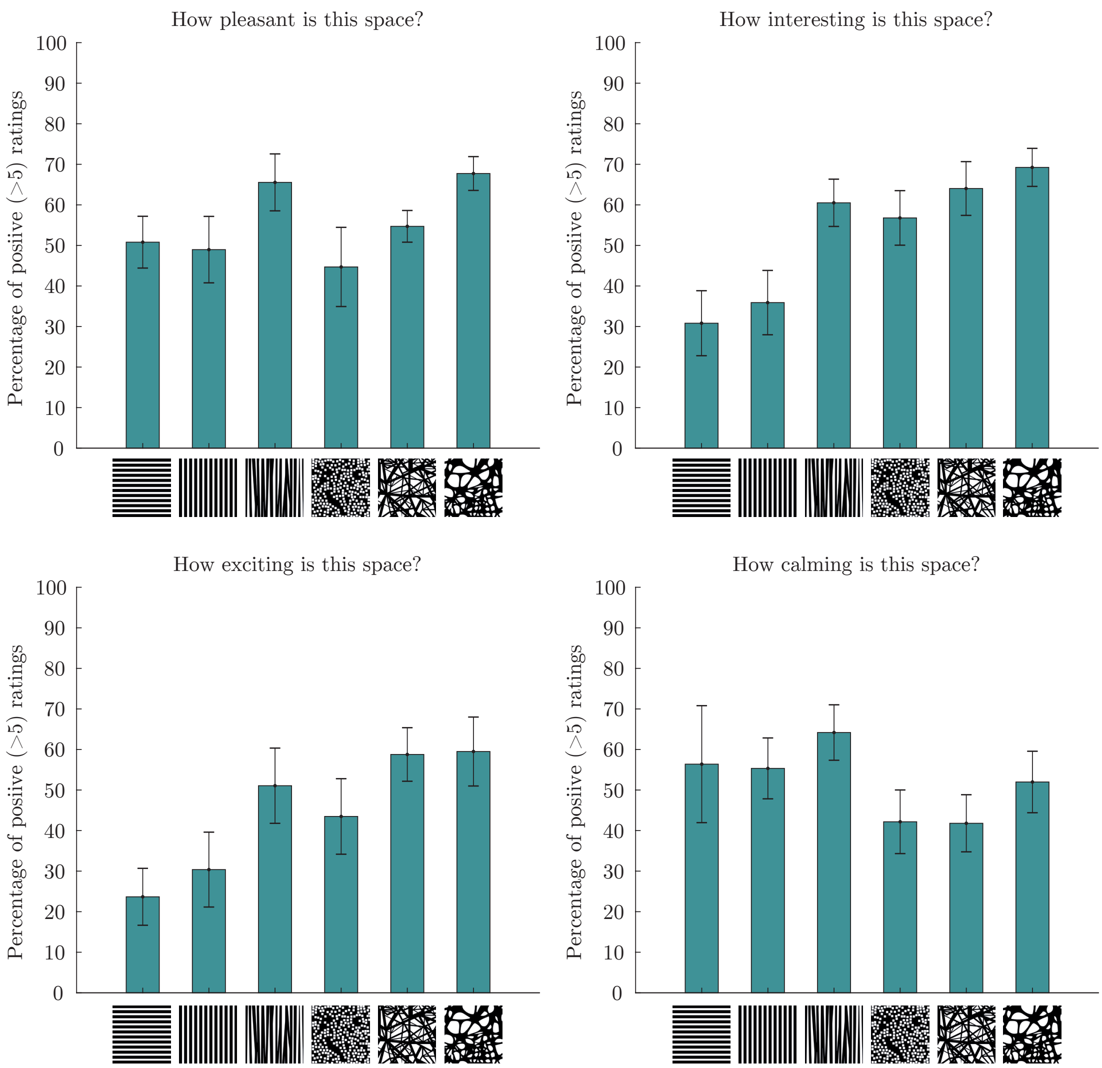


Figure 7.6 – Mean and standard deviation of the percentage of positive responses (>5, on a scale from 0 to 10) for each façade variation, averaged across sky type and spatial context conditions. Results are shown for the ratings of how pleasant, interesting, exciting, and calming is the space, from the experimental phase A in Chapter 6.

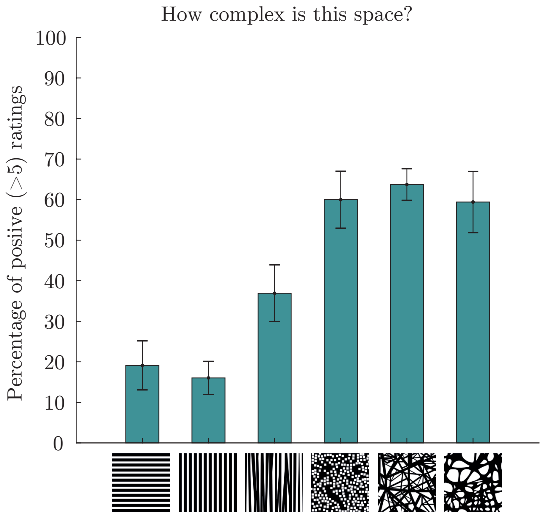


Figure 7.7 – Mean and standard deviation of the percentage of positive responses (>5 on a scale from 0 to 10) of how complex the space was perceived for each façade variation, averaged across sky type and spatial context conditions.

The calculation of the Pearson correlation coefficient between the percentage of positive responses in the attributes *exciting* and *interesting* across façade variations, shown in Figure 7.6, showed a statistically significant strong positive correlation ($\rho = 0.98$, $p = 0.0004$) between the two attributes. This finding agrees with previous work investigating the perception of 360° VR scenes of interior grayscale architectural spaces, which showed a significant positive correlation ($\rho = 0.77$) between evaluations of excitement and interest [Rockcastle, 2017]. Similarly, the percentage of positive ratings regarding how *interesting* and *complex*, as well as how *exciting* and *complex* the space was perceived showed a positive correlation (interesting-complex: $\rho = 0.88$, $p = 0.018$, exciting-complex: $\rho = 0.85$, $p = 0.032$) but fail to meet the Bonferroni-corrected significance level of 0.017 for the three analyses. Figure 7.8 (left) shows the distribution of mean ratings of excitement against the mean ratings of complexity, averaged across all stimuli with the same façade variation. The data points corresponding to each façade geometry variations are represented with the simplified designs of the façade for ease.

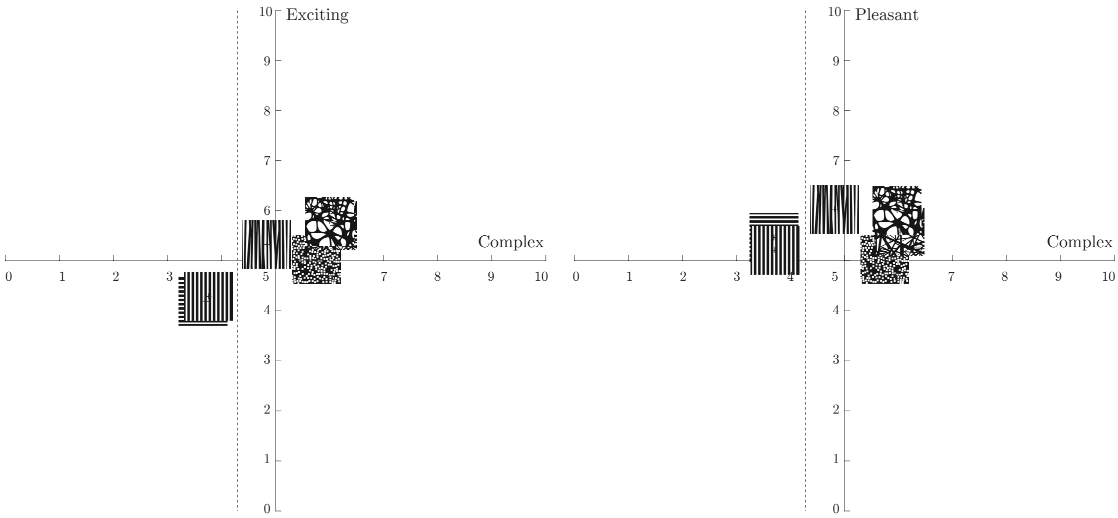


Figure 7.8 – Mean responses for each façade variation across sky type and spatial context conditions for the evaluations of how exciting or pleasant (y axis) and how complex (x axis) the space is perceived. The distribution of responses shows that ratings of excitements generally increased with ratings of complexity. On the other hand, scenes with façade variations that were perceived as moderately complex were also generally perceived as the most pleasant, showing an inverted U-shaped curve between these two dimensions. The dotted line indicates a possible lower bound of positively perceived complexity, below which scenes were evaluated as less pleasant and less exciting.

As discussed earlier in Section 7.1.1, the relation between perceived *complexity* and *pleasantness* (or preference) is of particular interest. To investigate this relation further, Figure 7.8 shows the mean ratings for the evaluations of how *pleasant* the space was perceived plotted against the corresponding mean evaluations of how *complex* the space was perceived. This figure demonstrates that the relation between these two attributes closely resembles an inverted U curve, with the façade designs that were rated as high or low in complexity being simultaneously evaluated as less pleasant, and the façade design with a moderate degree of perceived complexity being evaluated as the most pleasant. This relationship between the two attributes provides partial evidence that Berlyle's hypothesis of an inverted U curve between perceived complexity and pleasantness [Berlyne, 1971] might also apply to the perception of architectural features. However, Pattern 4, the façade variation with small and irregularly distributed rectangular openings, is an outlier, as it led to evaluations of both moderate complexity and moderate pleasantness. This finding suggests that the size of the façade openings, in addition to the complexity of their composition, is another important factor contributing to the pleasantness of the space. However, the relation between impressions of pleasantness and complexity, as well as of excitement and complexity, can be used to derive a possible lower bound of perceived complexity, shown in Figure 7.8, below which scenes are evaluated more negatively.

In order to further investigate the potential of computational measures as predictors of subjective responses, the selected 32 metrics were calculated for each image in the testing dataset. In a second step, the mean value across each of the three sky types was calculated for each façade variation. The resulting output can be found in Appendix A.9. This procedure resulted in a unique distribution of metric outputs across façade variations for each metric, similar to Figure 7.6. Following this step, we examined the similarity between the distributions of the metric outputs, applied to the testing scenes, and our reference for the participant responses, shown in Figures 7.6 and 7.7. Although the metrics are applied to different scenes that those seen by the participants, to ensure the reliability of experimental image dataset for the following analyses, the relative perceptual differences between façade variations are expected be comparable to those elicited by the experimental stimuli based on the findings of the previous chapter.

As an initial visual inspection of the data showed many metric output distributions that appeared similar to the reference distribution of participant responses, we conducted the selection process using an objective measure of distance between the tested and target distributions. Specifically, in order to select the most promising metrics, we employed the Kullback-Leibler (KL) divergence [Kullback and Leibler, 1951], a widely used measure for the evaluation of differences between two probability distributions. An outcome of a zero KL divergence indicates that two distributions are identical. This measure has been used to examine the similarity of model outputs to a reference distribution of participant ratings in the field of linguistics [Kluth and Schultheis, 2018], and, in the context of our study, it will be employed to identify the most promising image-based metrics in terms of their similarity with the participant responses. A promising metric would have a low KL divergence, and could have either a positive or an inverse relationship with the reference distribution. As KL is a distribution-wise asymmetric measure, this measure was calculated between each metric output distribution and the reference distributions shown in Figures 7.6 and 7.7, as well as for the inverted reference distributions with a reversed x axis. Each distribution was normalized to a sum of one prior to the calculation.

Figure 7.9 shows the KL divergence calculated for the normalized distribution of the frequency of positive responses across façade variations, (ordered from the first —Pattern 1— to the last —Pattern 6— variation), as well as for the reverse distribution of participant responses, for each of the studied perceptual attributes. Darker colors represent a higher divergence, and white a smaller divergence between the pairs of distributions, the latter signifying a promising metric with high similarity to the participant responses. The two metrics resulting to the lowest KL divergence for every attribute —taking into account both distributions of the frequency of positive responses and comparing the fourth decimal place when necessary— were selected for further investigation and are highlighted in the figure.

KL Divergence calculated using the frequency of positive responses across façade variations ordered from the first (Pattern 1) to the last (Pattern 6) studied façade geometry

	Pleasant	Interesting	Exciting	Calming	Complex
GIF	0.011	0.033	0.041	0.016	0.128
JPEG	0.032	0.020	0.027	0.063	0.054
PNG	0.019	0.023	0.028	0.044	0.078
TIFF	0.014	0.046	0.058	0.012	0.144
Fractal D	**0.011**	0.036	0.046	0.014	0.128
JPEG-CANNY2014	0.050	0.017	0.023	0.090	0.030
PNG-CANNY2014	0.228	0.122	0.122	0.316	0.036
TIFF-CANNY2014	0.139	0.148	0.144	0.133	0.302
RAW-CANNY2014	0.014	0.057	0.069	**0.009**	0.162
JPEG-CANNY1986	0.051	0.019	0.025	0.090	0.033
PNG-CANNY1986	0.208	0.109	0.110	0.291	0.030
TIFF-CANNY1986	0.120	0.134	0.133	0.110	0.291
RAW-CANNY1986	0.021	0.076	0.088	0.009	0.198
Entropy	0.011	0.043	0.053	0.012	0.139
JPEG-PERIM4	0.038	0.018	0.025	0.072	0.044
PNG-PERIM4	0.160	0.073	0.072	0.239	0.014
TIFF-PERIM4	0.098	0.116	0.115	0.090	0.267
RAW-PERIM4	0.028	0.083	0.096	0.011	0.207
JPEG-PERIM8	0.038	0.017	0.023	0.073	0.043
PNG-PERIM8	0.143	0.058	0.057	0.220	**0.009**
TIFF-PERIM8	0.114	0.137	0.138	0.099	0.300
RAW-PERIM8	0.018	0.061	0.071	0.014	0.167
JPEG-SOBEL	0.164	0.075	0.068	0.255	0.027
PNG-SOBEL	0.195	0.100	0.092	0.294	0.037
TIFF-SOBEL	0.047	**0.009**	**0.007**	0.095	0.046
RAW-SOBEL	0.097	0.037	0.030	0.173	0.031
Michelson	0.013	0.044	0.055	0.015	0.138
RMS	0.011	0.043	0.054	0.011	0.141
mSC1	0.063	**0.010**	**0.016**	0.109	**0.013**
mSC2	0.100	0.064	0.078	0.143	0.046
mSC3	0.124	0.150	0.174	0.140	0.170
mSC4	0.298	0.425	0.462	0.277	0.499

KL Divergence calculated using the frequency of positive responses across façade variations ordered from the last (Pattern 6) to the first (Pattern 1) studied façade geometry

	Pleasant	Interesting	Exciting	Calming	Complex
GIF	0.022	0.054	0.066	0.018	0.152
JPEG	0.037	0.119	0.134	**0.008**	0.277
PNG	0.031	0.102	0.116	0.009	0.245
TIFF	0.011	0.038	0.048	0.014	0.130
Fractal D	0.015	0.048	0.060	0.012	0.147
JPEG-CANNY2014	0.057	0.149	0.166	0.017	0.324
PNG-CANNY2014	0.237	0.410	0.433	0.150	0.687
TIFF-CANNY2014	0.201	0.184	0.195	0.201	0.225
RAW-CANNY2014	0.014	0.035	0.046	0.020	0.121
JPEG-CANNY1986	0.055	0.148	0.164	0.016	0.323
PNG-CANNY1986	0.214	0.379	0.401	0.132	0.647
TIFF-CANNY1986	0.174	0.155	0.166	0.178	0.193
RAW-CANNY1986	0.013	0.027	0.034	0.027	0.102
Entropy	0.013	0.044	0.055	0.013	0.139
JPEG-PERIM4	0.043	0.129	0.145	0.010	0.293
PNG-PERIM4	0.180	0.333	0.355	0.102	0.584
TIFF-PERIM4	0.140	0.132	0.139	0.144	0.183
RAW-PERIM4	0.013	0.020	0.026	0.031	0.092
JPEG-PERIM8	0.045	0.132	0.148	0.011	0.297
PNG-PERIM8	0.171	0.317	0.340	0.095	0.559
TIFF-PERIM8	0.152	0.131	0.138	0.163	0.169
RAW-PERIM8	0.013	0.040	0.048	0.019	0.134
JPEG-SOBEL	0.234	0.404	0.436	0.145	0.645
PNG-SOBEL	0.263	0.450	0.481	0.168	0.708
TIFF-SOBEL	0.114	0.204	0.230	0.065	0.354
RAW-SOBEL	0.182	0.325	0.357	0.109	0.520
Michelson	**0.011**	0.048	0.058	0.010	0.148
RMS	0.014	0.042	0.053	0.014	0.134
mSC1	0.090	0.180	0.203	0.040	0.351
mSC2	0.082	0.193	0.212	0.039	0.387
mSC3	0.070	0.161	0.175	0.059	0.320
mSC4	0.197	0.266	0.272	0.231	0.383

Figure 7.9 – Kullback–Leibler (KL) divergence between the normalized distributions of the percentage of positive (>5) evaluations in each perceptual attribute and the corresponding normalized values of the studied computational metrics applied to the test scenes for each façade variation. The two metrics with the lowest overall divergence per attribute are highlighted.

7.1.2.4 Results of correlation analyses using the experimental scenes

According to the outcomes of the KL divergence, a total of seven promising metrics (Fractal D, Michelson, TIFF-SOBEL, mSC1, JPEG file size, RAW-CANNY1986 and PNG-PERIM8), shown in Table 7.4, were selected for further analysis.

This second step in the selection of promising metrics revealed mSC1 as a promising candidate for the prediction of multiple attributes, namely how interesting, exciting, and complex the space was perceived. Due to the strong correlation between the evaluations of how *interesting* and *exciting* the space was perceived, as well as the selection of identical most promising candidate metrics for both attributes, in the subsequent analysis we will focus solely on the evaluation of how exciting the scene was perceived, which has been shown to be a more promising dimension from the literature. Moreover, given the consistent results of a significant correlation between JPEG file size and perceived complexity of natural and urban scenes in the literature [Forsythe et al., 2011; Marin and Leder, 2013; Cavalcante et al., 2014; Machado et al., 2015; Marin and Leder, 2016] (as can be seen in Table 7.1), we will also conduct correlation analyses between this particular metric and the percentage of positive responses for the complexity of the scene.

Table 7.4 – The two most promising metrics per attribute based on KL divergence, and the equivalent Pearson's correlation coefficient ρ between the metric outputs and the percentage of positive responses from the experimental data, averaged across scenes with the same façade variation.

Attribute	Metric	KL divergence	Pearson's ρ
Pleasant	1. Fractal D	0.011	-0.07
	2. Michelson	0.011	0.12
Interesting	1. TIFF-SOBEL	0.009	N/A
	2. mSC1	0.010	N/A
Exciting	1. TIFF-SOBEL	0.007	0.66
	2. mSC1	0.016	0.71
Calming	1. JPEG	0.008	-0.83*
	2. RAW-CANNY1986	0.009	0.35
Complex	1. PNG-PERIM8	0.009	0.97**
	2. mSC1	0.013	0.95**

Significance levels are marked as follows: * = $p < 0.05$, ** = $p < 0.01$.

Following the same procedure that was described in Section 7.1.2.2, the equirectangular projection renderings from the experimental dataset were used to generate perspective views containing solely the façade. The resulting images, with a resolution of 1121x135 pixels, were used as input for the calculation of the image-based measures for each of the 36 experimental scenes. An example of the perspective views and perimeter images resulting from this procedure can be seen in Figure 7.10. The average metric output of all scenes with the same façade variation was calculated for each measure, resulting to a set of six values per measure, as illustrated in Figure 7.11.

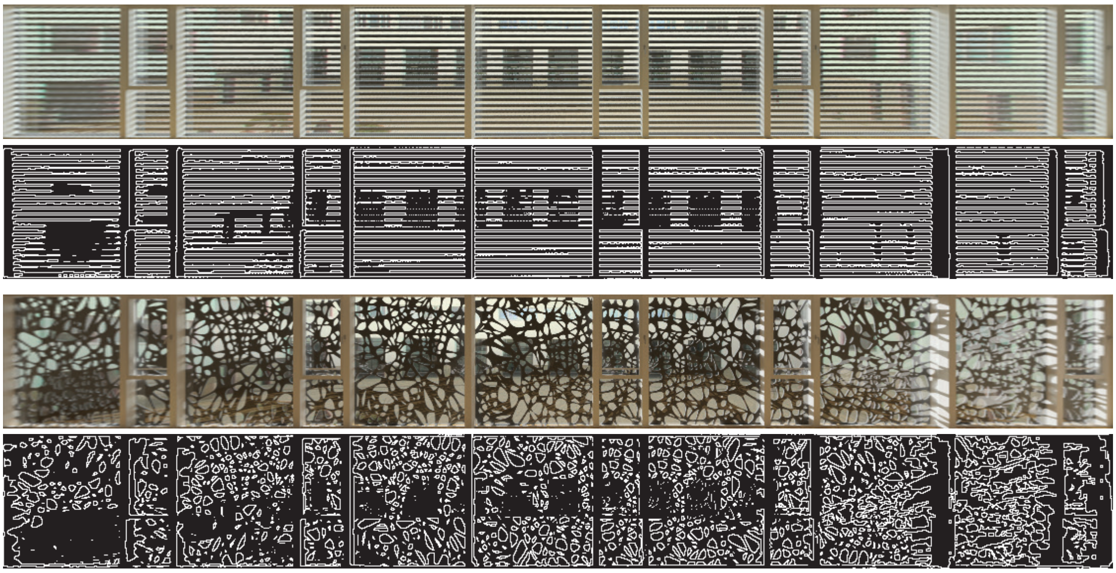


Figure 7.10 – Example of the perspective views of the façade and the binary image resulting from the perimeter detection PERIM8 for two experimental scenes. The depicted scenes correspond to Pattern 1 with overcast sky (top) and Pattern 6 with clear sky and a low sun angle (bottom), both in the social context condition.

The resulting metric outputs were used to calculate the Pearson's correlation coefficient between each metric and the percentage of positive responses for the equivalent perceptual attribute. In order to account for the number of comparisons and the simultaneous low power of the analysis due to the limited sample size, a Bonferroni-Holm corrected significance level was used to interpret the results, following Marin and Leder [Marin and Leder, 2013, 2016]. The results of the correlation analysis are shown in Table 7.4. The percentage of positive responses regarding the perceived *complexity* of the space was shown to correlate significantly both with the PNG-PERIM8 ($\rho = 0.97$, $p = 0.0018$) and the mSC1 ($\rho = 0.95$, $p = 0.0034$) metrics, with a particularly high correlation coefficient. Figure 7.11 shows the distribution (normalized to the maximum value) of these metrics against the equivalent normalized distribution of the percentage of positive responses of perceived complexity. Similarly, a significant positive correlation was found between the JPEG file size and the percentage of positive responses for perceived complexity ($\rho = 0.94$, $p = 0.006$). The JPEG file size was also shown to correlate negatively with the percentage of positive responses regarding how *calming* the space is perceived ($\rho = -0.83$, $p = 0.04$), but failed to meet our adjusted significance threshold. No significant correlations were found for any of the remaining perceptual attributes (all $ps > 0.11$).

As the limited sample size greatly reduces the power of these analyses, we repeated the correlation analysis for the metrics with the highest correlation for the attributes *exciting* and *calming* (mSC1 and JPEG file size, respectively) by using the 36 pairs of values as individual data points, instead of reducing them to six values averaged over the sky type and spatial context variations. The analysis showed a significant negative correlation ($\rho = -0.60$, $p = 0.0001$) between the JPEG file size and the percentage of positive evaluations for the attribute *calming*, as well as a significant positive correlation ($\rho = 0.58$, $p = 0.0002$) between mSC1 and the percentage of positive evaluations for the attribute *exciting*.

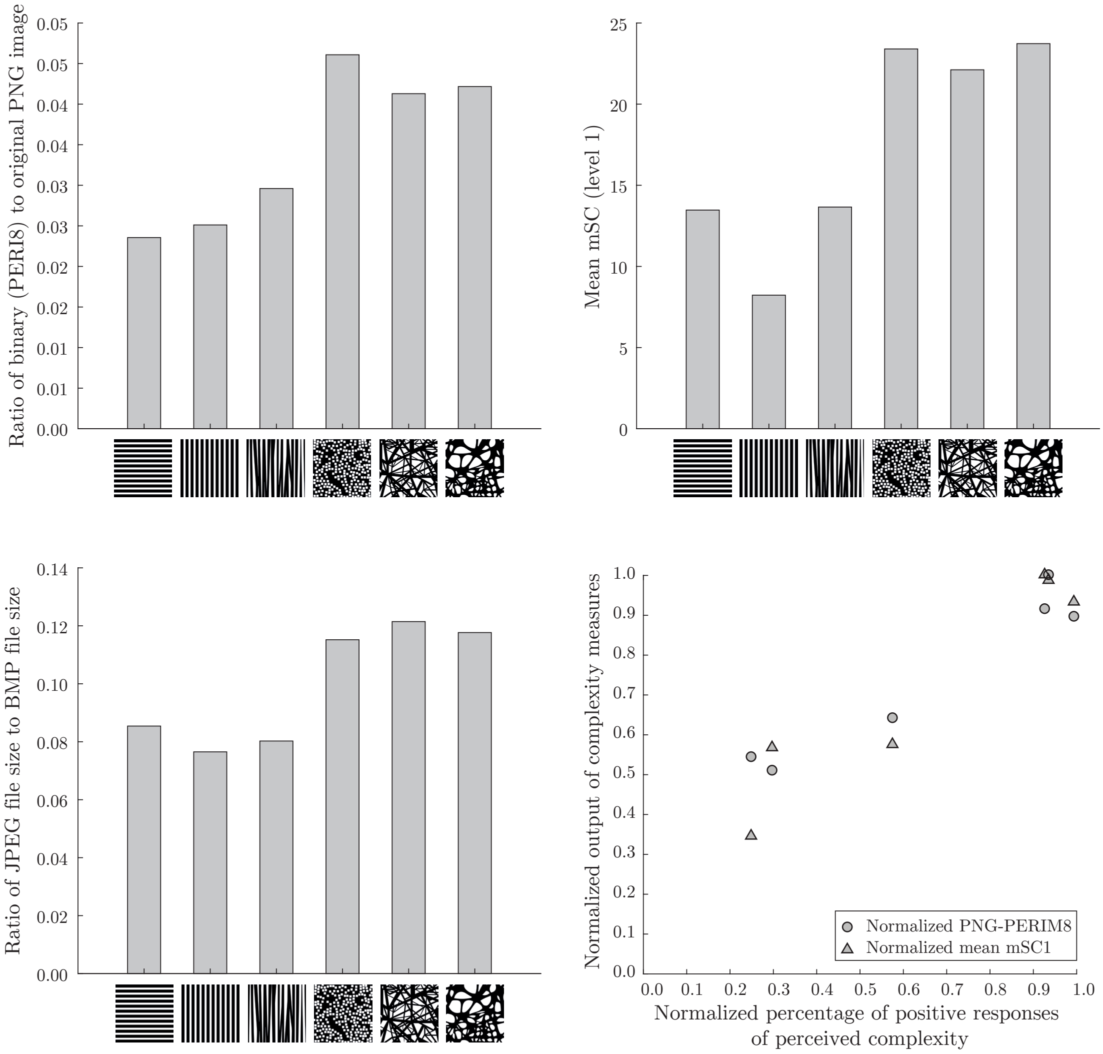


Figure 7.11 – Distribution of the outputs of the metrics PNG PERIM8 (shown divided by the file size of the corresponding original PNG image for ease), mSC1, and JPEG file size (shown as the ratio of JPEG to BMP file size), and normalized distribution of the PNG PERIM8 and mean mSC1 metrics (y axis) plotted against the percentage of positive responses of perceived complexity (x axis). All depicted data correspond to the 36 scenes from the experimental study in Chapter 6 and are averaged within each façade variation.

The finding of a significant correlation between these image-based metrics and the ratings of exciting and calming, when treating the 36 scenes as individual data points, is a very positive outcome and highlights the potential of these metrics as predictors of façade-driven effects. Nevertheless, these findings should be interpreted with caution, as this extended dataset contains images that are very similar due to minimal differences in the cropped perspective views between the scenes with variations in sky type and spatial context.

7.1.2.5 Objective thresholds of positively perceived complexity

The relationship between impressions of complexity and pleasantness, as well as between impressions of complexity and excitement, suggested a potential lower bound of positively perceived complexity. The results of this section, demonstrating the capabilities of specific image-based metrics as predictors of perceived complexity, can be used to quantify this threshold. Specifically, the relationship between these two pairs of perceptual impressions shown in Figure 7.8 can be coupled with the equivalent values of the computational measures to determine a complexity-based threshold, below which a façade design is less likely to lead to higher evaluations of pleasantness and excitement. Since Pattern 4 was found to be an outlier in the inverted U-shape curve between pleasantness and complexity, it is not possible to derive an equivalent upper bound of positively perceived complexity, and additional studies are needed to investigate this topic.

By setting a minimum mean rating of excitement and pleasantness equal to 5 and 6, respectively, and using Figure 7.8, we can select the average outputs of the image-based metrics for the Pattern 1 as the lower cutoff points for complexity. Following this step, we can derive the equivalent bounds for the PNG-PERIM8 and mSC1 measures. The metric PNG-PERIM8 is reported as the ratio of size of the PNG binary image divided by size of the original PNG image to provide a usable reference. Using the Table A.6 in the Appendix A.10, we identify a lower complexity threshold of 0.025 for PNG-PERIM8 and 8.23 for mSC1. This threshold differentiates Pattern 1 and 2 —the horizontal and vertical stripes— from the other studied façade variations, and, based on the experimental findings of this thesis, is suggested as a lower bound of positively perceived complexity, below which façade geometry designs are expected to be perceived as less exciting and less pleasant. As these thresholds are derived from a very limited number of data points, further work is encouraged to test their applicability across additional façade geometry variations as well as experimental settings.

7.1.3 Discussion

The study presented in this section investigated the potential of existing computational measures of contrast and complexity as predictors for the façade-driven perceptual effects that were discovered in Chapter 6. Starting from an initial set of 32 measures, derived from the literature, the two most promising measures were selected for the attributes *pleasant*, *interesting*, *exciting*, *calming*, and *complex*, based on the similarity between the measure outputs when applied to a test set of scenes and the subjective responses to scenes with the same façade geometry from Chapter 6.

Findings revealed a strong positive correlation between two image-based computational measures (PNG-PERIM8 and mSC1) and the corresponding percentage of positive evaluations of how *complex* the scene was perceived. This result is important not only for the advancement of our understanding of subjective complexity, but also because of the relationship between subjective complexity and other perceptual attributes, such as excitement and pleasantness, which was demonstrated in the current study. In particular, the analysis of the participants' responses regarding how *pleasant* and *complex* the space was perceived showed that reported pleasantness was generally higher for façade variations of intermediate perceived complexity, and lower for variations of low and high perceived complexity. However, Pattern 4, the façade variation with irregularly distributed small openings, was found to be an outlier, leading to moderate ratings of complexity and also moderate —rather than high— ratings of pleasantness. This finding partially supports Berlyne's theory of an inverted U-shaped curve between pleasantness and complexity [Berlyne, 1971], and suggests that in the context of façade design, the size of the openings —in addition to their complexity— is also an important factor contributing to the pleasantness of the scene. The relation between how exciting and complex the scene was perceived showed that ratings of excitement increased with complexity. These findings, in combination with the successful prediction of perceived complexity using image-based metrics, were used to derive a possible lower threshold of positively perceived complexity, below which a façade variation is less likely to lead to high ratings of pleasantness and excitement.

The outcomes of the present study demonstrated a significant positive correlation between evaluations of complexity and computational measures of complexity (PNG-PERIM8, JPEG file size) and contrast (mSC1), and a positive, but not significant —after the Bonferroni-Holm correction— correlation between the evaluations of how *calming* is the space and the JPEG file size. The correlation between perceived complexity and the file size of the compressed JPEG image format, as well as the perimeter-based measures are well established in existing studies employing paintings and photographs of natural and urban scenes, as shown in Table 7.1. The present study confirms these findings, and extends their application to the field of architectural design, using visual stimuli that are derived from contemporary architecture and have controlled characteristics. Similarly, the first sub-sampling level of mSC (referred to as mSC1) has been shown to correlate significantly with ratings of complexity ($\rho = 0.60$) in Rockcastle et al. [2017], in agreement with our findings. The metric mSC1 was also shown to be one of the most promising metrics in terms of its similarity with ratings of excitement according to the KL divergence. However, no significant correlation was found in the subsequent analysis with the Bonferroni-corrected significance threshold. As this outcome could be influenced by the limited sample size —as we employed the mean value for each set of six scenes that have the same façade variation—, the analysis was repeated with the 36 unique scenes treated as individual data points. This second analysis showed statistically significant moderate correlations both between the JPEG file size and impressions of how calming the space was perceived, and between mSC1 and impressions of excitement.

7.1.3.1 Limitations

An important shortcoming of the current study was the limited sample size used in the correlation analyses. As the façade geometry was found to be the driving factor of the participants' perceptual impressions of the space, the data from the 36 experimental scenes was reduced to average values representing the six façade geometry variations. On the other hand, the treatment of the 36 experimental scenes as individual data points, which was done to further analyze specific outcomes, could be criticized as leading to an artificial increase of the sample size, since the input images for the metrics under examination are very similar for the same façade variation.

In order to further test the capability of JPEG file size and mSC1 as predictors of impressions of calm and excitement, respectively, across additional façade variations, we employed the 20 renderings and equivalent participant responses from the paper-based survey of architects in Section 5.3. Following the procedure that was used for the image analyses in this section, a perspective view containing solely the window of the scene was extracted from each image and used to calculate the corresponding measures. The output of the metrics for each image were then correlated with the frequency of selection of the equivalent façade variation as the most calming, in the case of the JPEG file size, or the most exciting, in the case of mSC1. No significant correlation was found between either measure and the corresponding subjective responses (all $ps > 0.42$). Although the immersive experiment and the paper-based survey differ greatly both regarding the stimuli and the questions asked to the participants, which could explain this discrepancy, further work is necessary to examine the capability of these measures as predictors of calm and excitement driven by façade geometry.

Madan et al. [2018] argued that when trying to predict affective responses to photographs with diverse content (ranging from faces to objects), there is a discord between the characteristics of the stimuli that are captured by current computational measures, and those that drive affective responses related to arousal. In the same vein, Marin and Leder [2013] investigated the correlation between computational measures and impressions of complexity and excitement across domains, employing photographs of environmental scenes, paintings, and music excerpts. Even though compression-based measures applied on music stimuli showed significant positive correlations with both reported complexity and excitement, image-based computational measures correlated solely with perceived complexity*. Contrary to these findings, Rockcastle et al. [2015; 2017a; 2017b] demonstrated consistent positive correlations between image-based contrast measures and ratings of excitement, particularly with the contrast metric mSC, in studies that investigated participant impressions of simulated scenes of interior spaces. The present work, in alignment with Rockcastle et al., demonstrated a strong correlation between the JPEG file size and evaluations of how calming the space was perceived, and a moderate-to-strong correlation between the mSC1 metric and evaluations of ex-

*Although the standard deviation of RMS contrast values was found to correlate moderately with ratings of arousal (exciting-calming) of representational paintings in [Marin and Leder, 2013], this finding was not replicated for different exposure times to the stimulus [Marin and Leder, 2016], neither for photographs of natural scenes in further experimental studies by the authors [Marin and Leder, 2013, 2016].

citement. These findings indicate that the prediction of responses to the characteristics of the built environment is indeed possible, and suggest that the discrepancy with the aforementioned studies, where no correlation was found between image-based metrics and affective responses, might be due to their use of different image content.

However, further testing of these two metrics using the stimuli and data from the survey of architects in Section 5.3 showed that neither metric was able to successfully predict subjective responses. This finding restricts the applicability of those metrics to additional façade variations and motivates the conduction of dedicated studies with a wide range of façade designs to examine further the predictive capabilities of image-based metrics.

In the case of mSC, this negative result, in combination with the moderate correlation when applied to the extended experimental dataset, suggests that while the metric is sensitive to changes in the lighting conditions and their interaction with the design of a space [Rockcastle, 2017], it might be less sensitive to changes in the details of the same space, such as variations in the façade design. It is also worth noting that the stimuli used in the present analysis differ from those in previous applications of mSC, as in the current study we employed a high level of detail and colored materials, in contrast to the empty grayscale architectural interiors used in Rockcastle et al. [2017]. As the presence of furniture and color in a scene has been shown to significantly affect participant impressions of the space, such as the satisfaction with brightness [Omidfar Sawyer and Chamilothori, 2019], these methodological differences might impact not only the image features captured by the mSC metric, but also the features that are most salient for the participants. Lastly, in the present study, mSC1 (mSC applied to the original resolution) was shown to outperform mSC5 (mSC applied to the fifth sub-sampling level), which was the best performing measure in Rockcastle et al. [2017a; 2017b]. As the images in all our analyses are comparable with those in Rockcastle et al. in terms of the angular view represented by each pixel, the difference in the performance of the mSC1 and mSC5 metrics could be explained by the image content itself. Specifically, in Rockcastle et al., the mSC metric is applied to an image depicting the whole interior scene, and thus the sub-sampling is used to extract the most salient features of the scene [Rockcastle, 2017]. In the current study, where metrics were applied to an image representing solely the façade in accordance with the findings from Chapter 6, reducing the resolution of the image was shown to reduce the metric's ability to differentiate between certain façade geometry variations, indicating that sub-sampling was not necessary.

7.1.3.2 Future research directions

Following the promising findings of this section regarding the prediction of façade-driven perceptual responses, future work is encouraged to investigate this topic further by employing a broad range of façade designs. Moreover, dedicated studies examining systematic variations in the shape and spatial distribution of openings, perforation ratio, and viewing distance are needed to uncover the perceptual effects of specific façade characteristics and their relation to quantifiable features of the visual stimulus. Another important research direction regards the use of additional image-based metrics. One such as example is the spatial frequency of images, which has been suggested as a promising indicator of visual discomfort [Penacchio and Wilkins, 2015]. A second approach regards the identification of curvilinear forms, which have been shown to be evaluated more positively than rectilinear ones in architecture and object design [Bar and Neta, 2006; Dazkir and Read, 2012; Vartanian et al., 2013], a finding that is supported by the ratings of pleasantness in the present study. Future work could examine the potential of image-based metrics that differentiate between curved and straight elements, such as the number of non-straight edges, which has been shown to relate to impressions of naturalness [Berman et al., 2014; Kardan et al., 2015]. The link between perceived complexity and image compression is also particularly interesting from the perspective of visual processing in the human brain, where the principles of efficient image encoding are suggested to apply to the processes of the human visual system [Olshausen and Field, 2000; Scholte et al., 2009].

7.2 Building envelopes for energy efficiency, visual comfort, and delight

The findings of Chapters 5 and 6 provided strong evidence that the façade geometry can significantly alter the way occupants experience the same space, an effect which proved to be robust across different spaces and window sizes. In addition, the experimental results from Section 5.2 demonstrated that the characteristics of the façade openings can influence not only the subjective, but also the physiological responses of occupants. Lastly, the outcomes of the previous section indicated that these effects could be predicted —and thus, orchestrated— using image-based computational algorithms. The present section illustrates the application of these findings in a real-world setting by presenting a short overview of a proof-of-concept study for a shading system that combines states with different expected perceptual effects.

This section starts by outlining the current state of static and kinetic shading systems, and illustrates the potential for innovation in this field drawing from the findings of the current thesis. Next, it presents as an example a novel kinetic shading system that encapsulates this potential by shifting states to shape the occupants' experience of the space. The final part of the section discusses the implications of this novel shading system for the fields of architecture and lighting, as well as future directions in this area.

7.2.1 Responding to occupant needs with adaptive façade systems

Given the critical role of the building envelope for building energy consumption and occupant comfort [Knaack et al., 2014; Jin and Overend, 2014], daylighting control systems are of particular importance. Depending on the climate and orientation, static shading systems limit incident solar radiation and can in turn reduce energy consumption for cooling [Cho et al., 2014; Mandalaki et al., 2012], as well as overall energy consumption [Bellia et al., 2013], while providing adequate daylight levels and limiting glare [Christoffersen et al., 1997; Dubois, 2003; Yun et al., 2014]. However, they obstruct the view to the outside [Aldawoud, 2013; Bustamante et al., 2015], while their fixed state means that the positive reduction of cooling loads in the summer —for the northern hemisphere— is translated to an increase in heating loads in the winter [Dubois, 2003; Tzempelikos and Athienitis, 2007]. On the other hand, dynamic shading systems that are manually controlled have been shown to be rarely manipulated by occupants [Rubin, 1978; Rea, 1984; Inoue et al., 1998; Escuyer and Fontoynont, 2001], which can result in overoptimistic predictions regarding potential energy savings [Reinhart, 2002; Van Den Wymelenberg, 2012]. In the case of manually controlled blinds, visual comfort has been found to be the primary factor which causes occupants to close the blinds [Inkarojrit, 2006; Meerbeek et al., 2014], while access to the view out is the main stated reason for opening the blinds [Meerbeek et al., 2014].

The adoption of shading systems that are not controlled solely by the user, but can respond automatically to a set of predefined conditions, is an important paradigm shift in the design of the building envelope. Such systems change states in response to exterior conditions and interior requirements, aiming to achieve a balance between solar gains, daylight and view access, and discomfort glare [Lee et al., 2004]. Although dynamic façades represent a novel direction in architecture [Moloney, 2011], the explicit motivation in the application of such systems remains widely the same as for static configurations, revolving around building energy consumption and user comfort. A review of 130 buildings with adaptive façade elements [Aelenei et al., 2016] showed that the primary reasons for adopting such systems relate to solar radiation and outdoor temperature, and categorized the purpose of these installations into five groups: thermal comfort, energy performance, visual performance, indoor air quality, and acoustic performance. However, the aesthetic aspect of the resulting façade is often mentioned as an important element of the design. Such is the case of the Tesselate system, consisting of closely stacked perforated screens that shift relative to each other and create variations in the shape and size of their openings, which is described as both "an intriguing and functional object" [Drozdowski, 2011]. In the same vein, Meagher [2015] suggested that the kinetic behavior of dynamic systems has a poetic component and can enhance the experience of the building.

The findings of the present thesis uncover a new direction in the field of dynamic façades by demonstrating that the façade geometry significantly influences how an occupant experiences the surrounding space. Specifically, these findings can be used in the design of a kinetic shading system which changes states not only in response to criteria relating to occupant comfort and building performance, but also to shift the occupants' impressions of a space. This approach builds on the aesthetic effects of dynamic shading systems, as suggested by Meagher [2015], integrating the demonstrated façade-driven perceptual effects to orchestrate the occupants' experience of the space and enhance impressions such as how interesting or calming a space is perceived.

Following the method that is presented in this thesis, it is possible —and worthwhile— to investigate the effects of additional façade designs, as well as of incremental changes in the characteristics of the façade geometry, which can in turn be used in static or kinetic façade applications to induce desired occupant responses. Moreover, the stimuli and outcomes of Chapter 6 can be directly used as a reference for the design of façades with specific expected perceptual effects. In an experimental study that investigated the acceptance of automatically operated dynamic shading, Bakker et al. [2014] showed that less frequent and discrete transitions between façade states were more appreciated compared to frequent and smooth ones. This finding supports the use of the façade designs that were investigated in this thesis as different states of a dynamic façade. The question that emerges is which of the studied façade variations would be particularly promising candidates for such an application, and whether the resulting dynamic façade could be applied in a real setting. To address this question, the next section will examine the potential of integrating the experimental findings from Chapter 6 in the design of a kinetic shading system, providing a proof-of-concept for the introduction of orchestrated perceptual effects as a new dimension in dynamic façades.

7.2.2 A novel perception-based kinetic shading system*

In order to illustrate the application potential of the façade-driven effects that were revealed in this thesis in the design of a dynamic shading system, the most straightforward and feasible approach is to start from two façade variations that were found to elicit contrasting perceptual responses. One of the most intriguing findings from Chapter 6 was the significant difference in the participants' perception of the space between the façade variation with vertical stripes (Pattern 2) and the one with slightly skewed vertical elements (Pattern 3). Specifically, the variation with the skewed vertical elements led to the same scene being perceived as more pleasant, interesting, exciting, and calming compared to the straight vertical elements.

Figure 7.12 presents an overview of these findings, showing the percentage of positive responses for a specific perceptual attribute as a means to illustrate the participants' consensus. The two façade variations will be referred to as "vertical" and "skewed" in this section. In particular, results showed that the shift from the straight to the skewed vertical elements leads to an estimated increase of 10% in how interesting the space is perceived (1.09 units in the 11-point scale that was used in the study) and a 9.5% increase in how exciting the space is perceived (1.05 units in the 11-point scale). Moreover, the geometric similarity between these two façade variations render them very promising for a kinetic façade application, due to the mechanical feasibility of changing the façade state from one to the other.

*This study was conducted in the framework of a master's thesis project [Baehr-Bruyère, 2019] co-supervised by the author and later summarized in a journal paper [Baehr-Bruyère et al., 2019]:
J. Baehr-Bruyère, K. Chamilothori, A. Vassilopoulos, J. Wienold, snd M, Andersen, "Shaping light to influence occupants' experience of space: a novel kinetic shading system with composite materials," *Proceedings of CISBAT 2019, Journal of Physics: Conference Series, (to appear).*

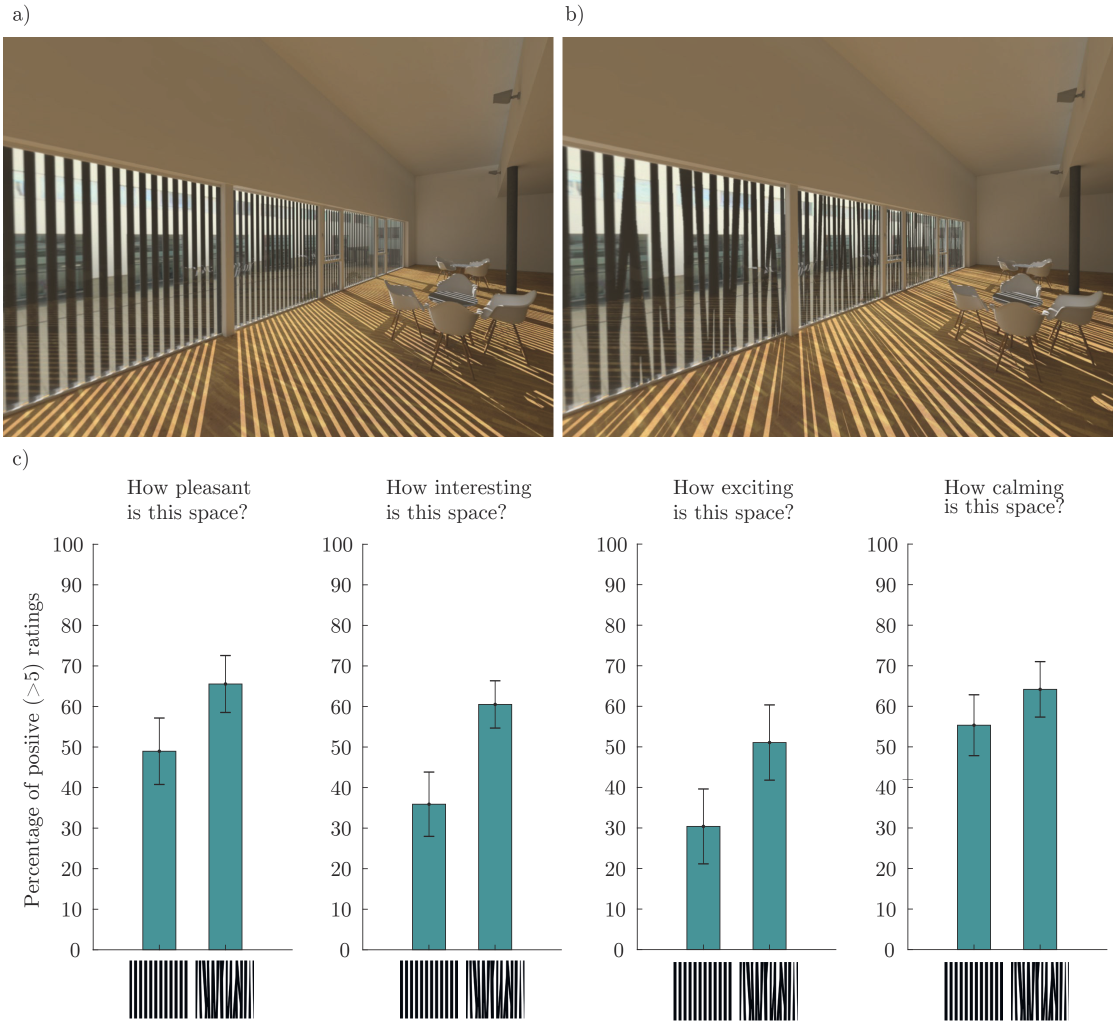


Figure 7.12 – Illustration of the space with (a) the vertical and (b) the skewed façade elements, a clear sky with low sun angle and social context, and (c) mean and standard deviation of the percentage of positive responses (>5, on a scale from 0 to 10) for the attributes of how *pleasant*, *interesting*, *exciting*, and *calming* the space was perceived, which showed significant differences between the evaluations of the two façade variations in the results of Chapter 6.

These experimental findings motivated a Master's thesis project [Baehr-Bruyère, 2019], conceived and co-supervised by the author, which focused on the development of a kinetic shading system that applies these façade variations in a real-world setting. Specifically, the multi-purpose space from the experiments in Chapter 6 was used as a case study to ensure the applicability of the outcomes of this project. The design of this kinetic shading system aims to take into account both the aforementioned perceptual effects of vertical and skewed elements and established requirements for the performance of shading systems. Through its kinetic behavior, the proposed shading system aims to address occupant needs for protection from glare and overheating, while allowing daylight and view access, and offering façade geometry variations that can enrich the occupants' experience of the space.

To fulfill these objectives, the developed design uses the aforementioned façade geometry variations from Chapter 6 as a basis and translates them into states of a kinetic façade through the use of shape-changing façade components. In particular, Baehr-Bruyère [2019] proposed a novel shading system that employs flexible elements to shift through different states, using torsion as a means to create different façade openings. These elements are designed to shift from a state that is fully open and maximizes the daylight and view access, to one that is fully closed and minimizes the incident solar radiation, and to intermediate twisted states that consist of skewed vertical elements and are expected to induce visual interest. Figure 7.13 illustrates the design concept, depicting a single element that changes shape through individual rotations of the top and bottom part. According to Loonen's [2013] classification of adaptive façade systems, the proposed design corresponds to the macro scale, with a kinetic behavior at the level of the building component.

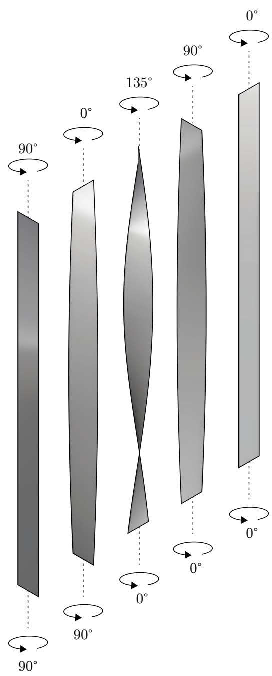


Figure 7.13 – Illustration of the design concept of the kinetic shading system, depicting the change of state through individual rotations of the top and the bottom part of the each element. The first variation from the left aims to maximize the view out, the last one aims to restrict the incident solar radiation, and those in between aim to the creation of visual interest in the scene.

In order to realize this design concept, Baehr-Bruyère [2019] employed glass fiber reinforced polymers (GFRP), due to their high strength-to-stiffness ratio which allows significant elastic deformations before failure, as well as the high degree of customizability of the material structural and optical properties that they offer through the lamination process. The elastic properties of GFRP have been utilized in existing dynamic façade applications such as the Flectofold [Körner et al., 2016] and Flectofin [Lienhard et al., 2011] shading systems which combine flexible and rigid parts of GFRP to create a folding movement, and the One Ocean pavillion, which employs GFRP elements that bend to create variable façade openings [Knippers et al., 2013]. In this proof-of-concept study, the use of GFRP materials allows the shading system to respond to both performance-driven and perceptual objectives, and to shift the façade geometry from vertical to skewed elements using the same façade components.

In addition to the desired elastic behavior of the façade elements, the employed material should achieve a direct transmittance of zero and a maximum diffuse trasmittance of 15%, which is necessary for sufficient glare protection [European Committee for Standardization (CEN), 2019]. Drawing from studies on the impact of FRP properties on visual transmittance [Pascual et al., 2014], Baehr-Bruyère [2019] explored the thickness and material composition of the façade elements to fulfill the desired optical properties, while considering the structural reliability of the resulting system. GFRP laminates with varying properties were fabricated to examine the material properties, and showed that further development is needed to reach the desired diffuse transmittance level. An example of the fabricated GFRP elements, applied in a mock-up model, are shown in Figure 7.14.

Figure 7.14 – Photographs of the mock-up model, showing the twisted GFRP elements as seen from the exterior (left) and the interior (right). The left and right part of the model differs in the direction of the glass fiber layers in the lamination process, resulting to different optical properties. Courtesy of Joëlle Baehr-Bruyère, 2019.

While this design builds on the façade variations of Chapter 6, their interpretation in a shading system imposes some limitations that distance the resulting façade from the experimental stimuli. In this regard, the proposed kinetic shading system approximates the façade-driven perceptual effects that were revealed in the previous chapter in favor of ensuring the functionality of the system. To create an effective shading system, the closed state must sufficiently protect from glare and overheating, while maximizing the daylight provision to reduce for the need for artificial lighting. These requirements translate to façade elements that are placed in close proximity to restrict direct light in the closed state of the shading system, and to the choice of translucent materials. In addition, the open state of the shading systems aims to maximize the access to view out, which is achieved by rotating the elements so that the only apparent obstruction (depending on the viewpoint of the occupant) is the thickness of the material. As a result, the kinetic shading system has a different material and perforation ratio than the façade variations used in Chapter 6. Lastly, the state with skewed elements is created by taking advantage of the elastic behavior of the material, and as such, the resulting pattern is three-dimensional. These discrepancies indicate that the participant responses to the façade variations used in the previous chapter cannot be directly applied to the developed shading system. Nevertheless, the geometric characteristics of the resulting façade variations resemble closely those of the experimental stimuli. Thus, a similar positive perceptual effect is assumed to follow the shift of the façade state to the condition with the twisted elements, increasing how pleasant, interesting, exciting, and calming the space is perceived.

In continuation of this work, Baehr-Bruyère et al. [2019] investigated the daylighting performance of the proposed kinetic shading system in a simulation study, using a material with a 15% diffuse transmittance, necessary to achieve a "good effect" of glare control according to standards [European Committee for Standardization (CEN), 2019], and a reflectance of 50%. The purpose of this study was to examine the adequacy of the shading system in terms of daylight performance, which in turn would demonstrate its viability as an alternative shading solution which complements conventional shading functions by enhancing the occupants' experience of the space. To this end, a section of the multi-use space that was described in Section 6.1.1.2 was used as a case study for the climate of the Geneva area. Figure 7.15 illustrates the studied section of the multi-use space and shows the shading system with a rotation of 135° at the top part of the individual components.

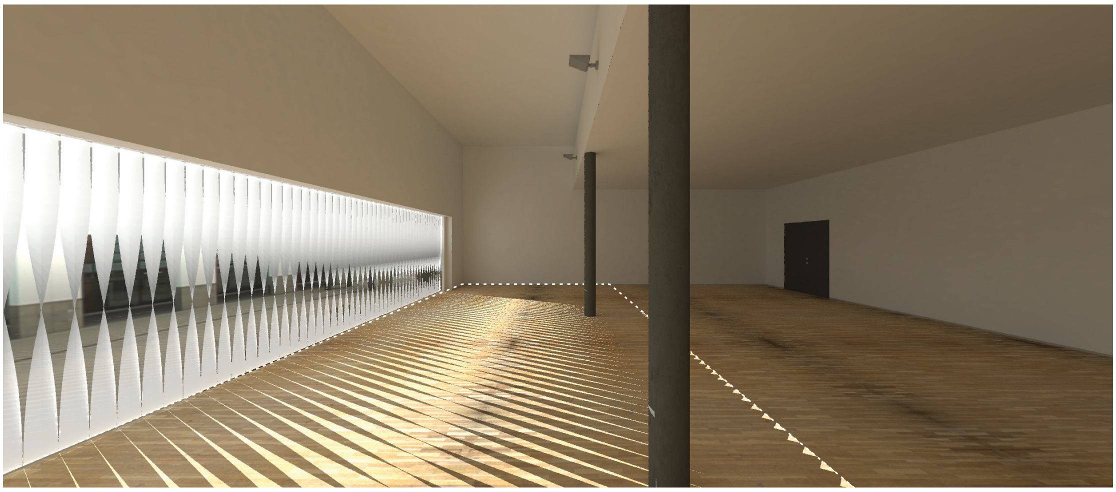


Figure 7.15 – Illustration of the multi-use space with twisted façade elements (shown with a 135° rotation at the top part of each element), rendered at 9:00 on March 15th in sunny conditions. The studied area is highlighted. Courtesy of Joëlle Baehr-Bruyère, 2019.

In order to perform analyses that are comparable to the thresholds of daylighting standards, simulations were conducted on a 5.76m x 21.75m section —rather than the entirety— of the multi-use space, located at the south-east corner of the space, which was the most critical in terms of both adequate illumination and glare protection. Analyses were conducted using DIVA-for-Rhino [Jakubiec and Reinhart, 2011] following the new European standard "Daylight in Buildings" EN17037 [European Committee for Standardization (CEN), 2019]. In particular, the daylight provision $DP_{300lux[50\%]}$ and $DP_{300lux[50\%]}$ (target illuminance of 300 and 500 lux, respectively, achieved for at least 50% of daylight hours in 50% of the used space) and protection from glare $DGP_{e<5\%}$ (an annual Daylight Glare Probability that doesn't exceed 0.35 for more than 5% of the occupied time) were used to investigate the daylight performance of the system across different states. For this baseline analysis, the shading system was assumed to retain a single state from those in Figure 7.13 throughout the year, and individual simulation studies where conducted for the fully open and closed states, as well as for variations of twisted elements, differing in their geometry to allow more light from the top or the bottom of the element.

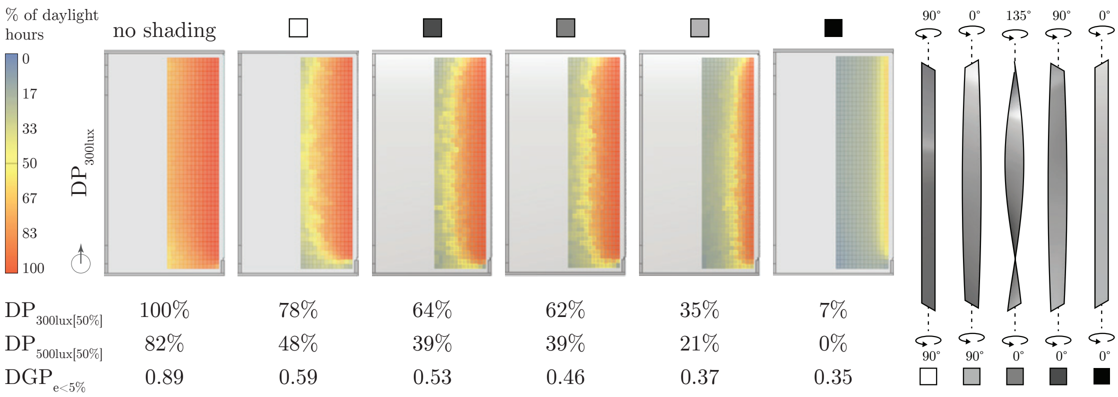


Figure 7.16 – Results of the annual $DP_{300lux[50\%]}$ and $DP_{500lux[50\%]}$ (DP with target illuminance E_T equal to 300 and 500 lux, respectively) and Daylight Glare Probability for each of the states of the shading system, assuming the same state throughout the year. Adapted from [Baehr-Bruyère, 2019] with permission.

Results showed that the open state offers adequate daylight provision ($DP_{300lux[50\%]} =$ 78%) while the closed state prevents discomfort glare ($DGP_{e<5\%} = 0.35$), as shown in Figure 7.16. These outcomes demonstrate that the shading system can fulfill the daylight performance requirements through these two states, while the intermediate twisted states are promising in terms of daylight provision, particularly for a threshold of 300 lux. Regarding overheating when using the closed state and the specified material, the shading system was found to correspond to a shading coefficient F_c of 0.15 for perpendicular incident sunlight, slightly higher than the equivalent typical values for closed aluminum blinds, which are close to 0.12 [WAREMA Renkhoff SE, 2018], motivating further work to improve the reduction of solar heat gains of the proposed system.

Building on these promising results for the glare protection and the daylight provision of the individual shading system states, Baehr-Bruyère et al. [2019] investigated the daylight performance of the kinetic shading system when considering a combination of the aforementioned states, to examine the application potential of the twisted states which are expected to contribute positively to an occupants' experience of the space.

Given the difficulty of modeling accurately the behavior of adaptive façades [Loonen et al., 2017], Baehr-Bruyère et al. [2019] developed a custom function to optimize the choice of the façade state based on three simultaneous conditions: avoiding direct sun penetration, achieving a $DGP_{e<5\%}$ lower than a defined boundary, and maximizing the illuminance level reached by at least 50% of the floor area (calculated as the median illuminance across the sensor nodes on the floor plane). Two different set points are defined for $DGP_{e<5\%}$, 0.40 and 0.45, corresponding to a good and a reasonable level of glare protection [Wienold, 2010], respectively. The first threshold was set for an expected office use of the space, while second threshold was employed as a less restrictive boundary for a social use of the space. As an example, the calculated schedule of the state changes in the kinetic system for the threshold of a maximum $DGP_{e<5\%}$ of 0.45 is shown in Figure 7.17, resulting to a $DGP_{e<5\%}$ of 0.43 and an illuminance level of 520 lux for at least 50% of the floor area.

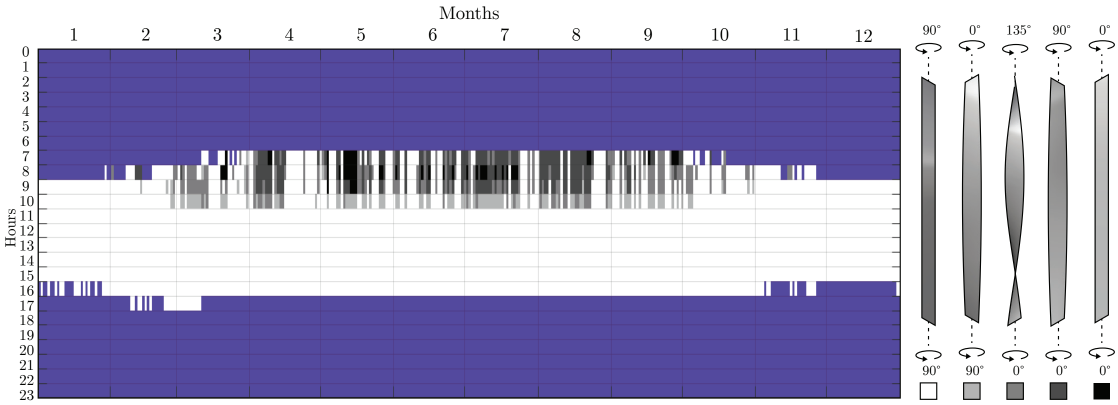


Figure 7.17 – Schedule of state changes in the kinetic system across the year based on the three conditions of avoiding direct sun penetration, achieving a $DGP_{e<5\%}$ lower than 0.45, and maximizing the illuminance level reached by at least 50% of the floor area. Adapted from [Baehr-Bruyère et al., 2019] with permission.

Results demonstrated that the twisted states, particularly those with a 90° and 135° rotation at the top part, were able to often protect from glare during the morning period. Moreover, Figure 7.17 shows that the open and twisted states were very often sufficient in providing adequate glare protection, leading to very few cases of a fully closed shading system. In particular, from the total changes of shading system state shown in Figure 7.17, 84% correspond to an open state, 15% to a twisted state, and solely 1% to a closed state. The dominant use of open and twisted shading system states allows view access and a sense to connection to the outside, as shown in Figure 7.15. This finding is particularly positive, considering that the automatic closing of blinds has been consistently found to be unacceptable by occupants [Rubin, 1978; Reinhart and Voss, 2003; Meerbeek et al., 2014] and that access to view is one of the main reasons for the occupants' interaction with blinds [Sadeghi et al., 2016].

The combination of traditionally used open and closed states of the shading system with the developed twisted element variations reveals that the design integration of façade states with perceptual objectives is not only viable, but, in the present application, contributes also to protection from glare and to the provision of daylight and view. Compared to conventional blinds, the proposed design in this proof-of-concept study leads to an expected increase of how pleasant, interesting, calming, and exciting the space is perceived for 15% of the time when the shading system is used, without compromising its performance. These findings demonstrate the promise of the proposed concept, which is capable of responding to criteria of visual comfort, visual delight, and view access, while minimizing the energy consumption for lighting through the provision of daylight.

7.2.3 Discussion

The proof-of-concept study that was presented in this section examined the potential of integrating promising façade variations with expected perceptual effects in the design of a dynamic façade, drawing from the experimental studies of the previous chapter. The findings of the present thesis outline an exciting new direction in the design and development of shading systems, showing that the geometry of the façade openings can be used to alter an occupant's experience of the surrounding space. In particular, the knowledge generated in this thesis can be used to improve the acceptability of shading systems and to positively influence the occupants of a space.

As conventional designs of vertical blinds have been found to be perceived as unappealing [Omidfar et al., 2015] and low in visual interest [Abboushi et al., 2019] in the literature, as well as in the present thesis, further developments are needed to create shading systems that are more positively evaluated by occupants. The outcomes of Chapters 5 and 6 show that the integration of façade geometry variations of positively perceived complexity in the design of shading systems has the potential to address this conflict between the daylight performance and the appraisal of shading systems. The proof-of-concept study in this section builds on the findings of the previous chapter and demonstrates the potential for dynamic façades which address not only well established needs for visual comfort and energy efficiency, but also traditionally unquantifiable aspects of the occupants' experience of space, such as pleasantness and visual interest.

Specifically, this section presented the work of Baehr-Bruyère [2019], which employed flexible GFRP elements for the design of a kinetic shading system that shifts between open, closed, and intermediate twisted states, the latter resembling closely the façade variation with skewed vertical elements from Chapter 6 and expected to lead to an increase of how pleasant, interesting, exciting, and calming the space is perceived. Simulation studies showed that the proposed design can sufficiently fulfill the daylight performance requirements, demonstrating that this perceptual dimension of façade geometry can be integrated in the design process without compromising the functionality of the shading system. Through the development of a custom function that optimized the choice of the shading system state based on daylight performance requirements, Baehr-Bruyère et al. [2019] showed that the intermediate twisted states, which are expected to enhance the occupants' experience of the space, contribute also in addressing occupants' needs for visual comfort and daylight access. In particular, the open and twisted states of the proposed shading system provided sufficient glare protection for the majority of the year, leading to very few cases of fully closed blinds. This outcome, in combination with the anticipated positive perceptual effects of the twisted shading system states — which, in this application, are expected to occur for 15% of the usage time of the shading system—, support the stance that the adoption of perceptual objectives can enrich the design process of shading systems and lead to designs that are perceived more positively.

The translation of the research findings of Chapter 6 in a real-world application through this proof-of-concept study highlights the necessity for further studies to identify the perceptual impact of additional façade aspects. As illustrated in Figure 7.15, one such aspect is the three-dimensionality of the façade design and its impact on the light distribution, the view access, and the appearance of the space. Similarly, the view quality in relation to the façade —both in terms of overall view access and of accessible view content, such as visible view layers [Hellinga and Hordijk, 2014]— is another promising research direction.

The proposed kinetic shading system has important potential for further optimization, for example through the individual control of each element, which could further improve the daylight performance of the system and provide customized conditions. Indicative directions for optimization could be to maximize view access, depending on the position of the occupant, or to control the complexity of the façade openings and the resulting sunlight patterns by varying the rotation of individual shading system elements. In the same vein, the establishment of image-based measures that can predict the occupant responses to façade variations, which was examined in Section 7.1, has great potential not only as a means to verify or guide the architects' intent, but also for parametric form finding in façade design, which has to date been used in combination with genetic algorithms solely to achieve criteria of daylight performance and energy efficiency [Gagne and Andersen, 2010; Sharaidin et al., 2012; González and Fiorito, 2015].

Another important research direction for the design of kinetic façades that aim to orchestrate specific occupant impressions is the control strategy of the façade. While the study that was presented in this section showed that it is possible to combine indicators of daylight performance and energy efficiency with expected façade-driven perceptual effects, the issue lies in the control logic for the kinetic behavior. A central question is, of course, which indicators can be used to predict the desired state for the occupant regarding these perceptual effects, and whether this choice should be left to the occupant. Moreover, the option of a manual override has been shown to be strongly preferred by occupants [Frontczak et al., 2012; Bakker et al., 2014; Meerbeek et al., 2014]. This option raises the issue of how to reconcile this feature with the "ideal" behavior of the façade in terms of energy performance, and whether these façade-driven perceptual effects could be used to increase the user acceptance of the façade behavior by introducing states which are perceived more positively.

7.3 Chapter summary

This chapter began by investigating the potential of image-based measures of contrast and complexity as predictors of the façade-driven perceptual effects that were demonstrated in Chapter 6. Drawing from the literature, 32 promising metrics were selected and applied on a set of test scenes, generated with the same procedure as the experimental stimuli of the previous chapter and depicting the same façade variations applied in a smaller space with different materials and view to the outside. The percentage of positive responses (ratings higher than 5 on the rating scale from 0 to 10) from the experimental study in Chapter 6 was used as a reference for the perceptual effects of each façade variation on how *pleasant*, *interesting*, *exciting*, *calming*, and *complex* the space was evaluated. The difference between the distribution of the metric outputs and the percentage of positive responses across the six façade variations was used to select the two best performing metrics (in terms of similarity with the subjective responses) for each perceptual attribute. These metrics were then applied to the scenes that were shown to the participants, and correlation analyses were conducted to investigate the association between the metric outputs and the participant responses. Results revealed a number of successful indicators. Specifically, the percentage of positive responses regarding how complex the space was perceived was shown to correlate significantly with the complexity metrics PNG-PERIM8 and JPEG file size, as well as the contrast metric mSC1. Strong but not significant correlations were also found for the perceptual attributes of how exciting was the space and the metric mSC1, as well as between how calming was the space and the JPEG file size. Due to the limited sample size in this study —corresponding to the six studied façade variations—, further data is needed to test the predictive accuracy of these metrics across a wider range of façade characteristics, with the ultimate aim to establish a prediction model of façade-driven perceptual effects. In addition, the participants' responses indicated an inverted U-shaped curve between the ratings of perceived complexity and pleasantness. This finding was combined with the metrics that were identified as promising indicators of perceived complexity to propose a possible lower bound of computational complexity. The proposed bound outlines a zone of low perceived complexity, below which façade variations are expected to lead to lower evaluations of pleasantness and excitement, and motivates additional studies to test its applicability in other settings.

The second section of this chapter demonstrated how the findings of the present thesis can be integrated in a real-world application. Specifically, drawing from the findings of Chapter 6, two façade variations with contrasting perceptual effects (straight and skewed vertical elements) were selected as states of a kinetic shading system in a proof-of-concept study. This kinetic shading system, developed by Baehr-Bruyère [2019], employs flexible composite (GFRP) elements to shift through façade states that are fully open, fully closed, or twisted, the latter creating irregular openings that resemble the skewed vertical elements from the experimental stimuli of the previous chapter. Following simulation analyses, the resulting shading system was shown to provide both sufficient protection from glare in its closed state, and sufficient daylight provision in its open state, to according to the new European standards for daylight in buildings [European Committee for Standardization (CEN), 2019], as well as adequate protection from overheating. Moreover, the states of twisted composite elements, which are expected to increase the occupants' impressions of how pleasant, interesting, exciting, and calming is the space based on the findings of the present thesis, were shown to contribute to the daylighting performance of the shading system and reduce the need for a fully closed façade state, with few occurrences of the closed state being necessary across the year. This work highlights the potential of further research for the creation of dynamic façades which change states to address not only needs of energy efficiency, visual comfort, and access to daylight and view, but also to orchestrate the occupants' experience of the space and increase the acceptability of the shading system.

Chapter 8

Conclusion

The work presented in this thesis aims to broaden our understanding on the joint impact of architectural elements and daylight on occupants. Specifically, the fundamental question underpinning this work is whether the spatial characteristics of the façade geometry and the corresponding daylight patterns can influence human responses.

Through multiple empirical studies, the present thesis demonstrates that indeed, the geometric characteristics of façade design and their interplay with daylight significantly affect human responses, and uncovered trends regarding the perceptual effects of these characteristics. Moreover, to answer this central research question, this thesis extends to several related research areas, making contributions not only in the fields of architecture and lighting, but also in research methodology, environmental psychology, and visual perception.

The present chapter summarizes the key findings and contributions of this thesis, and discusses the future directions of this work. The first part of this chapter presents the achievements of the present work and outlines their impact for research and practice. Next, the remainder of this chapter presents possible developments of the present work that were identified as promising for further investigation.

8.1 Achievements and impact

This section will present the major achievements of this thesis, starting from those that relate directly to the effect of façade geometry and daylight patterns on human responses and continuing with contributions that relate to methodological considerations. Next, the section will continue by discussing the limitations of the experimental studies in this thesis and identifying the resulting boundary conditions within which the research findings can be confidently applied.

8.1.1 Human responses to façade and daylight patterns

Even though the importance of daylight for architectural design is undeniable, little attention has been paid to the joint impact of architectural elements and daylight on occupants. In particular, although recent studies underline the importance of façade elements for occupant perception, we are lacking a systematic examination of the joint impact of the façade geometry and the resulting daylight patterns on occupants. At the same time, this topic is increasingly relevant, given the growing use of decorative façade patterns in contemporary architecture. This thesis set out with the aim to examine whether the façade and daylight patterns in a space influence human responses and to broaden our understanding on this subject.

Using experimental studies, the present thesis demonstrated that the façade geometry and the corresponding daylight patterns in a space significantly influence both the subjective and physiological responses of participants, addressing the key research objectives 1 and 2 (as stated in Section 1.2.2). In particular, building on the positive findings of Chapter 4, the virtual reality-based experimental method that was developed in this thesis was employed to investigate the responses of participants to interior scenes with varying façade geometry and lighting conditions. This research objective was examined in three different experimental studies presented in Chapter 5 and Chapter 6, with a total sample size of 359 unique participants. To ensure the validity of the conclusions, the façade material, depth, and perforation ratio was kept constant within each experimental study. These experiments revealed a consistent significant effect of façade geometry on the participants' responses, providing concrete evidence that the façade characteristics and the resulting daylight patterns alter an occupants' experience of the space.

While previous studies in the literature examined the observers' emotions or their specific impressions of a sunlight pattern, the work in this thesis is the first to shift the focus of the investigation towards the impressions of a space, which is suggested as a more stable variable. In addition, the combined effect of façade and daylight patterns was investigated across a range of façade geometry variations and spatial attributes. As such, these outcomes of this research have critical implications for the field of architecture and lighting, demonstrating that the façade design and its interplay with light can be used to orchestrate different impressions of a space. Specifically, the façade and daylight patterns consistently affected the evaluations of how pleasant, interesting, exciting, calming, and complex the space is perceived. Moreover, findings revealed that the façade geometry can significantly influence even spatial attributes that are traditionally considered as "objective", such as the brightness, spaciousness, and satisfaction with the amount of view in a space.

The results of the experimental study in Chapter 6, which employed façade variations with a 40% perforation ratio, showed that the façade geometry dramatically affected the satisfaction with the amount of view in the space, with cases of an estimated maximum decrease of 22.9% in reported satisfaction. As this effect was driven primarily by a specific façade variation, this dissatisfaction is shown to stem from the fragmented view of small and irregularly distributed façade openings. Moreover, the same façade variation led to significantly lower evaluations of how bright and spacious the space was perceived. Given the prevalence of similar façade designs in contemporary architecture, these findings are highly relevant, and show that the perceptual effects of such façade configurations should be taken into consideration, particularly for applications where the view to the outside is desired.

Prevalent façade designs: horizontal and vertical stripes

The comparison of specific pairs of studied façade variations was used to pinpoint the façade characteristics that influenced the participant responses. Specifically, the significant difference in the appraisal of two identical scenes with irregularly and regularly distributed rectangular openings in the results of Sections 5.1 and 5.2 demonstrated that the spatial distribution of façade openings is an essential factor in an occupant's experience of space. In particular, the irregular spatial distribution led to significantly higher evaluations regarding how pleasant, interesting, exciting, and complex the space is perceived. Similarly, the findings of the extensive experimental study in Chapter 6 showed that a façade design with slightly skewed vertical elements led to significantly higher ratings of how pleasant, interesting, exciting, calming, and complex the space was perceived compared to straight vertical elements. Further analysis showed that the façade with skewed vertical elements led to an estimated increase of 9.5 to 10% in how interesting and exciting the space was evaluated compared to the one with straight vertical elements. These findings make several contributions to the current literature, with important implications for the building sector. Firstly, results showed that prevalent façade elements, which have regularly distributed openings, might not be perceived positively by occupants. Secondly, these findings reveal that seemingly small changes in the design of the façade, such as the change from straight to slightly skewed vertical elements, can have a dramatic impact in how occupants experience a space, rendering the interior more pleasant, interesting, exciting, and calming.

Moreover, façade designs with horizontal and vertical stripes resulted in the same space being evaluated as significantly less pleasant, interesting, and exciting compared to scenes with other façade geometry variations. In particular, the findings of the preliminary experimental study in Sections 5.1 showed that the façade variation with irregularly distributed openings led to significantly higher evaluations of how interesting and exciting the space was rated compared to the horizontal stripes. This result was confirmed in the subsequent experimental study in Section 5.2, where participants were exposed to the same façade variations. In that study, this finding was replicated solely for a social function scenario of the presented space, indicating an influence of the spatial context towards the participants' perception of horizontal stripes. The extensive experimental study in Chapter 6, which employed additional façade geometry variations and scenes with furniture that explicitly corresponded to a social or working environment, brought additional insights to this topic. In particular, no significant differences were found between façade variations with horizontal and vertical stripes for any of the studied perceptual attributes, suggesting that these two variations are perceived similarly. However, both horizontal and vertical stripes were shown to lead to significantly lower evaluations of how pleasant, interesting, exciting, and calming the space was perceived, when compared with façade variations with irregular façade openings.

As discussed in Chapter 3, in the experiments of this thesis the depth of the studied façade variations was held constant to restrict the number of experimental factors and to allow better control over the light distribution in the space. Consequently, façade systems with horizontal and vertical blinds were represented through simplified two-dimensional patterns with repetitive elements. This approach limits the generalizability of the findings in cases where depth is an additional degree of freedom, such as systems with curved or rotated elements. Nevertheless, the findings of the present thesis challenge the current state of prevalent façade and shading system designs, bringing into question the suitability of repetitive horizontal and vertical elements for applications were impressions of visual interest are of importance. In the same vein, these outcomes demonstrate that irregularity and complexity in the façade design can be a desirable feature, particularly for applications were there is no conflict between the attention to a task and the surrounding environment, such as in a social context. The kinetic façade that was presented in Section 7.2.2 is one such possible direction, demonstrating the potential of improving the design of shading systems by adopting perceptual objectives alongside established performance indicators in the design process.

Physiological responses to façade and daylight patterns

An important objective of this thesis was the investigation of the influence of façade and daylight patterns on both subjective and physiological human responses. The findings of the experimental study in Section 5.2, where participants were exposed to three façade variations under a clear sky in random order, demonstrated in a virtual reality setting that the façade variation influenced not only the participants' impressions, but also their heart rate. Specifically, the mean heart rate change —corresponding to the difference in mean heart rate between a neutral scene, used as baseline in the beginning of the experiment, and the daylit scene with each façade variation— was employed as an indicator of heart rate response. Results demonstrated that the mean heart rate change was significantly lower when participants were immersed in a scene with a façade with irregularly distributed openings, compared to the same scene with horizontal stripes.

This finding demonstrates for the first time that façade elements and their interplay with light can have a quantifiable, physiological effect on occupants. Moreover, it shows the importance of examining an occupants' physiological responses alongside subjective evaluations to broaden our understanding of the effects on the built environment on humans and bring measurable evidence to support design choices. The outcomes of Section 5.2 showed also a significant —albeit small-to-moderate— negative correlation between mean heart rate change and ratings of interest. This finding is consistent with the literature in psychophysiology regarding the orienting response to a stimulus, which states that a shift of attention towards non-aversive novel or significant stimuli is followed by heart rate deceleration. In light of these results, the spatial characteristics of the façade and their interaction with the light landscape are revealed as a means to induce visual attention, and in turn, physiological responses that might be beneficial in a specific context, such as in health care environments. Even though further research is necessary to test the robustness of these findings in a real setting and examine the impact of exposure time to the visual stimulus, the outcomes of this study showcase the potential of employing façade-driven effects in architectural design.

Effects of complexity in the façade and daylight patterns

The experimental findings of Chapters 5 and 6 demonstrated that the spatial distribution of the façade openings is an important visual feature. These results are also in line with the outcomes of the paper-based survey in Section 5.3, which examined the consensus in the evaluations of architects regarding the expected perceptual effects of façade geometry. Specifically, architects were asked to choose the most and least exciting and calming variations of an interior daylit scene across 20 variations of façade geometry. The results of this survey showed that the selection of façade variations that were rated as the least exciting and the most calming only contained designs with regularly distributed openings, while those that were rated as the most exciting and least calming consisted solely of designs with irregularly distributed openings. This survey also revealed a high level of consensus among architects, with variations selected as the most or least effective in rendering a space calming or exciting by up to 50% of the respondents. The agreement between architects makes the subject of empirical evidence even more pertinent, in order to verify whether the assumed perceptual effects of façade geometry are indeed applicable to occupants. The findings from the experimental study in Chapter 6, which employed stimuli that were deemed as promising based on the survey of architects, are generally in alignment with the expected effects of variations with low to medium perceived complexity, but differed in cases of variations with high perceived complexity. This result underlines the importance of examining the occupants' perception and motivates the integration of evidence-based design in the architectural education and practice.

The findings of the experimental studies in Chapters 5 and 6 suggest that façade variations that led to higher evaluations of complexity also led to the space being evaluated as more exciting and interesting, with the findings of Chapter 6 showing a moderate significant correlation between impressions of complexity and interest, as well as between impressions of complexity and excitement. This finding contributes to the literature in the field of environmental psychology, which indicates that complexity is linked with visual attention and sensory stimulation. However, complexity is not the sole attribute that matters, as illustrated by the negative effect on certain spatial attributes induced by the façade variation with irregularly distributed small openings that were discussed above. In particular, scenes with this façade variation, while they were found as more exciting, interesting, and complex compared to both the horizontal and vertical stripes, they also led to significantly lower ratings of satisfaction with the amount of view, as well of how calming, bright, and spacious the space was perceived compared to these commonly used façade variations. Moreover, stimuli that led to high levels of reported complexity were not necessarily the most preferred. The findings of Chapter 6 showed that the relation between the perceived complexity and the pleasantness of a scene resembles an inverted U curve, with intermediate complexity levels generally being perceived as more pleasant compared to either low or high levels of perceived complexity. This outcome is an important contribution to the fields of architecture, visual perception, and environmental psychology, demonstrating that this inverted U-shaped curve between impressions of complexity and pleasantness, which has been found using diverse visual stimuli, is also applicable to variations of façade and daylight patterns. It is thus of particular interest to identify an objective measure that can predict impressions of complexity, which can in turn allow the establishment of ranges of positively perceived complexity in façade design. This research direction and the exploration of the predictive capabilities of objective measures of complexity will be discussed later in this section.

Effects of sky type, spatial context, and regional differences

In line with the research objectives 1.2 and 1.3 of the present work, this thesis also examined the effect of the lighting conditions, of the function of the space, and of possible regional differences on the responses of participants. The results of the experimental studies in Chapters 5 and 6 showed no significant effect of sky type on the impressions of the space, indicating that the façade geometry was the main factor influencing the participants' evaluations. As the façade geometry was the sole within-subject factor in these experiments, this finding indicates that the participants' responses were influenced by the façade variations under the same sky type, and this effect was consistent across the studied lighting conditions. This outcome is particularly relevant for architecture, as it reveals that the perceptual effects of façade design can be anticipated not only within a specific lighting condition, but rather across lighting conditions, rendering the façade geometry an important driver of the occupants' experience of the space throughout the year.

In the same vein, although initial findings in the studies of Sections 5.1 and 5.2, where participants were asked to imagine working or socializing in a space without a visual reference, found an effect of space function on participant impressions, this result was not replicated in the experimental study of Chapter 6. As the experimental scenes in the latter study were specifically designed to be convincing for the aforementioned different uses of space and contained also a visual reference of the intended use, this finding suggests that when participants were immersed in realistic scenarios of a space function, the effect of the façade geometry overshadowed that of the use of space. While this result is limited by the range of studied stimuli, as well as the restricted luminance range of the virtual reality headset, it motivates further work to test whether the occupant impressions of façade and daylight patterns are indeed comparable between different functions of space use.

By replicating the same experimental study in Greece and Switzerland, the present thesis examined the regional differences in the perception of the studied scenes, in alignment with the research objectives. The experimental results of Chapter 6 showed no significant differences between the responses of participants in these two countries. Even though studies in the literature have shown differences in perception between cultural groups, they usually employ groups that are more culturally and geographically diverse. The experimental findings in this thesis contribute to the literature on this subject by indicating that these regional differences might not be present within Europe. Moreover, the results of Chapter 6 demonstrate that the perceptual impressions of façade and daylight patterns are similar between central and southern Europe, using Switzerland and

Greece as case studies. This is a particularly promising outcome for applications of the findings of the present thesis in the building sector, confirming that the studied façade variations are perceived similarly within these European regions.

In addition, further analyses in the same section demonstrated the robustness of façade-driven effects to changes in the type of space and the window size where the façade is applied. These outcomes show that the façade geometry is the main driver of the occupants' spatial experience, inducing perceptual effects that are robust to regional differences, as well as to variations in the sky type, the features, and the function of the space. Following these findings, the façade geometry emerges as a powerful design tool that can shape an occupants' experience of space, with a high application potential across space configurations, as well as across latitudes, at least within the European context.

Prediction of façade-driven perceptual effects

Following the robust façade-driven perceptual effects that were demonstrated in Chapter 6, the experimental data and findings from that section were used further to examine the prediction of these effects, corresponding to the research objective 1.4 of Section 1.2.2. To this end, Section 7.1 explored the capability of existing image-based metrics of contrast and complexity as predictors of the perceptual effects of façade geometry. Specifically, 32 variations of image-based metrics, selected from the literature, were applied to a set of test scenes with the same façade configurations as those used in the experimental study of Chapter 6. The similarity between the distribution of the metric outputs and the distribution of the percentage of positive responses for each perceptual attribute across façade variations was used to select the two most promising metrics for the prediction of how pleasant, interesting, exciting, calming, and complex the space was perceived. These metrics were then applied to the original experimental stimuli from Chapter 6 and their predictive capability was tested through correlation analyses between the metric outputs and the corresponding responses of participants. Results showed strong and significant correlations between specific image-based metrics and the percentage of positive evaluations regarding how complex and calming the space was perceived, and a strong but not significant correlation between image-based metrics and the percentage of positive evaluations of perceived excitement. In particular, the JPEG file size, the contrast metric mSC1, and the perimeter-based metric PNG-PERIM8 were found to be particularly promising indicators of perceived complexity. Building on these findings and the relationship between impressions of pleasantness and complexity that was discussed above, a minimum threshold of positive complexity, below which a façade design is expected to be less likely to lead to high evaluations of pleasantness and excitement, was suggested using these two metrics. These suggested thresholds of positive complexity are highly promising for applications in architecture, as they could be used to inform and support the design process, anticipating the effects of façade design on occupants. As these thresholds and findings are derived from a very limited number of façade variations, future work is encouraged to determine their applicability in a real setting and across a wider range of façade configurations.

Regarding the impressions of how calming and exciting the space was perceived, the JPEG file size and the mSC1 metric were found to correlate with the percentage of positive ratings on how calming and how exciting the space was perceived, respectively. However, further testing with the stimuli and data from the paper-based survey of architects in Section 5.3 revealed that neither metric could successfully predict the equivalent impressions of participants. Given the restricted number of façade geometry configurations used in the selection and testing of these metrics, additional studies are necessary to examine their predictive capabilities and establish objective indicators of façade-driven perceptual effects. Nevertheless, the very strong correlations between the aforementioned image-based metrics and impressions of complexity are particularly promising for the fields of architecture, lighting, visual perception, and environmental psychology. In combination with the aforementioned relationship between impressions of complexity and pleasantness, the establishment of image-based predictive metrics of perceived complexity has great potential for both architecture and lighting design, and could contribute to the design process through integration in design support tools. Moreover, the present findings extend the current knowledge on the prediction of perceived complexity with image-based computational measures, a topic of particular interest for the disciplines of visual perception and environmental psychology.

Application of façade-driven perceptual effects in the design of shading systems

In addition to investigating whether the façade-driven effects that were identified in Chapter 6 can be predicted by image-based measures, Chapter 7 examined their application potential in the design of a shading system. To this end, Section 7.2 presented a novel kinetic shading system that shifts states to not only address requirements for energy efficiency and user comfort, but also to induce occupant delight by increasing the impressions of pleasantness, interest, excitement, and calm. The design of this shading system was driven by the finding of significant differences between the impressions of a space with straight and with slightly skewed vertical elements, that was demonstrated in Chapter 6. Drawing from these findings, the proposed design uses composite vertical elements that twist to change shape and shift between different states. This kinetic shading system shifts between a fully open state that maximizes the view out, a fully closed state that minimizes the incident solar radiation, and intermediate twisted states that aim to induce visual interest. A proof-of-concept study demonstrated the potential of this design by showing that it successfully fulfills requirements for daylight provision and glare protection, while allowing increased view access and creating visually interesting scene features through the twisted states and the resulting daylight patterns. These outcomes motivate further research to verify the expected perceptual effects of the proposed kinetic shading system in a real setting. Nevertheless, this work showcases the application potential of the findings of the present thesis in the design of static and kinetic façade systems that push the boundaries of current practices and contribute to the creation of spaces that are not only comfortable and energy efficient, but also delightful for their occupants.

8.1.2 Contributions to research methods

In addition to the aforementioned achievements, the present thesis made important methodological contributions through the development and validation of a novel experimental method and the use of complementary physiological indicator in the investigation of human responses to architectural elements and lighting conditions.

Virtual reality as a surrogate to real spaces for empirical research

One of the main obstacles in research where daylight is an independent variable, as is the case in the present thesis, is the difficulty of controlling the lighting conditions. While virtual environments have been widely used in place of real spaces in lighting research to address this challenge, the literature reveals several factors of importance to ensure the adequacy of these environments as surrogates to real experimental settings. Firstly, the use of photometrically accurate imaging methods is essential for lighting research, ensuring that the virtual conditions correspond to correct photometric quantities. In the same vein, given the limited luminance range of display devices, this photometrically accurate image has to be mapped to a low dynamic range, rendering the tone-mapping method a central element for the precise control of the visual stimulus. In addition, immersion and interactivity are shown to be important features for the perceptual accuracy of a virtual environment, particularly regarding the pleasantness and the distribution of light in the space, attributes which are crucial for the research objectives of the present work.

This thesis began with the development of a novel experimental method that addresses these factors, combining virtual reality with visual stimuli generated from photometrically accurate images. In line with the research objective 1.1, the adequacy of this experimental method was examined in two independent studies that used simulation- and photograph-based immersive scenes. These experimental studies, described in Chapter 4, compared the perceptual accuracy of immersive scenes against the equivalent real daylit environments and were the first to demonstrate the validity of using virtual reality for lighting research on perception. Specifically, the experimental study in Section 4.1, that compared real daylit environments and simulation-based immersive scenes, demonstrated a high level of perceptual accuracy and perceived presence in the virtual environment and no significant effects of using the virtual reality headset on the physical symptoms of the user.

The second experimental study, described in Section 4.2, employed both real and photograph-based virtual environments with a dual aim: to test the perceptual accuracy of highly detailed immersive scenes shown with an improved version of the virtual reality headset, and to compare the performance of the three most promising tone-mapping operators according to the literature —Reinhard02, Ward97, and Durand02— in a virtual reality setting. To the author's knowledge, this is the first study to examine the perceptual accuracy of different tone-mapping operators for virtual reality against real daylit environments, contributing not only to lighting research, but also to the fields of computer graphics and display technologies. The analysis showed no statistically significant differences between the participants' responses in the real and the virtual environments regarding how pleasant, interesting, exciting, calming, and bright the space was perceived or how diffuse, contrasted, and uniform the light was in the space. These findings demonstrated that the immersive virtual scenes can be used to adequately convey the visual experience of a real space for the studied perceptual attributes, and validated the use of the developed method for this thesis. Since no effect of environment was found for any of the studied attributes and tone-mapping operators, a second indicator based on effect size was used to compare further the perceptual accuracy of the three operators. The results showed that Reinhard02 was the most perceptually accurate tone-mapping operator overall, followed by Durand02 and Ward97. Moreover, the outcomes of this study identified instances where one tone-mapping operator might outperform others for specific perceptual attributes, and thus these findings can be used as a reference for the selection of a suitable tone-mapping operator for virtual reality according to the studied attributes.

Following these findings, the developed virtual-reality based method, combining physically-based simulation, tone-mapping with the Reinhard02 operator, and projection in a virtual reality headset, was used for the core experimental studies of the present thesis. Moreover, these particularly positive results showcase the potential of this experimental method for empirical studies not only in the context of this work, but in multiple research areas that investigate the perception of interior scenes, such as lighting, architecture, and environmental psychology.

Although the limited dynamic range of the device restricts its use for studies that necessitate visual stimuli with high luminance —such as for the investigation of discomfort glare—, the proposed method is a highly promising experimental tool that allows complete control over the visual stimulus, while offering immersion and accelerating the conduction of experiments. In addition, the advantages of this experimental method are particularly relevant for the examination of robustness and consistency in experimental results, as the control and mobility of the visual stimulus offered by head-mounted displays allows the seamless replication of experiments with identical stimuli.

The developed experimental method, which combines immersive virtual reality with scenes based on photometrically accurate images, has already been employed in other investigations, a fact which highlights its usefulness for the lighting research community. In particular, this method was used to investigate the interactions between the visual and thermal perception of occupants [Chinazzo et al., 2017, 2019], as well as the visual interest [Rockcastle et al., 2017b] and the perception of brightness [Omidfar Sawyer and Chamilothori, 2019] in simulated daylit interiors. Moreover, due to the growing interest of the public towards virtual reality technology and the immediate personal experience offered through the use of a virtual reality headset, the developed method is highly promising for public outreach and education on lighting science.

Physiological indicators in studies investigating human perception

As discussed earlier in this chapter, the present thesis was the first to demonstrate in a virtual reality setting that the façade and daylight patterns in a scene can influence an observer's physiological response, and specifically their heart rate. Although further research is necessary to test the robustness of these findings and their generalizability in a real environment, these results showcase the potential of using physiological indicators as complementary measures in experimental studies that investigate human perception. While the findings of Section 5.2 showed a significant effect of façade and light patterns on the participants' mean heart rate, but not on skin conductance indicators, both measures are useful in drawing research conclusions according to literature that relates physiological and emotional responses. By employing physiological indicators in combination with traditionally used subjective evaluations, research on the perception and preference of occupants can greatly increase the validity of the conclusions drawn from empirical studies. In that regard, this thesis provides an example of the potential and the relevance of this approach for research in the intersection of architecture, lighting, and human perception.

8.1.3 Applicability of research findings

One of the most critical limitations of the experimental studies in the present thesis is the limited exposure time to the studied scenes, ranging from roughly half a minute to a few minutes of immersion in the virtual environment. While this approach is common practice for the collection of both subjective [Cauwerts, 2013; Abboushi et al., 2019] and physiological [Laumann et al., 2003; Rajae-Joordens and Hanique, 2012] immediate responses to an environment, it restricts the generalizability of the findings to cases of longer exposure. As such, the experimental findings of this thesis can be applied to with equivalent duration of exposure time, such as transitional spaces (entrances, corridors) or other uses of space with a high occupant turnover rate (such as a waiting area in a hospital or a hotel lobby). Additional studies are necessary to examine the applicability of these findings over longer periods of time. Another perspective of this limitation is the exposure not only to a specific condition, but also to the broader visual characteristics of a façade design. As will be discussed further in Section 8.3, façade variations which in this thesis were evaluated as particularly interesting might not induce these responses if such designs are prevalent and thus lack novelty.

Along with the exposure time, the methodological choices for the characteristics of the studied experimental stimuli impose another set of boundary conditions on the generalizability of the research findings of this thesis. As explained in Chapter 3, the perforation ratio, depth, and material of the façade were kept constant across the studied façade variations in each experiment to ensure the validity of the conclusions that can be drawn from the present thesis. Consequently, experimental findings are expected to hold true for conditions with similar characteristics, and further studies are needed to test and expand their applicability over a wider range of attributes. Similarly, the view to the outside was held constant within each experimental study. This approach, while necessary to limit the number of independent variables, raises the question of the impact of view content on the perception of space. A particularly attractive or interesting view —in contrast to the neutral view used in this thesis— might overshadow the effect of the façade design, or even lead to the façade being perceived as an obstacle to the view, rather than a source of visual interest.

Another important point for the applicability of the research findings of this thesis is the restricted luminance range of the virtual reality headset that was used in the experimental studies. While the studies in Chapter 4 demonstrated that the virtual reality-based experimental method can accurately reproduce the perception of real daylit spaces, the experimental stimuli in virtual reality are restricted to comfortable lighting conditions. As a result, the perceptual effects of façade and daylight patterns that were uncovered in this thesis are expected to hold true in equivalent settings, and further studies are needed to test their generalizability in high luminance and potentially visually uncomfortable lighting situations.

8.2 Future research directions

This thesis made important contributions to the fields of architecture and lighting research, broadening our knowledge about the effects of façade geometry and daylight patterns on human responses, and introducing novel experimental methods that facilitate the conduction of empirical research. In this process, several promising research directions for future work were identified and will be discussed in this section.

Starting from improvements in research methods, it would be of interest to advance further the experimental method that was developed in this thesis by increasing the user interaction in the scene. Although current technological limitations restrict the usability of real time physically-based rendering in virtual reality, a virtual environment that can be freely navigated and explored, particularly with real movements, has the potential to vastly increase the participants' sense of presence in the scene. Methods such as rendering to texture [LaMar et al., 1999] or GPU-based lighting simulation [Jones and Reinhart, 2014] are promising ways to generate immersive environments that can allow the user to interact with the scene. Moreover, new technological advancements that allow the representation of additional sensory modalities, such as devices that allow the perception of stiffness [Salerno et al., 2019] or temperature [Maeda and Kurahashi, 2019] in the virtual environment, can also enhance the realism of the scene and permit the study of multiple human senses and their interactions.

The work of the present thesis has shown that a static 360° immersive environment, where the observer can only look around, is sufficiently perceptually accurate to represent the experience of a real environment. However, there is no doubt that increasing the user's interaction with the immersive scene will further increase the experiential realism of the virtual environment [de Kort and IJsselsteijn, 2006]. The question that emerges, thus, is the level of both visual and experiential realism that is necessary for different investigations, and how much can improvements in either area contribute to the perceptual accuracy of the virtual environment. Another important subject for future work regards the validation of the use of rating scales in virtual reality. The methodological choices that concerned the rating scales used in the present thesis were based on the existing literature, where rating scales are predominantly used in a physical questionnaire. Further studies are necessary to investigate the effects of administering a verbal questionnaire in virtual reality with and without a visual reference, and to test against real environments methodological choices such as the number of rating scale items [Atli and Fotios, 2011], or the use of other subjective assessment methods, such as paired comparisons [Houser and Tiller, 2003].

Following the positive findings from the use of physiological measures in this thesis, future research is encouraged to examine the potential of additional indicators for the investigation of human responses to the surrounding environment. Two interesting options that can be easily combined with virtual reality are electroencephalogram (EEG) and eye-tracking devices. Both measures seem very promising for architecture and lighting research, with previous studies demonstrating significant effects of design characteristics of interior spaces on EEG responses [Hakak et al., 2016], and links between gaze direction and design composition of both architectural interiors and façades [Weber et al., 2002; Hasse and Weber, 2012]. Interdisciplinary collaboration is crucial to ensure rigor in the collection of such data, as well as the validity of the hypotheses, analyses, and interpretation of the results.

An important research direction to extend the findings of this thesis is the conduction of experiments in real environments. Investigations in real-world settings, either in laboratories or field studies, will significantly contribute in testing the robustness and generalizability of the façade-driven perceptual effects that were demonstrated in the present work. If these effects are confirmed in real spaces, and possibly linked with quantifiable indicators such as absenteeism, task performance, or stress levels of occupants, they would provide an important incentive in considering both the potential and the implications of façade design on human factors. The conduction of experiments in real environments can also allow the investigation of the impact of different activities performed by occupants on their preference and perception. While the present work employed verbal or visual references to different scenarios of use of the experimental scenes, the conduction of several activities by the participants would greatly increase the validity of the findings. Moreover, such studies are necessary to address an important open problem: what is the relation between the attention to a task, visual interest, and visual comfort? In the same vein, when does sensory stimulation, for example from architectural elements or light patterns, shift from being desirable to being uncomfortable in a real setting?

On the subject of architectural façade elements, additional studies are needed to unveil the effects of specific design characteristics on human responses. This thesis focused on varying the shape and distribution of the façade openings, while keeping the perforation ratio, depth, and material of the façade constant within each experimental study. Further research is essential to determine the perceptual impact of varying these façade attributes. Of these aspects, the perforation ratio is of particular importance, given the existing knowledge on the considerable impact it has on assessments of beauty and preference [Friedenberg and Liby, 2016]. Additional studies that investigate the perceptual effects of the three-dimensionality of façade designs, using stimuli with varying depth, rotating elements, or complex shapes, are also necessary to broaden our knowledge on the joint impact of architecture and light on occupants.

Similarly, another topic of interest is the examination of incremental changes in the geometry of the façade, which can help pinpoint the specific visual features that impact the perception of occupants. Experiments with a wider range of façade characteristics are necessary to uncover additional links between façade design and occupant perception, which can in turn be used in the design of static and kinetic façade systems. Such experiments would simultaneously allow further investigation on the promising predictors of façade-driven perceptual effects that were identified in this thesis, that could be used to inform and support the design process.

The present thesis showed no significant influence of sky type on the perception of space, indicating that the effect of the façade geometry overshadowed that of the lighting conditions. Due to the use of façade geometry as a within-subject experimental factor, this outcome signifies that when exposed to a single sky condition, the participants' impression of space was affected by the different façade designs, a finding which was constant across the studied sky types. Additional studies employing the sky type as a within-subject factor are necessary to investigate this finding further and to compare the relative effect of façade geometry and of sky type on the perception of occupants.

Another promising research direction is the investigation of the perceptual effects of façade geometry in combination with the view to the outside. The view through the façade influences not only the contrast between the foreground and the background, but also the impressions [Aries et al., 2010] and gaze behavior of occupants [Sarey Khanie, 2015], and has been shown to depend on the view content, such as the presence of nature, the view distance and the number of visual layers [Hellinga and Hordijk, 2014; Matusiak and Klöckner, 2015; Sarey Khanie, 2015]. As a result, the effects of the façade geometry on occupant impressions of the space —as well as the robustness of the prediction of these effects— might be greatly affected by the access and the quality of view to the outside. Further studies are encouraged to employ varying conditions of view out to examine the relative effect of view content and façade design on space perception.

The operability of the façade system —for example, if it is retractable or fixed— is another important aspect which has been found to influence the occupants' satisfaction with the indoor environment [Pastore and Andersen, 2019b]. Although this façade attribute was not addressed in the present thesis, the level of façade operability could also affect the impressions of the space, as it relates to the perception of enclosure and view access, and is thus an interesting area for future studies.

The size and occupancy level of a space, as well as its function, could also affect the relevance of the façade operability and the corresponding effects of perceived personal control on occupants. The interior scenes used in the experiments of this thesis did not include occupants, to avoid introducing an additional independent variable. Nevertheless, the occupancy level of a space has been found to influence physical and psychological discomfort of occupants [Aries et al., 2010] and can affect the satisfaction with the environment [Duval et al., 2002]. Moreover, although the experiments of Chapter 6 specifically tested the robustness of facade-driven perceptual effects across two spaces of different sizes, the furniture placement in relation to their volume and the lack of occupants render them similar in terms of perceived personal space. Additional investigations are necessary to examine spaces with even more contrasting volume and available surface per occupant: would these findings apply in a crowded office, or a vast airport terminal?

The subject of sociocultural effects on the perception of façade and daylight variations also warrants further research. Although no significant differences were found between the responses of participants in Switzerland and Greece, such effects might exist between populations with wider cultural and geographical differences. Moreover, the experimental studies in this thesis were conducted with participants from western, educated, industrialized, rich and democratic (also referred to with the acronym "WEIRD") societies, a common limitation of research on human psychology and behavior [Henrich et al., 2010]. Additional demographic characteristics, such as age, social class, education level —some of which were not collected in the present thesis— can be used to further test the generalizability of research findings across different populations.

8.3 Outlook

The outcomes of this thesis showed a strong link between perceived complexity, visual interest, and attention to a stimulus, with significant correlations between impressions of complexity and interest, as well as between interest and heart rate deceleration, the latter being an indicator of visual attention. These findings relate to theories in environmental psychology, which state that visual characteristics of nature —including complexity— can induce involuntary visual attention, which in turn, contributes to restoration from stress. This link between the present work and environmental psychology outlines a very promising research area, and motivates further studies to examine the stress restoration potential of façade geometry variations.

Both the complexity and the novelty of a stimulus are considered crucial factors in the creation of interest. In this thesis, the stimuli that were perceived as complex were also novel, due to the prevalence of façade variations with regular openings. However, the novelty of a stimulus is an attribute that is expected to diminish with prolonged exposure to the stimulus, due to increasing familiarity. This possibility motivates further work to differentiate between the effects of novelty and complexity. If the visual characteristics of the stimulus, rather than its novelty, are driving human responses, these responses should be replicated with stimuli that are complex but not novel, such as the shadow of a tree.

While no significant effect of sky type was found in the present work, the effect of façade geometry was consistent across different lighting conditions. This outcome is particularly promising for applications in architectural practice and façade industry, as it delineates the façade as a critical design element with significant effects on occupants. The work of this thesis also demonstrates the importance of integrating occupant perception in space performance requirements, an area of growing interest in the recent years [Steemers and Steane, 2012; Amundadottir et al., 2017]. The façade-driven perceptual effects that were demonstrated in this thesis also imply that the visual characteristics that induced the participant responses could be found —or created— in other visual stimuli. Unfortunately, in this thesis, the façade geometry and the daylight patterns were investigated jointly, and thus it was not possible to examine whether the findings would be consistent in a scene where only light patterns are present. Further studies are necessary to investigate this possibility and examine whether the spatial characteristics of light can influence occupants independently of the architectural elements in a scene. This research direction has a high potential for applications in lighting design and the creation of artificial light patterns with visual characteristics that can elicit desired responses.

Lastly, the work of this thesis, which lies on the intersection of several disciplines, aims to motivate further research towards a greater understanding of humans and their responses to the built environment. This thesis hopes to instill in both researchers and practitioners the importance of establishing a "science of architecture", which bridges scientific methods and design with a focus on occupants. In the context of lighting and architecture, this thesis brings unique insights on how the built environment and its interplay with light influences humans, demonstrating that design decisions regarding a single building element —the façade— can have a profound impact on occupants and their experience of space.

Acknowledgements

The fascinating journey that led to this thesis included the help and support of many people. I would like to thank:

My advisors, Prof. Marilyne Andersen and Dr. Jan Wienold, for their extraordinary guidance, expertise, and enthusiasm. Marilyne, thank you for inviting me to be part of LIPID and providing an amazing environment for me to grow personally and professionally. Since our first meeting in Bressanone in 2013, your scientific curiosity, perseverance, and positive attitude have been an inspiration. Jan, your attention to detail and broad knowledge have been instrumental in my thesis and my attitude towards research. I am thankful for your continuous supervision and ingenious solutions to all kinds of scientific problems. Thank you both for allowing me to set and explore my own research path (and infamous "side projects") and supporting me in the process. I am looking forward to our next projects together.

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Alex, for his incredible patience and love, and for our continuous common adventures in Greece, Switzerland, and soon in the Netherlands.

My parents, for their love and unwavering belief that ”I can do everything”. You have both shaped not only me, but also this work through our long conversations and your insights on architecture and on research: this thesis is dedicated to you.

Appendix A

Appendix

A.1 Material for the simulation-based and photograph-based immersive scenes

A.1.1 Radiance sky description (gendaylit)

The gendaylit script in *Radiance* can generate a sky description based on given sky radiation measures, date and local standard time. As the experiment would take place in November, we calculated the diffuse horizontal and direct normal irradiance for overcast and clear skies in this month. Using the Geneva 067000 (IWEC) EPW weather file, we selected the days in November with overcast and clear skies and their hourly values were used to interpolate the diffuse horizontal and direct normal irradiance for every half hour. The values corresponding to the hour and sky type selected for our simulations, shown in Table A.1, were then used in the gendaylit script with the –W option to create descriptions of sky for each scene. The two scenes with overcast sky had an identical sky description and different images mapped on the Radiance sky.

A.1.2 Material properties for environmental projections in Unity 5

In order have full control over the environment projected in VR, we applied an unlit two-sided material to the cube, ensuring that the textures were unaffected by lighting sources in Unity and the scene appeared correctly from the user's point of view. The

Table A.1 – Diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI) used in gendaylit to generate the description of sky for each of the rendered scenes.

Time of day	9:30	10:30	11:30	12:30	13:30	14:30	15:30	12:30
Sky type	clear	clear	clear	clear	clear	clear	clear	overcast
DHI	493.6	686.8	742.5	86.6	737.1	729.6	653.5	486.6
DNI	93.3	84.5	86.6	92.6	86.1	83.3	74.6	3

material is created by manipulating the default *Unlit Shader* in Unity and adding the option *Cull off*, which enables the rendering of all faces of the objects in the Unity scene. These settings were applied in Unity 5.6.2f to develop the immersive scenes in this thesis.

A.1.3 Luminance comparison in the real and simulation-based environments

In order to provide a measure of the luminance discrepancy between the real environment and its virtual representation projected in the Oculus DK2, we compare the luminance in 7 reference points between the two environments. First, we group the 29 experimental sessions based on the sky type of the projected virtual scene in the session, either clear (N=5) or overcast sky (N=24). Using as reference the 180° HDR photograph of a randomly selected session from each group, transformed into an angular fisheye projection, we simulate the scene from the same viewpoint with the photograph as a 180° fisheye image with the equivalent rendering settings and ambient data as the virtual scene that was shown in this particular session. The luminance in the real space is directly measured from the HDR photograph, while for the projected images of the virtual space it is derived using the response curve of the Oculus DK2 display. As our reference for the luminance in the real space is an HDR photograph taken from a viewpoint behind the subject (Figure 4.8), rather than from their point of view, we choose to reproduce the virtual scene of the session from the same viewpoint. Although the resulting luminance measurements do not directly correspond to those from the subject's point of view, they allow for comparable assessment of the luminance deviation between the real and virtual scenes, shown in Figure A.1.

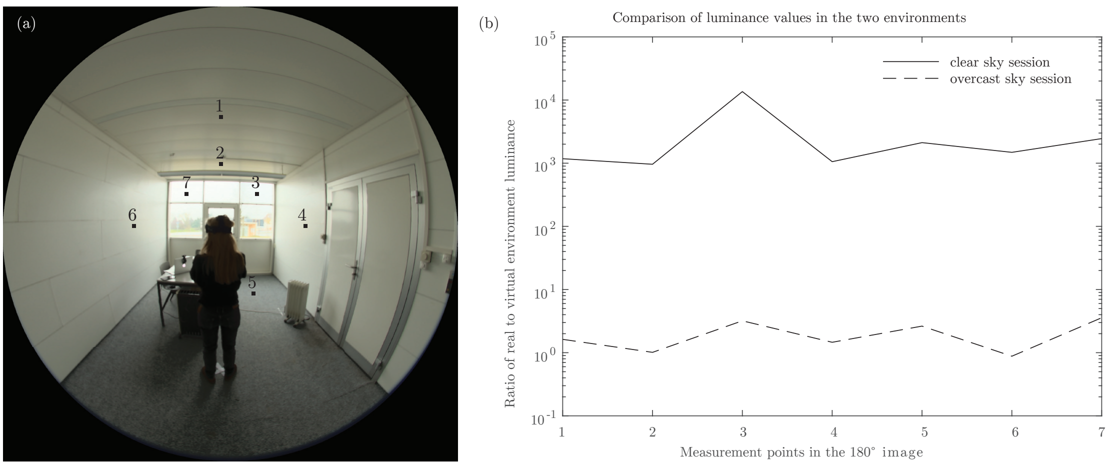


Figure A.1 – Reference points on the fisheye images (a) and ratio of the luminance measurements in those points between the real and virtual environments for the equivalent sessions in both sky types, using a logarithmic scale for the y axis (b).

A.1.4 Cubemap projections for the preliminary study comparing TMOs

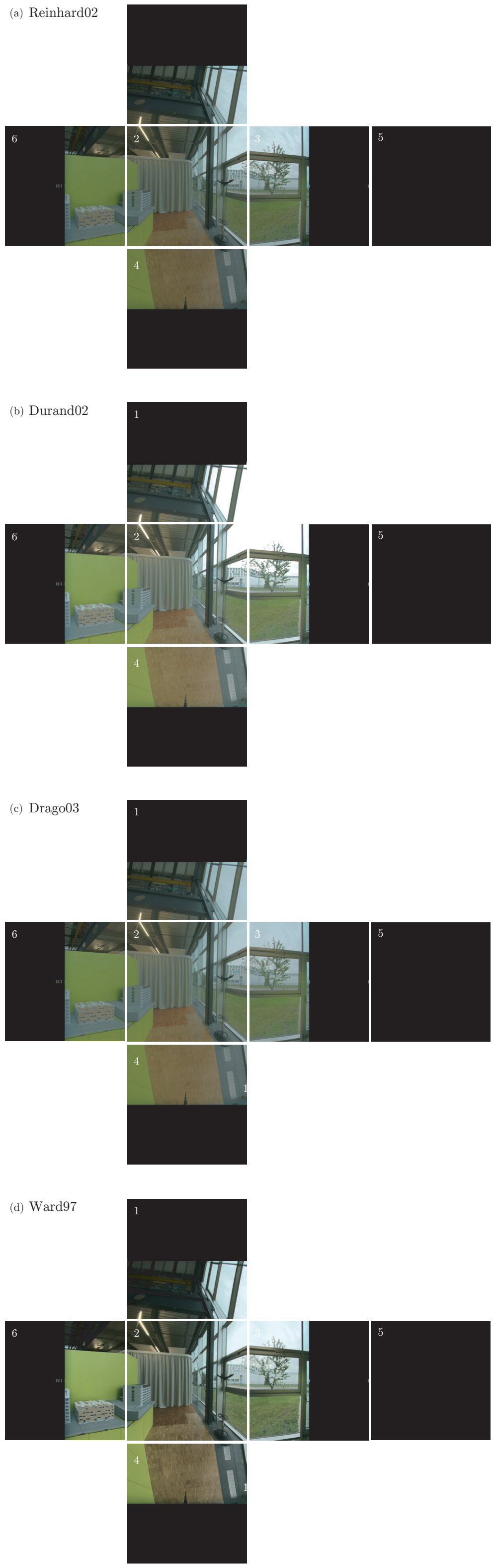


Figure A.2 – Illustration of the cubemap projection for the first scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

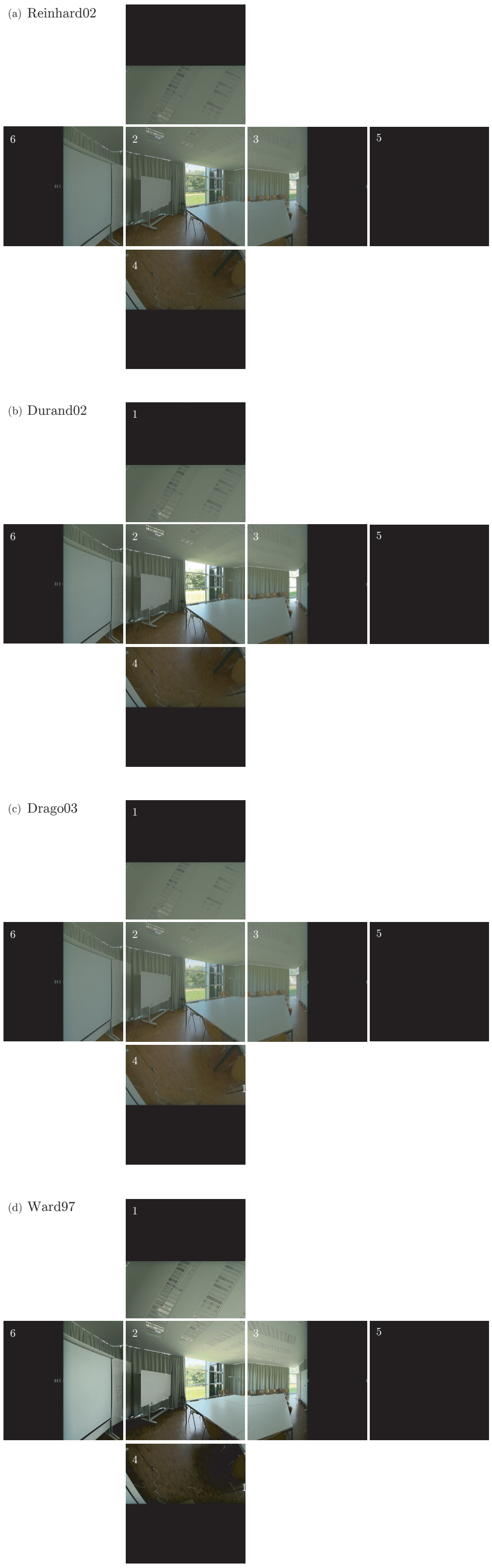


Figure A.3 – Illustration of the cubemap projection for the second scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

(a) Reinhard02

(b) Durand02

(c) Drago03

(d) Ward97

Figure A.4 – Illustration of the cubemap projection for the third scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

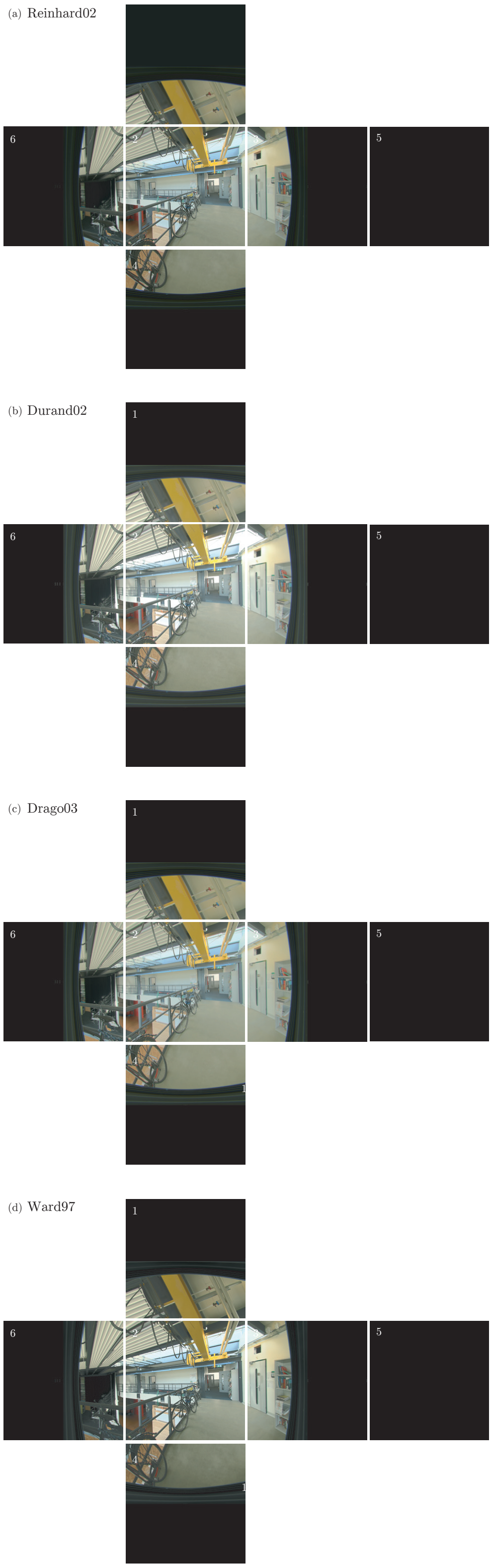


Figure A.5 – Illustration of the cubemap projection for the fourth scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

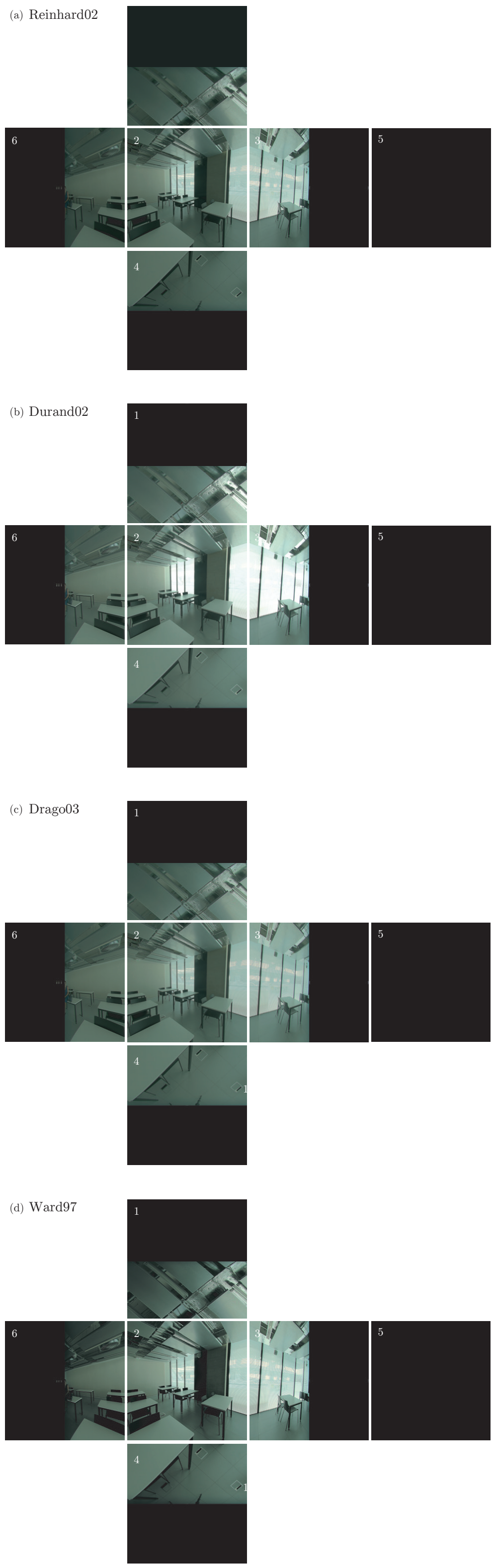


Figure A.6 – Illustration of the cubemap projection for the fifth scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

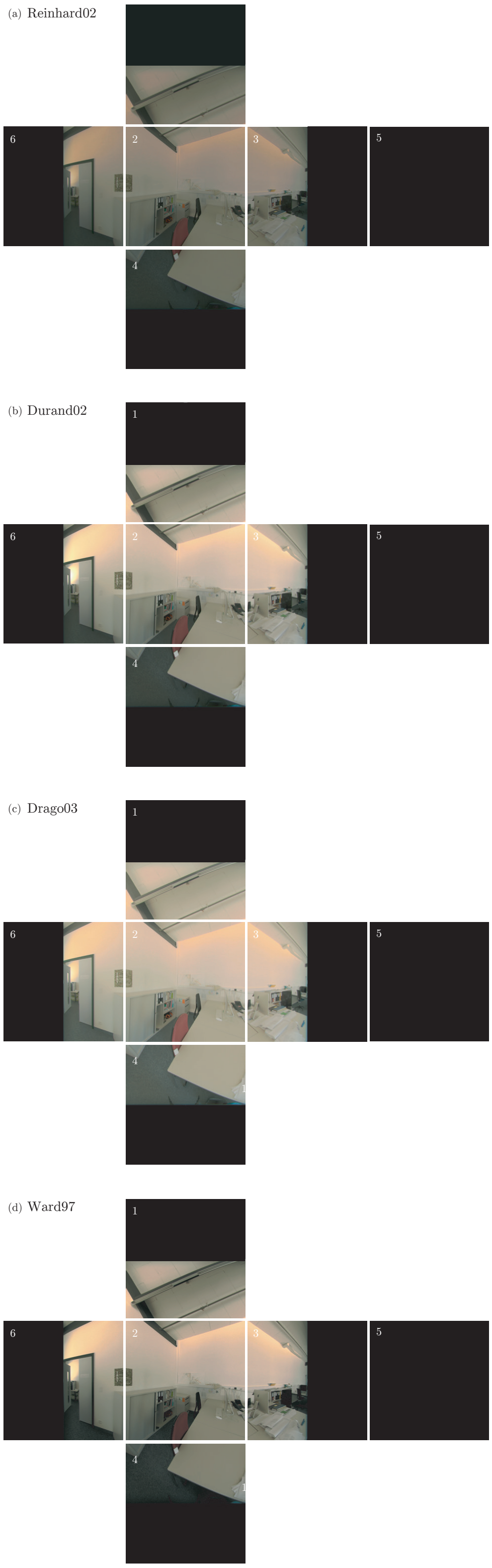
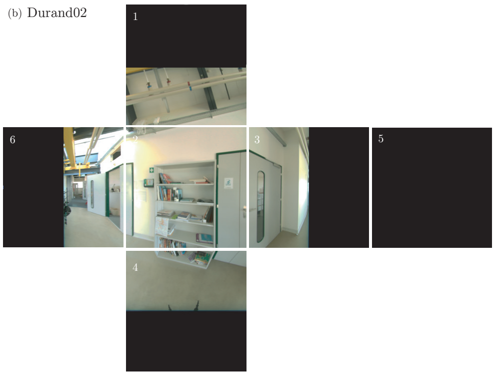


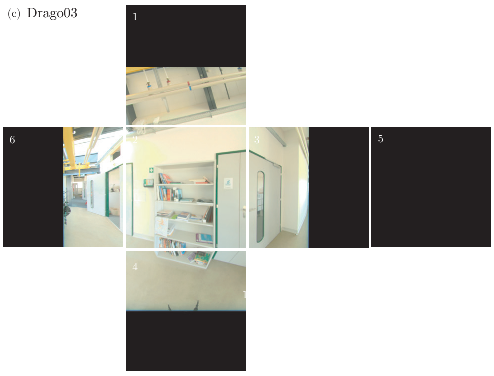
Figure A.7 – Illustration of the cubemap projection for the sixth scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

(a) Reinhard02

(b) Durand02



(c) Drago03



(d) Ward97

Figure A.8 – Illustration of the cubemap projection for the seventh scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

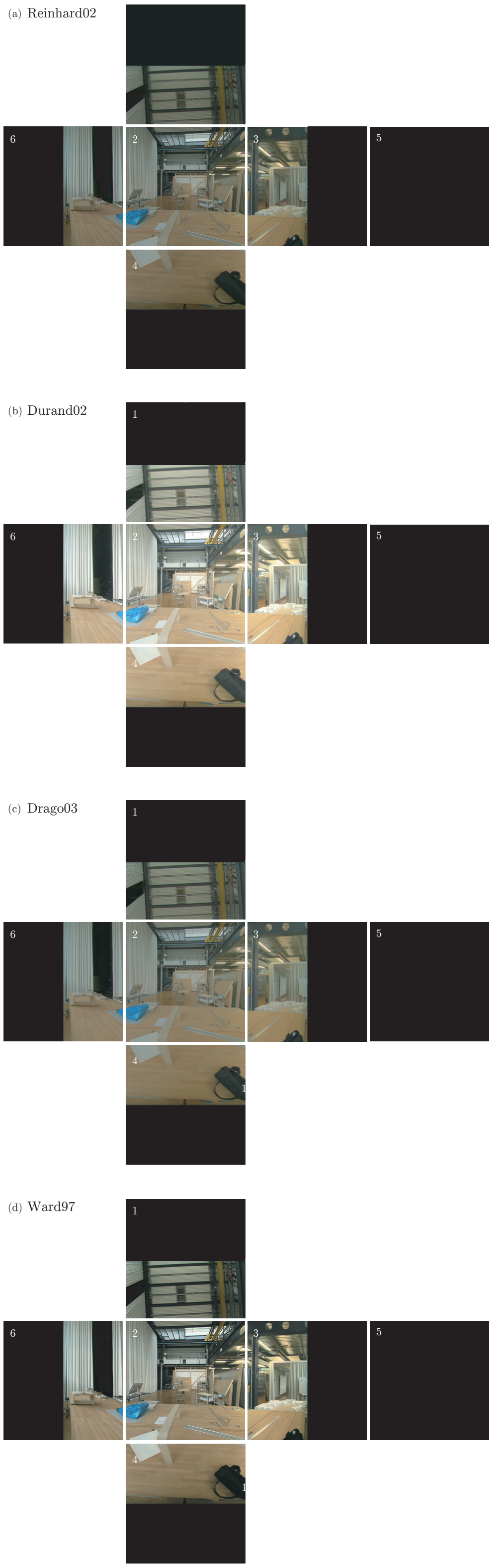


Figure A.9 – Illustration of the cubemap projection for the eighth scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

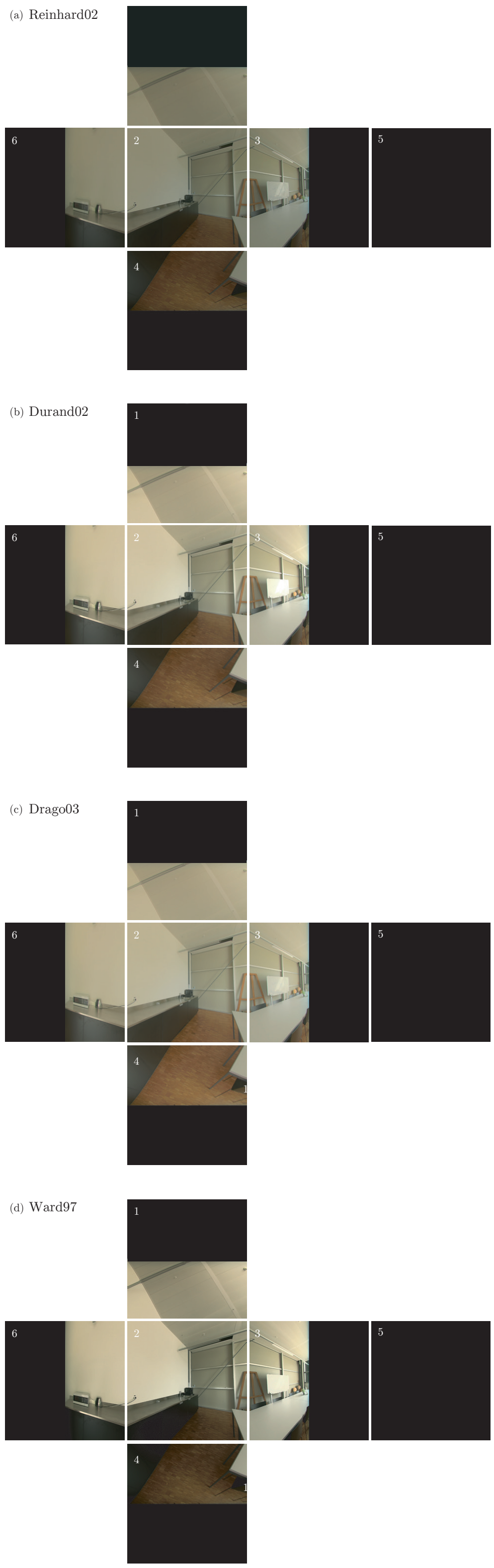


Figure A.10 – Illustration of the cubemap projection for the ninth scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

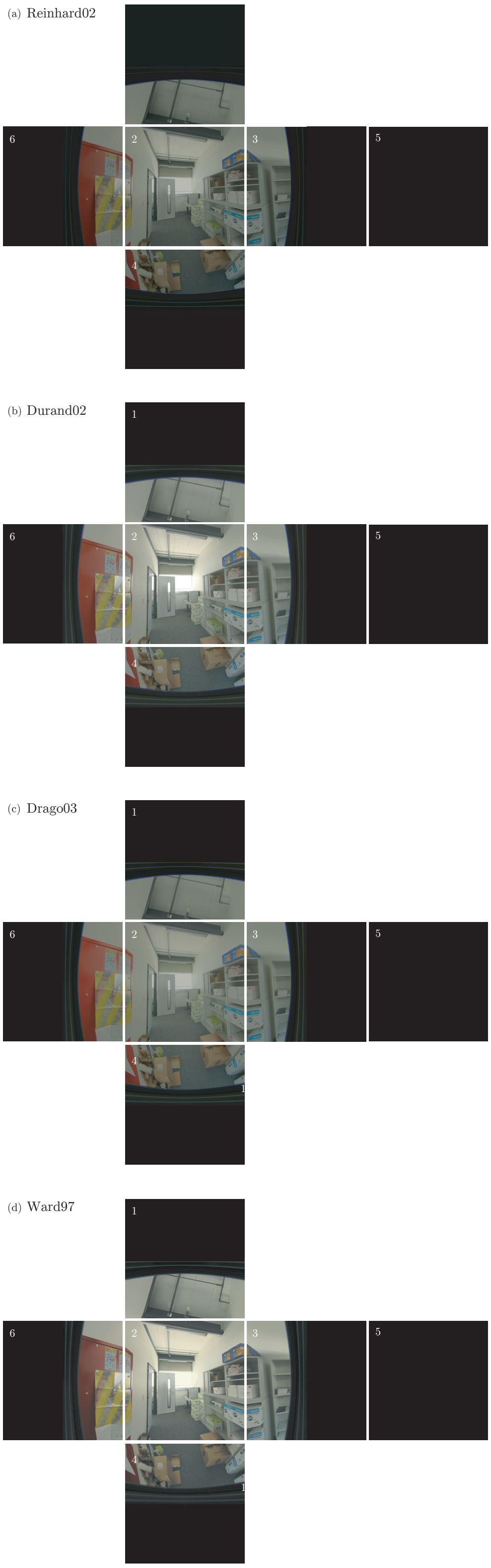


Figure A.11 – Illustration of the cubemap projection for the tenth scene shown in the preliminary study described in chapter 4.2.1, tone-mapped with the four studied tone-mapping operators.

A.1.5 Comparison of measured and HDR-derived vertical illuminance

In order to test the validity of the HDR images that were used to generate the tone-mapped immersive scenes, the vertical illuminance of the scene, measured at the lens level, was compared with the corresponding vertical illuminance derived from the calibrated HDR images after the completion of the experiments. The vertical illuminance of each HDR image was calculated using the Evalglare tool [Wienold and Andersen, 2016]. Due to technical problems, vertical illuminance measurements were collected in the real environment for 59 out of 63 experimental sessions. Of these, 85% did not exceed the commonly used 20% error rate when comparing the HDR-derived and measured vertical illuminance, while 98.3% did not exceed the threshold for a just noticeable change in illuminance [European Committee for Standardization (CEN), 2011], which is the principal concern for the purpose of this experiment. In the sole experimental session where this last threshold was exceeded, the difference in measured and HDR-derived vertical illuminance was equal to 10 lux (and thus considered negligible), and the session was retained for the further analyses of the participants' responses.

A.2 Effect of environment presentation order on perceptual accuracy

The presentation order of the experimental stimuli has been identified as a possible influencing factor in relevant studies [Bishop and Rohrmann, 2003; Newsham et al., 2010; Kuliga et al., 2015]. In this section, we investigate the effect of presentation order on the perceptual accuracy of the experimental method. To this end, we will present the relevant results of the two experiments that used simulation-based and photograph-based virtual environments, introduced in Chapter 4.

We categorize the responses of the participants into two groups: responses of participants that saw the real environment first (RF) or virtual environment first (VF), with sample sizes N_{RF} and N_{VF} respectively. As we are interested in identifying an effect on the perceptual accuracy of the method, we test the differences between the paired responses in the two environments, by subtracting the evaluations of the virtual environment from those in the real environment for the same participant. Due to the non-normality of our data, we use a Wilcoxon Rank Sum test for independent ordinal data to compare the perceptual accuracy of the two groups (participants who saw the real environment first, and participants who saw the virtual environment first) for all the studied attributes. As in this analysis we are seeking a significant difference and conducting multiple comparisons, we use a more conservative threshold for statistical significance using a Bonferroni correction and dividing the conventional significance level α of 0.05 with the number of items tested for each experimental study.

The analysis of the dataset of the study in the simulation-based virtual environment, with a total sample size of 29 participants with a Wilcoxon Rank Sum test conducted at the Bonferroni-corrected significance level $\alpha' = 0.05/5 = 0.01$ showed no statistically significant differences between conditions of presentation order for the perceptual accuracy of the studied attributes ($ps > 0.80$), with the exception of a medium sized significant effect on the perceived pleasantness ($z = 3.39$, $p = 0.00007$, $r = 0.63$). For the analysis of the dataset from the study with the photograph-based virtual environments, we use a Bonferroni-corrected significance level $\alpha'' = 0.05/8 = 0.00625$. A Wilcoxon Rank Sum test showed no statistically significant effect of presentation order on the perceptual accuracy of the studied attributes (all $ps > 0.007$).

In the case of the significant effect of presentation order on the perceptual accuracy of reported pleasantness, the means of the two groups, $\mu_{RF} = -0.714$ and $\mu_{VF} = 0.357$, are very enlightening, as each group consists of the responses in the virtual space subtracted from their paired responses in the real space. A mean with a negative sign shows that the virtual environment was rated more positively that the real one and vice versa for a positive sign. This finding indicates that the second environment that was experienced by the participant, independently of its type, was evaluated as more pleasant. Contrary to the findings of Newsham and others [2010], who identified an effect caused by a particular presentation order, reporting that there were fewer differences between real and virtual environments for participants who saw the real space first, we observed an effect of order which depends on the sequence rather of the type of presentation, impacting how pleasant the space was perceived. However, this finding was not replicated in second experimental study that employed photograph-based virtual environments. Although the results approached significance for specific attributes, such as the perceptual accuracy of the perceived excitement ($p = 0.007$), this was not the case for the perceived pleasantness of the scene. Nevertheless, it is interesting to note that the means of the two groups for the perceptual accuracy of perceived excitement ($\mu_{RF} = -0.781$ and $\mu_{VF} = 0.442$) follow the trend that was observed previously for the perceived pleasantness in the first study, with the second environment that was presented being evaluated more positively.

A.3 Effects of confounding variables on subjective and physiological responses to façade variations

In this section, we investigate possible effects of confounding variables on the findings of the study presented in section 5.2. To this end, we perform analyses on the effect of stimulus presentation order, time of day, and participant gender on all the studied variables for the three façade variations considered together. For brevity, only significant results are reported for this analysis. In addition, to address the air temperature variation in the experimental room, the data for all dependent variables was tested by comparing the two main temperature groups to ensure there is no effect of temperature. Results of a Wilcoxon Rank-Sum test revealed no significant effect of temperature for any of the studied variables. The effect of stimulus presentation order (with six possible combinations) was investigated with a Kruskal-Wallis test, and showed no influence on any of the dependent variables.

A Wilcoxon Rank-Sum test for the time of day of the experimental session (morning or afternoon) showed a significant effect of time on evaluations of pleasantness ($z =$

$2.04, p = 0.04, r = 0.14$) and interest ($z = 3.23, p = 0.001, r = 0.22$). The median ratings for the morning and afternoon sessions reveal that evaluations were more positive in the morning sessions for both how pleasant ($median_{morning} = 5$, $median_{afternoon} = 4$) and how interesting ($median_{morning} = 5$, $median_{afternoon} = 4$) the space was perceived, indicating perhaps that fatigue influenced the participants' judgements. The effect of gender was investigated with a Wilcoxon Rank-Sum test. Gender was shown to have a significant effect on how exciting the space was perceived ($z = 2.40, p = 0.02, r = 0.18$), as well as on ΔHR ($z = 3.69, p = 0.0002, r = 0.28$) and ΔSCR ($z = 3.28, p = 0.001, r = 0.25$). In particular, men evaluated the space as more exciting ($median_{men} = 4$, $median_{women} = 3$) and they showed a response of larger magnitude on both ΔHR ($\mu_{men} = -6.61$, $\mu_{women} = -1.61$) and ΔSCR ($\mu_{men} = 0.04$, $\mu_{women} = -0.02$). Although these findings do not affect the validity of the main results of this study, where gender was counterbalanced, they have important implications for the experimental design of future studies investigating these variables.

A.4 Paper-based survey on the expected perceptual effects of façade variations

Table A.2 – *Radiance* rpict parameters for the perspective view renderings (-vtv).

-ps	-pt	-pj	-dj	-ds	-dt	-dc	-dr	-dp	-st	-ab	-aa	-ar	-ad	-as	-lr	-lw
2	.05	.9	.7	.15	.05	.75	3	512	.15	4	.1	512	2048	1024	8	.005

Resolution: 966x648 pixels.

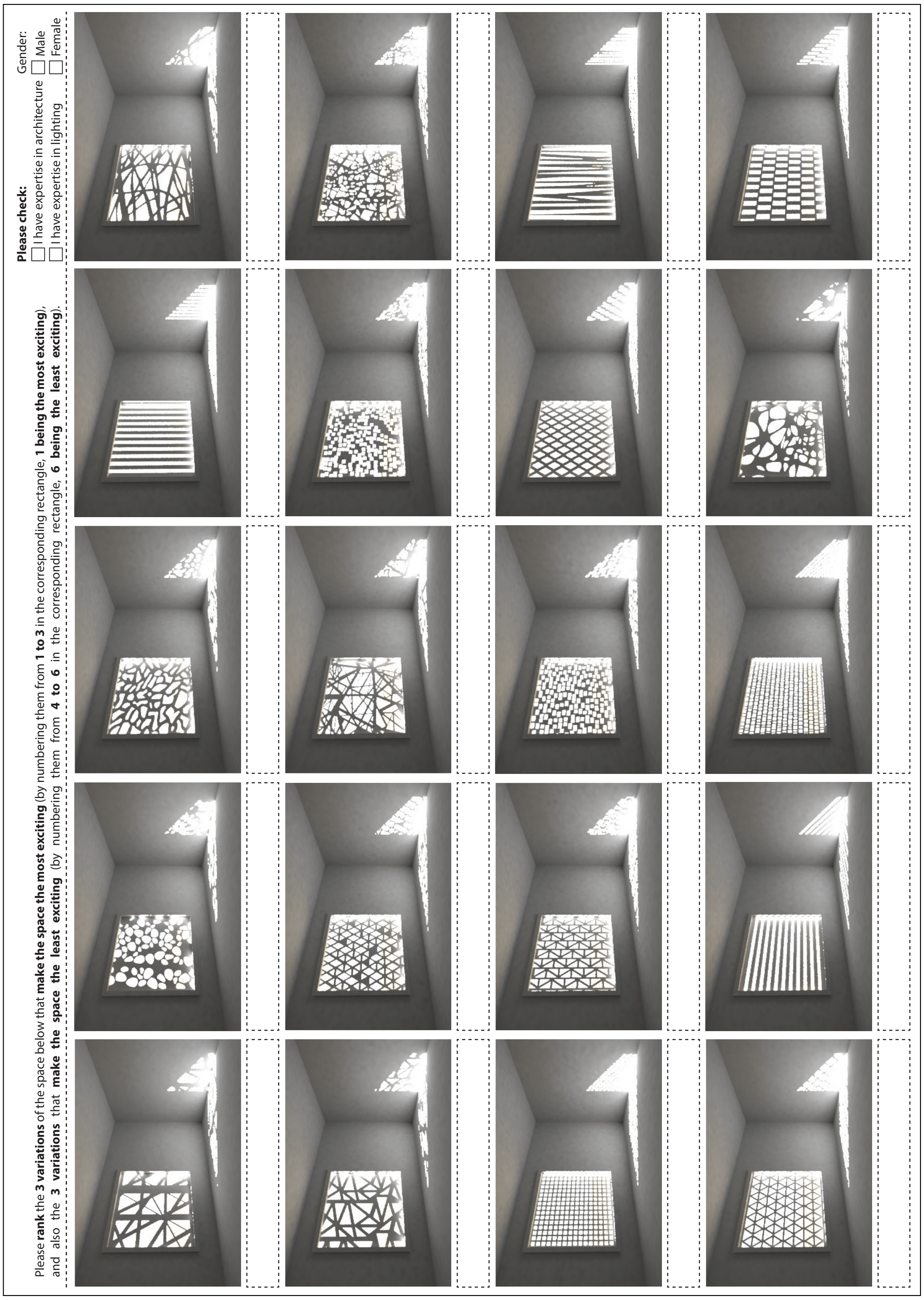


Figure A.12 – Example of the paper-based survey with a randomized order of façade variations. The back page of the paper can be found in Figure A.13

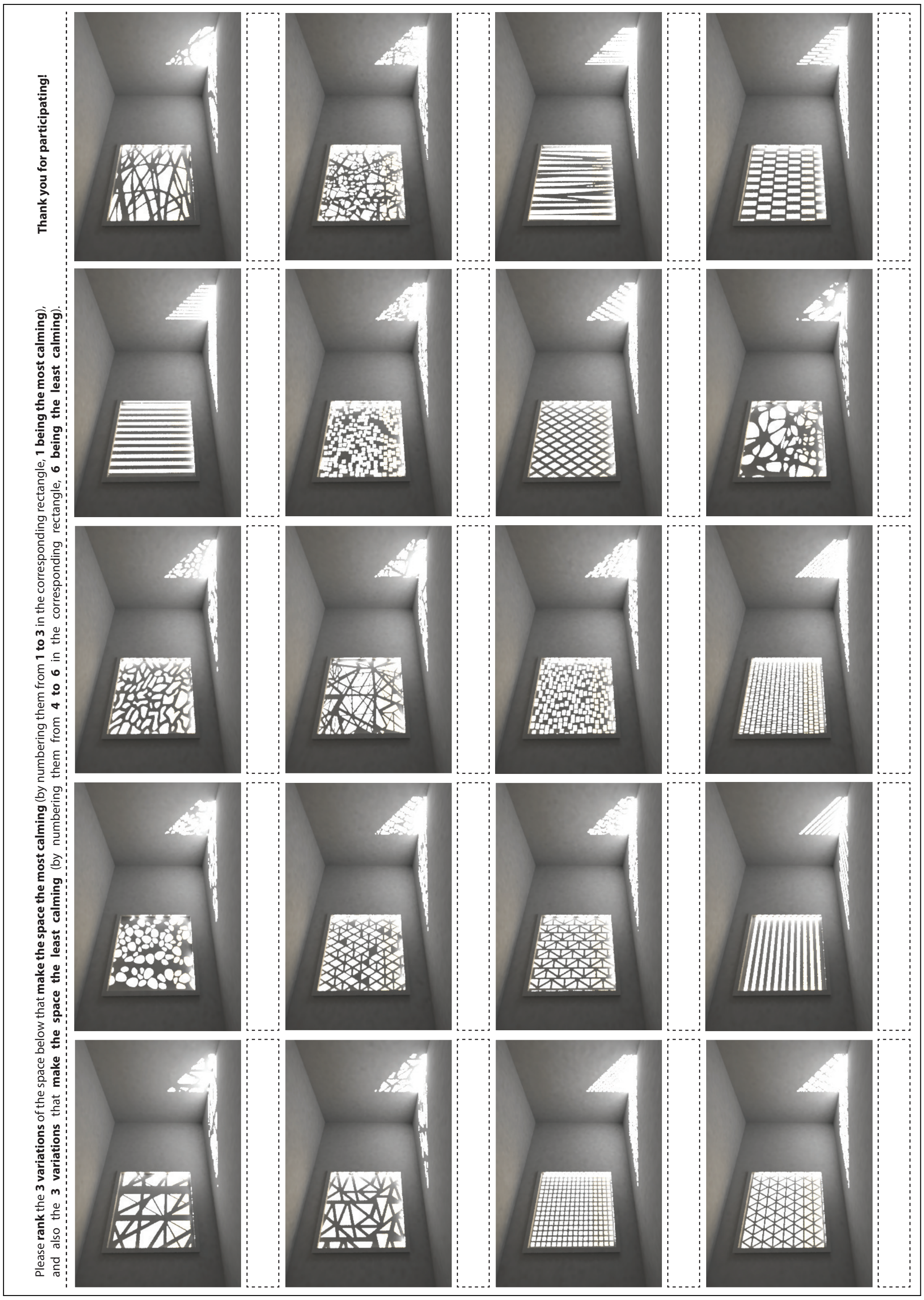


Figure A.13 – Example of the paper-based survey with a randomized order of façade variations.

A.5 Stimuli to test the robustness of façade-induced perceptual effects

A.5.1 Space type variations

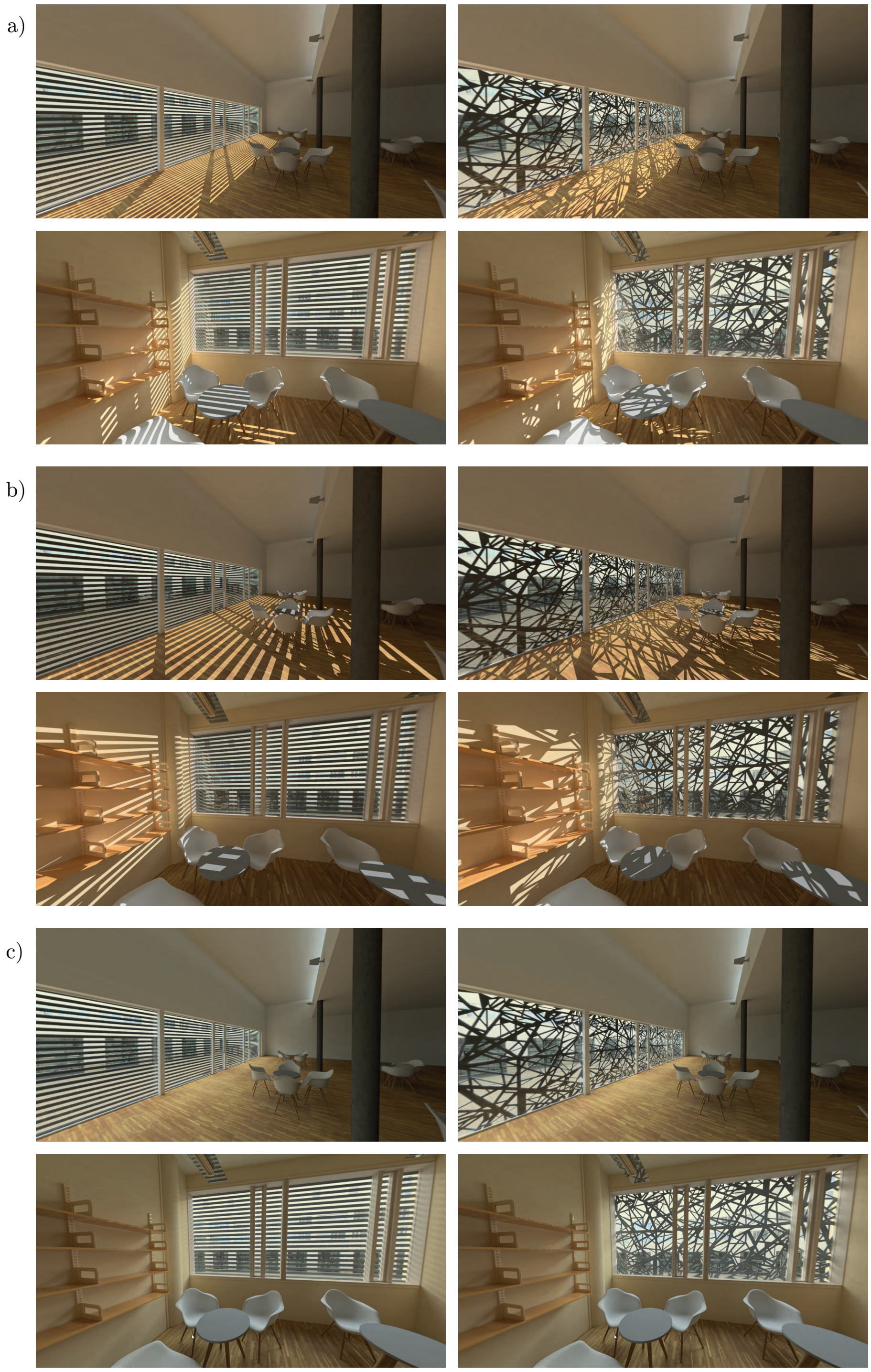


Figure A.14 – Perspective views of the scenes under (a) clear with high sun angle, (b) clear sky with low sun angle, and (c) overcast sky for the social context across the two façade variations and studied spaces.

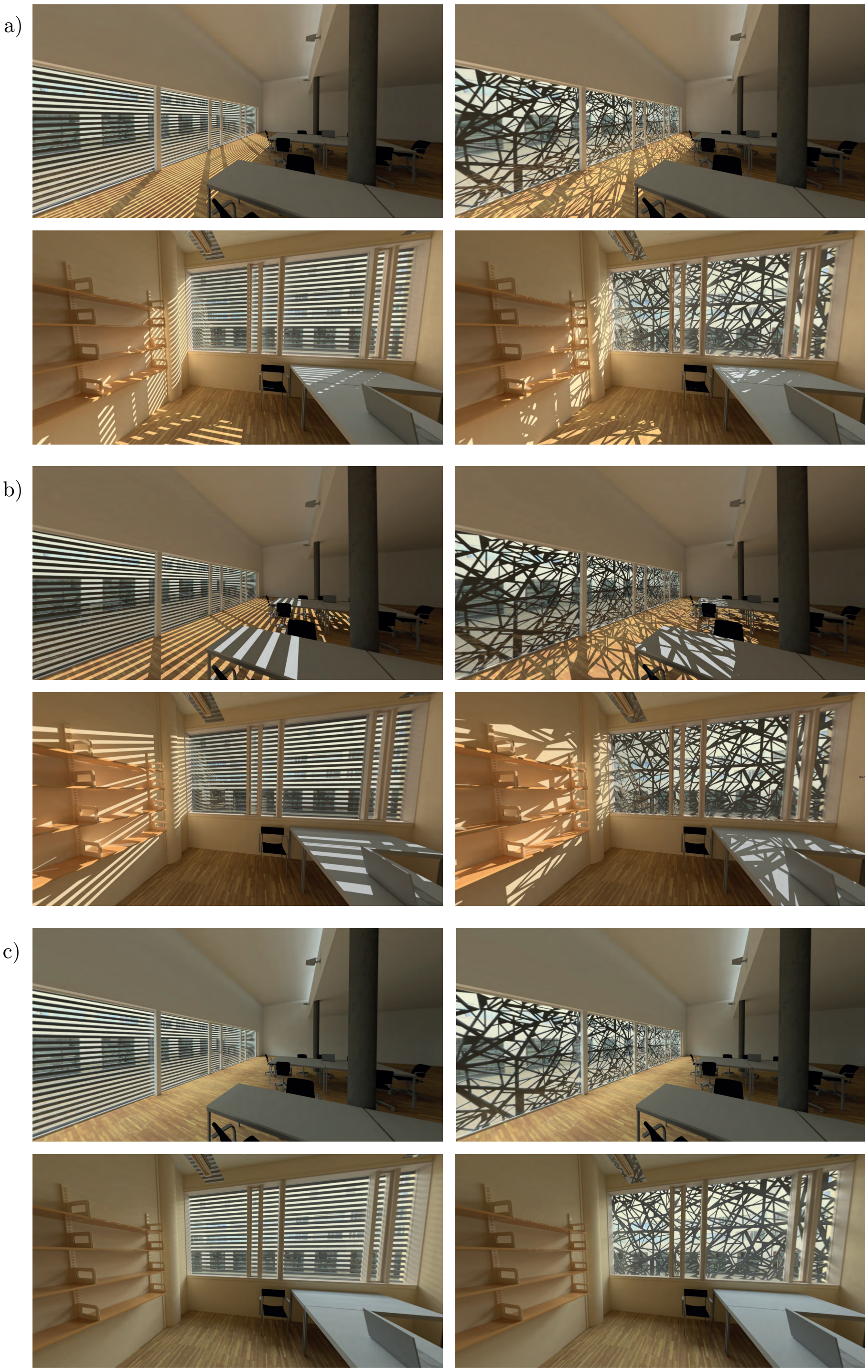


Figure A.15 – Perspective views of the scenes under (a) clear with high sun angle, (b) clear sky with low sun angle, and (c) overcast sky for the working context across the two façade variations and studied spaces.

A.5.2 Window size variations

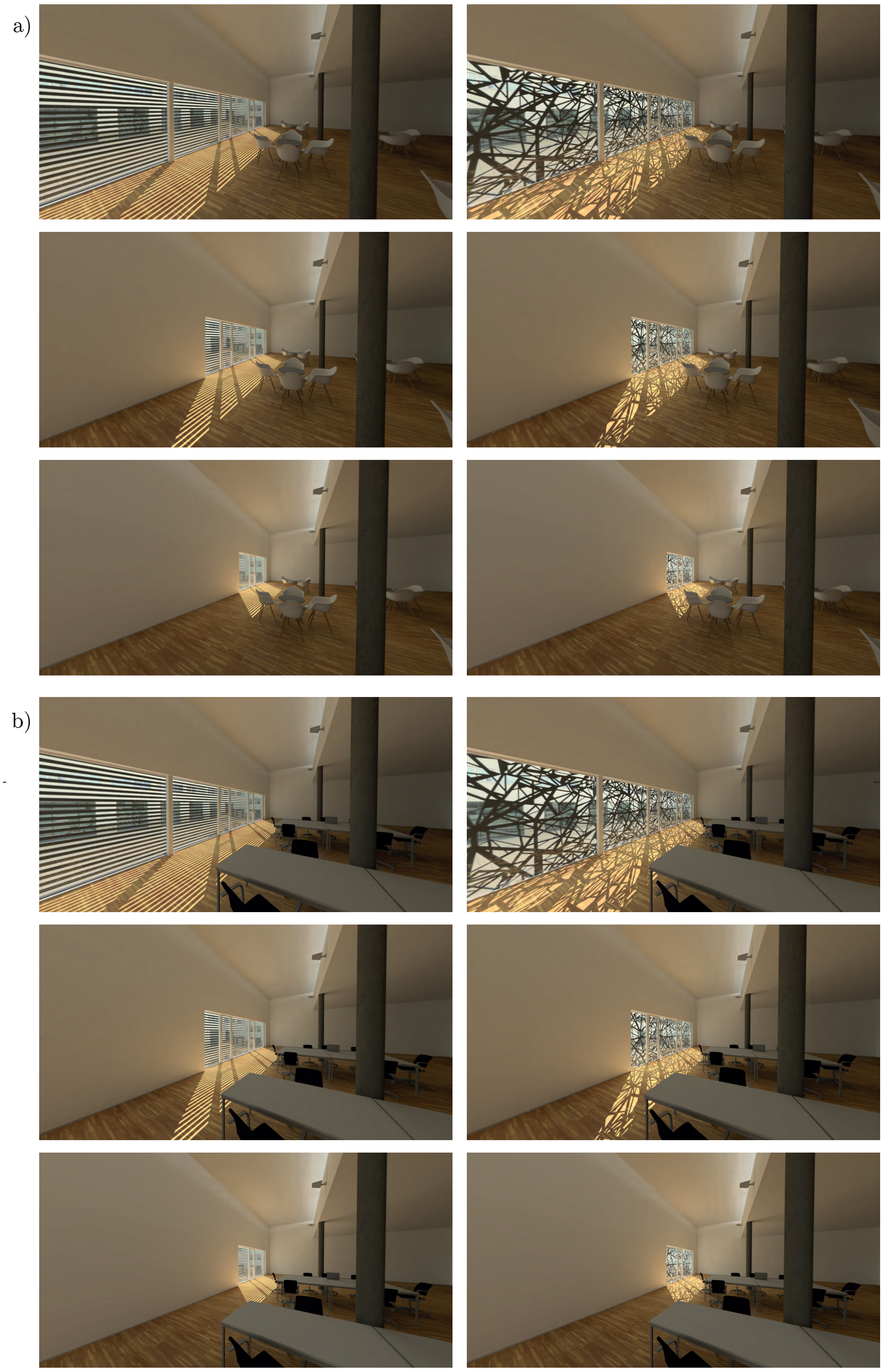


Figure A.16 – Perspective views of the scenes under clear sky with low sun angle and (a) social context or (b) working context across across the two studied façade variations and three window sizes.

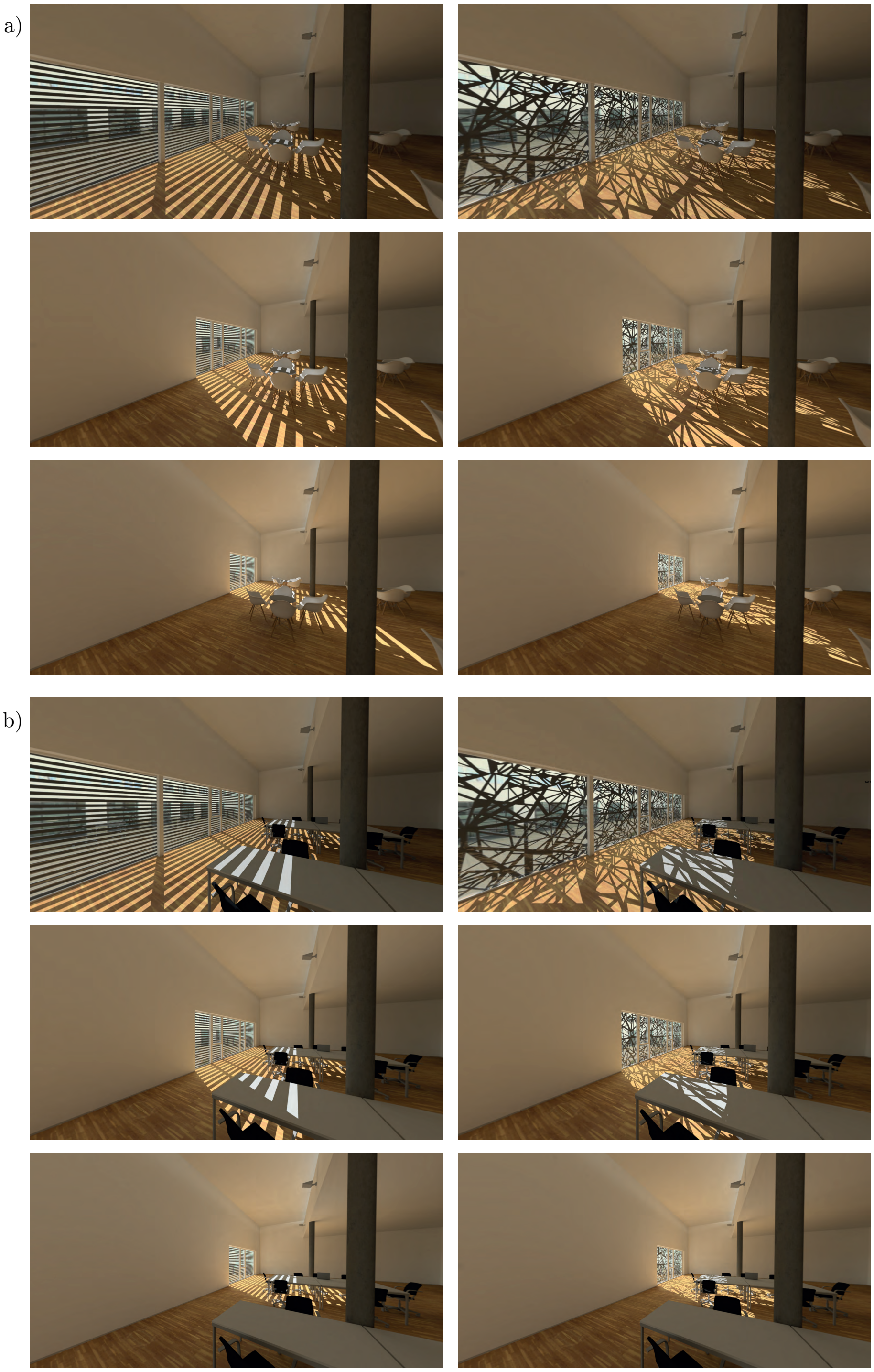


Figure A.17 – Perspective views of the scenes under clear sky with high sun angle and (a) social context or (b) working context across across the two studied façade variations and three window sizes.

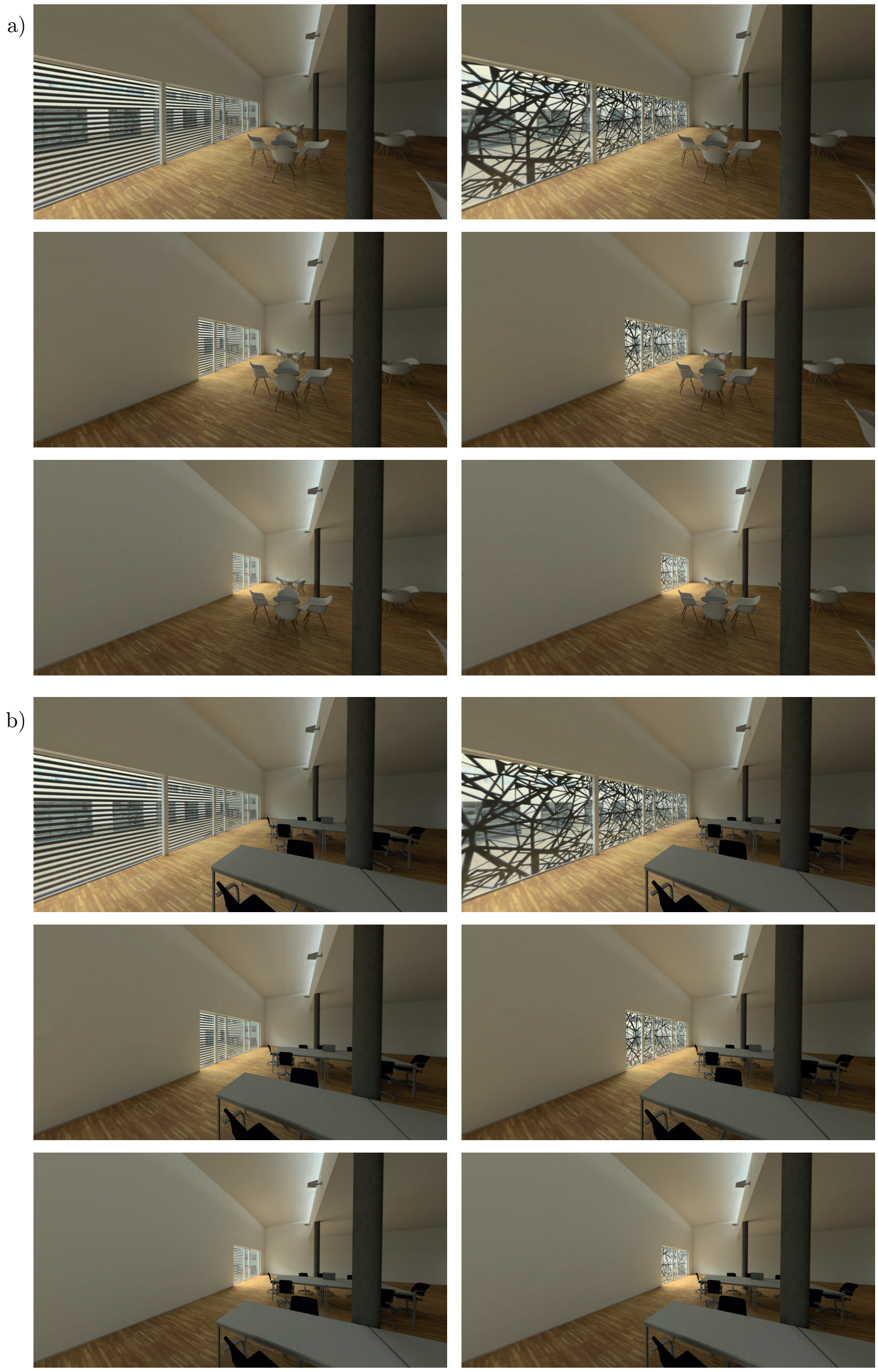


Figure A.18 – Perspective views of the scenes under overcast sky and (a) social context or (b) working context sky across across the two studied façade variations and three window sizes.

A.6 Definitions of perceptual attributes

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

INFORMATION ABOUT THE EVALUATION OF THE SCENES

In this experiment, you will be immersed in interior spaces in virtual reality and you are asked to **evaluate the space as a whole**. In the verbal questionnaire, you will be asked to evaluate the spaces regarding a series of attributes. In order to avoid language-related uncertainty, we provide the definitions of the studied attributes from the Cambridge Dictionary below.

1. **Pleasant**: enjoyable or attractive.
2. **Interesting**: holding one's attention.
3. **Exciting**: making you feel excited.
4. **Calming:** making you feel peaceful, quiet or relaxed.
5. **Complex**: having many parts related to each other in ways that may be difficult to understand.
6. **Bright**: full of light.
7. **Spacious**: having a lot of space.
8. **View**: what you can see from a particular place.

You can ask the researcher to repeat these definitions at any moment if you are uncertain about a question.

Figure A.19 – Document given to the participants in the beginning of the experimental session.

A.7 Descriptive statistics

Table A.3 – Means (M) and standard deviations (SD) for the perceptual impressions of the space in each façade variation. Results are shown for all studied sky types as well as for each sky type separately, averaged over the levels of all other factors.

How pleasant is this space?								
	Sky: all		Sky: clear high		Sky: clear low		Sky: overcast	
Façade variation	M	SD	M	SD	M	SD	M	SD
Pattern 1	5.47	2.00	5.60	1.70	5.46	2.19	5.33	2.08
Pattern 2	5.21	2.29	5.48	2.13	5.26	2.45	4.88	2.26
Pattern 3	6.03	1.90	5.80	1.88	6.33	1.80	5.94	2.01
Pattern 4	5.00	2.12	5.06	2.17	5.27	2.16	4.66	2.01
Pattern 5	5.57	2.15	5.50	2.16	5.67	2.16	5.55	2.14
Pattern 6	6.01	1.82	5.86	1.61	6.12	2.13	6.04	1.65

How interesting is this space?								
	Sky: all		Sky: clear high		Sky: clear low		Sky: overcast	
Façade variation	M	SD	M	SD	M	SD	M	SD
Pattern 1	4.50	2.04	4.78	1.87	4.49	2.06	4.22	2.18
Pattern 2	4.60	2.22	4.79	2.16	4.62	2.12	4.38	2.37
Pattern 3	5.70	2.08	5.37	2.02	6.00	2.08	5.72	2.12
Pattern 4	5.55	2.08	5.71	1.99	5.76	2.13	5.16	2.07
Pattern 5	6.16	2.09	6.10	1.93	6.48	2.07	5.88	2.25
Pattern 6	6.31	1.93	6.14	1.78	6.57	1.97	6.21	2.04

How exciting is this space?								
	Sky: all		Sky: clear high		Sky: clear low		Sky: overcast	
Façade variation	M	SD	M	SD	M	SD	M	SD
Pattern 1	4.19	2.01	4.26	1.87	4.20	2.04	4.10	2.13
Pattern 2	4.27	2.19	4.41	2.08	4.27	2.18	4.13	2.35
Pattern 3	5.33	2.02	5.09	1.96	5.64	2.04	5.22	2.02
Pattern 4	5.00	2.16	5.08	2.05	5.21	2.26	4.70	2.16
Pattern 5	5.72	2.12	5.63	2.01	5.89	2.06	5.62	2.30
Pattern 6	5.78	1.98	5.70	1.83	5.90	2.07	5.72	2.03

How calming is this space?								
	Sky: all		Sky: clear high		Sky: clear low		Sky: overcast	
Façade variation	M	SD	M	SD	M	SD	M	SD
Pattern 1	5.89	1.92	5.94	1.76	5.91	2.06	5.80	1.95
Pattern 2	5.59	2.21	5.81	2.02	5.58	2.45	5.37	2.13
Pattern 3	6.08	1.83	5.92	1.83	6.30	1.78	6.01	1.87
Pattern 4	4.98	2.12	5.09	1.87	5.23	2.32	4.60	2.11
Pattern 5	4.97	2.19	4.91	2.11	5.22	2.27	4.77	2.18
Pattern 6	5.47	2.04	5.29	1.77	5.56	2.42	5.56	1.85

Table A.4 – Means (M) and standard deviations (SD) for the visual appearance of the space in each façade variation. Results are shown for all studied sky types as well as for each sky type separately, averaged over the levels of all other factors.

How complex is this space?								
	Sky: all		Sky: clear high		Sky: clear low		Sky: overcast	
Façade variation	M	SD	M	SD	M	SD	M	SD
Pattern 1	3.69	1.93	3.74	1.88	3.53	2.02	3.82	1.91
Pattern 2	3.71	1.85	3.74	1.93	3.60	1.84	3.79	1.79
Pattern 3	4.81	2.03	4.65	1.93	4.90	2.19	4.89	1.96
Pattern 4	5.74	2.19	5.53	2.40	5.69	2.20	6.02	1.94
Pattern 5	6.03	2.26	6.09	2.19	5.90	2.48	6.10	2.11
Pattern 6	5.97	2.04	5.86	2.02	6.03	2.11	6.02	2.01

How bright is this space?								
	Sky: all		Sky: clear high		Sky: clear low		Sky: overcast	
Façade variation	M	SD	M	SD	M	SD	M	SD
Pattern 1	6.46	1.67	6.30	1.83	6.39	1.63	6.70	1.53
Pattern 2	6.67	1.71	6.57	1.73	6.76	1.68	6.68	1.74
Pattern 3	6.53	1.75	6.08	1.89	6.72	1.64	6.79	1.62
Pattern 4	5.37	1.80	5.22	2.01	5.58	1.74	5.29	1.62
Pattern 5	6.44	1.79	6.29	1.88	6.51	1.74	6.51	1.76
Pattern 6	6.26	1.69	5.91	1.85	6.39	1.64	6.50	1.50

How spacious is this space?								
	Sky: all		Sky: clear high		Sky: clear low		Sky: overcast	
Façade variation	M	SD	M	SD	M	SD	M	SD
Pattern 1	7.41	1.60	7.45	1.52	7.43	1.70	7.34	1.58
Pattern 2	7.60	1.57	7.57	1.72	7.59	1.50	7.66	1.51
Pattern 3	7.59	1.47	7.51	1.57	7.60	1.53	7.65	1.31
Pattern 4	7.12	1.83	7.09	1.88	7.36	1.76	6.89	1.86
Pattern 5	7.44	1.62	7.36	1.65	7.59	1.62	7.37	1.60
Pattern 6	7.41	1.51	7.41	1.45	7.58	1.48	7.24	1.61

How satisfied are you with the amount of view in this space?								
	Sky: all		Sky: clear high		Sky: clear low		Sky: overcast	
Façade variation	M	SD	M	SD	M	SD	M	SD
Pattern 1	5.35	2.21	5.50	2.15	5.34	2.25	5.18	2.23
Pattern 2	5.57	2.28	5.70	2.29	5.66	2.10	5.33	2.45
Pattern 3	5.64	2.27	5.20	2.25	5.79	2.26	5.94	2.27
Pattern 4	3.38	2.36	3.59	2.42	3.33	2.32	3.21	2.34
Pattern 5	5.89	2.21	5.72	2.15	6.10	2.14	5.84	2.35
Pattern 6	5.80	2.16	5.60	2.14	5.94	2.30	5.84	2.02

A.8 Equirectangular projection renderings of the test scenes

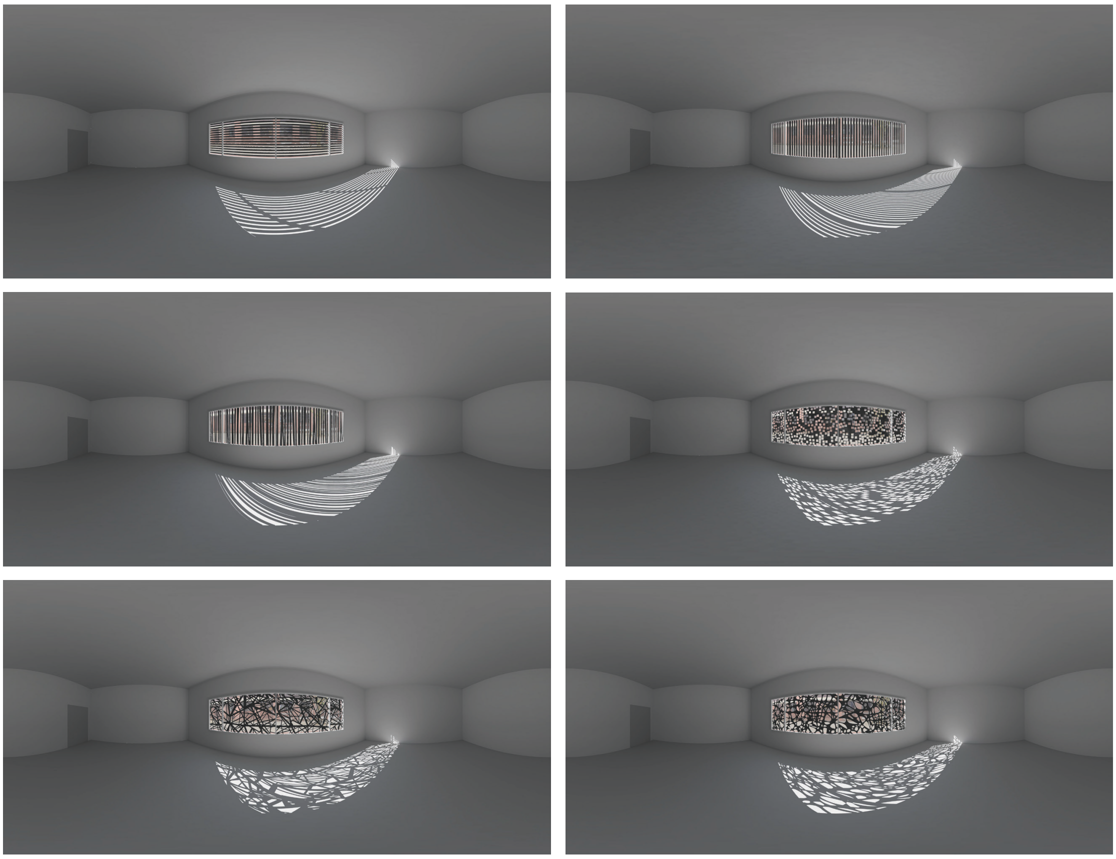

Figure A.20 – Equirectangular projection renderings (corresponding to the left eye) of the test scenes under clear sky with high sun angle across all façade variations.

*

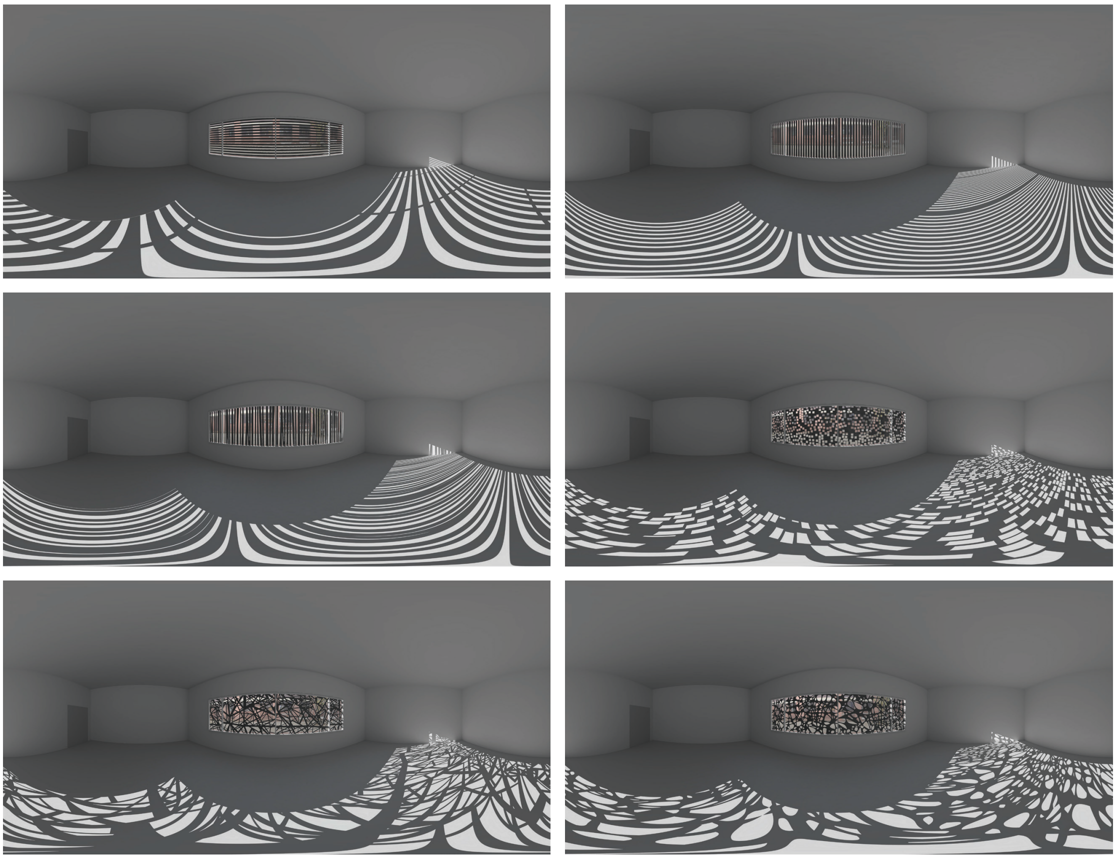

Figure A.21 – Equirectangular projection renderings (corresponding to the left eye) of the test scenes under clear sky with low sun angle across all façade variations.

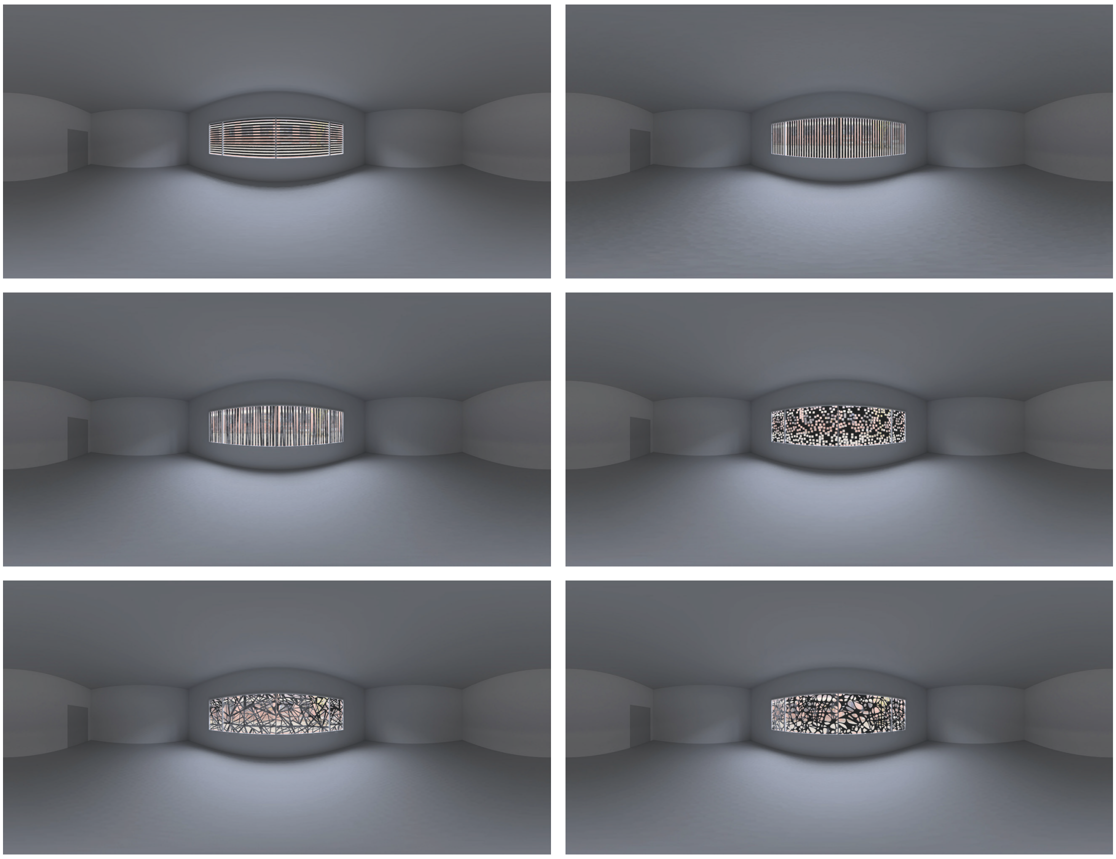

Figure A.22 – Equirectangular projection renderings (corresponding to the left eye) of the test scenes with overcast sky across all façade variations.

A.9 Output of the image-based measures applied to the test scenes

Table A.5 – Output of the 32 studied metrics, applied to the section of the test scenes corresponding to the façade and averaged across the three sky types to generate one value for each façade variation. Outputs based on file sizes are reported normalized to the maximum value.

Metric	Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5	Pattern 6
GIF	0.81	0.99	1.00	0.93	1.00	0.94
JPEG	0.66	0.60	0.63	0.94	1.00	0.99
PNG	0.71	0.64	0.67	0.78	1.00	0.92
TIFF	0.96	1.00	0.99	1.00	0.96	0.93
Fractal D	1.29	1.35	1.39	1.39	1.39	1.38
JPEG-CANNY2014	0.54	0.51	0.6	0.98	1.00	0.97
PNG-CANNY2014	0.24	0.17	0.23	0.93	1.00	0.97
TIFF-CANNY2014	0.1	1.00	0.92	0.54	0.57	0.54
RAW-CANNY2014	1.00	0.86	0.97	0.83	0.91	0.81
JPEG-CANNY1986	0.55	0.53	0.58	1.00	1.00	0.98
PNG-CANNY1986	0.28	0.18	0.26	0.97	1.00	0.97
TIFF-CANNY1986	0.14	1.00	0.91	0.55	0.54	0.54
RAW-CANNY1986	0.99	1.00	0.88	0.79	0.84	0.78
Entropy	7.19	7.22	7.34	7.14	7.33	7.14
JPEG-PERIM4	0.62	0.57	0.62	0.96	1.00	0.99
PNG-PERIM4	0.28	0.22	0.33	0.86	1.00	0.93
TIFF-PERIM4	0.19	1.00	0.8	0.55	0.58	0.54
RAW-PERIM4	0.97	1.00	0.88	0.81	0.82	0.7
JPEG-PERIM8	0.61	0.56	0.62	0.94	1.00	0.99
PNG-PERIM8	0.09	0.09	0.13	0.3	0.35	0.33
TIFF-PERIM8	0.18	1.00	0.79	0.53	0.51	0.48
RAW-PERIM8	1.00	1.00	0.88	0.85	1.00	0.85
JPEG-SOBEL	0.15	0.19	0.36	0.61	0.8	1.00
PNG-SOBEL	0.15	0.16	0.3	0.59	0.81	1.00
TIFF-SOBEL	0.26	0.5	0.73	0.67	0.8	1.00
RAW-SOBEL	0.19	0.26	0.49	0.52	0.72	1.00
Michelson	0.91	0.92	0.85	0.9	0.92	0.93
RMS	118.37	121.84	125.27	119.86	120.58	117.52
mSC1	12.86	13.49	24.21	33.19	30.32	32.15
mSC2	19.91	7.63	13.27	30.5	25.79	28.19
mSC3	31.34	7.82	10.05	26.32	20.16	25.44
mSC4	50.3	5.69	5.87	17.4	15.83	21.12

A.10 Output of the image-based measures applied to the experimental scenes

Table A.6 – Output of the 7 selected metrics, applied to the section of the experimental scenes corresponding to the façade and averaged across the three sky types and two spatial context conditions to generate one value for each façade variation.

Metric	Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5	Pattern 6
Fractal D	1.772	1.767	1.767	1.770	1.772	1.771
Michelson	0.761	0.744	0.764	0.782	0.767	0.774
TIFF-SOBEL*	0.036	0.189	0.225	0.161	0.175	0.186
mSC1	13.47	8.23	13.66	23.40	22.12	23.73
JPEG/BMP**	0.854	0.077	0.080	0.115	0.121	0.118
RAW-CANNY1986***	1.000	0.986	0.819	0.784	0.835	0.771
PNG-PERIM8*	0.024	0.025	0.030	0.046	0.041	0.042

* Reported as the ratio of the file size of perimeter image divided by the file size of the image before the perimeter detection.
** Reported as the ratio of JPEG file size to BMP file size for easier interpretation.
*** Normalized to the maximum value.

Appendix B

Image credits

Figure 1.1.
From top left to right:

1.1) Mirror Tower, LAN Architecture, Beirut, Lebanon, 2009. © LAN Architecture. Source: https://www.archdaily.com/39101/mirror-tower-lan-architecture

1.2) Petit Mont-Riond, CCHE, Lausanne, Switzerland, 2015. © Thomas Jantscher. Source: https://www.archdaily.com/792217/petit-mont-riond-cche

1.3) La Tallera, Frida Escobedo, Morelos, Mexico, 2010. © Rafael Gamo. Source: https://www.archdaily.com/320147/la-tallera-frida-escobedo

1.4) New University Library, rh+ architecture, Cayenne, French Guiana, 2013. © Jean-Michel André. Source: https://www.archdaily.com/475800/new-university-library-in-cayenne-rh-architecture

1.5) FT House, Reinach Mendonça Arquitetos Associados, Bragança Paulista, Brazil, 2014. © Nelson Kon. Source: https://www.archdaily.com/582253/ft-house-reinach-mendonca-arquitetos-associados

1.6) 2Y House, Sebastián Irarrázaval, Colico, Chile, 2013. © Felipe Díaz Contardo. Source: https://www.archdaily.com/799225/2y-house-sebastian-irarrazaval

1.7) Carabanchel Housing, Foreign Office Architects (FOA), Madrid, Spain, 2007. © Foreign Office Architects. Source: https://www.archdaily.com/1580/caranbachel-housing-foreign-office-architects

1.8) Wintergarden Façade, Studio 505, Brisbane, Australia, 2012. © John Gollings. Source: https://www.archdaily.com/253599/wintergarden-racade-studio-505

1.9) MuCEM, Rudy Ricciotti, Marseille, France, 2013. © Steven Massart. Source: https://www.archdaily.com/400727/mucem-rudy-ricciotti

1.10) TK139, at103, Tecamachalco, Mexico, 2012. © Rafael Gamo. Source: https://www.archdaily.com/276095/tk139-at103

1.11) Raas Jodhpur, The Lotus Praxis Initiative, Rajasthan, India, 2011. © André J. Fanthome and Rajen Nandwana.
Source: https://www.archdaily.com/423405/raas-jodhpur-the-lotus-praxis-initiative

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Yoshizawa, N., Aya, K., Kato, M., Yamaguchi, H., Hara, N., Miki, Y., Dumortier, D., Jost, S., and Iborra Bernard, M. (2015). A comparison study on spatial brightness evaluation between different cultural groups. In *Proceedings CIE Session 2015*. Manchester, United Kingdom, vol. 1.

Yun, G., Yoon, K. C., and Kim, K. S. (2014). The influence of shading control strategies on the visual comfort and energy demand of office buildings. *Energy and Buildings*, 84(Supplement C):70–85.

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Curriculum Vitae

Education

2015–2019 **École polytechnique fédérale de Lausanne (EPFL)**, PhD.
School of Architecture, ENAC, Lausanne, Switzerland
Laboratory of Integrated Performance In Design (LIPID).

Thesis: Perceptual effects of daylight patterns in architecture.
Directors: Prof. Marilyne Andersen, Dr.-Ing. Jan Wienold.

2008–2014 **Technical University of Crete (TUC)**, Dipl.-Ing. (with honors).
School of Architectural Engineering, Chania, Greece
Research thesis: Memorigami — Climate-responsive envelopes.
Director: Prof. Konstantinos-Alketas Oungrinis.

Design Thesis: The octahedron project, sustainable community housing in Chania.
Directors: Prof. Konstantinos-Alketas Oungrinis, Prof. Aristomenis Varoudakis.

Positions

2015–2019 **EPFL**, Lausanne, Switzerland.
Doctoral Assistant and PhD Candidate, LIPID.

2014, Jun-Dec **EPFL**, Lausanne, Switzerland.
Research Intern, LIPID.

2013–2014 **TUC**, Chania, Greece.
Research Assistant, Transformable Intelligent Environments Laboratory.

Industry Consulting

2017 **Corrado Tibaldi Design Consultancy**, Chambésy, Switzerland.
Preparation and delivery of short staff training program on parametric modeling for object design using Rhinoceros and Grasshopper.

Awards and Scholarships

2019 **ANFA 2019 Poster Competition**. Second prize, Academy of Neuroscience for Architecture, San Diego, CA, USA.

2018 **Light Symposium 2018 Paper Competition**. Finalist, invited speaker, KTH Royal Institute of Technology, Stockholm, Sweden.

2018 **2018 Human Factors Prize**. Finalist, submission co-authored with G. Chinazzo, J. Wienold, and M. Andersen. Human Factors and Ergonomics Society, Santa Monica, USA.

2014 **Limmat Stiftung Excellence Award**. Limmat Stiftung, Zürich, Switzerland.

2009–2011 **Scholarship of Academic Achievements**, TUC, Chania, Greece.

CONTRIBUTIONS TO SUCCESSFUL GRANT APPLICATIONS

2018–2022 **Swiss National Science Foundation Research Grant**, SNSF, Bern.
Contributor in grant application "Visual comfort without borders: Interactions on discomfort glare" in the sections relating to the background, problem statement, and method for investigating contrast as a source of visual interest.
PI: Jan Wienold, LIPID, EPFL.

2016–2019 **Velux Research Fellowship**, Velux Stiftung, Zürich.
Main contributor in grant application "Identifying the impact of regional differences on the perceived quality of daylit architectural spaces: A comparison study across different latitudes" (100% PhD funding).
PI: Prof. Barbara Szybinska Matusiak, Light & Colour Group, Norwegian University of Science and Technology, co-PI: Prof. Marilyne Andersen, LIPID, EPFL.

2013–2014 **UNISTEP University Students Entrepreneurship Project**, TUC, Chania.
Main contributor in grant application for the development of a prototype adaptive shading system using passive actuation with shape memory alloys.
PI: Prof. Konstantinos-Alketas Oungrinis, TIE lab, TUC.

TEACHING EXPERIENCE

2018–2019 **EPFL**, Lausanne, Switzerland.
Teaching Assistant and Guest Lecturer: AR-442 "Architecture and sustainability: performance studies".
Master level course (1st semester, 4 credits, 15 students).

2016–2019 **EPFL**, Lausanne, Switzerland.
Teaching Assistant: AR-440 "Comfort and architecture: sustainable strategies".
Master level course (1st semester, 3 credits, 14-26 students).

2018 **Aarhus University**, Aarhus, Denmark.
Guest Lecturer: "Electric lighting design", Prof. Werner Osterhaus.
Master level course (1st semester, 5 credits, 9 students).

2018 **University of Oregon**, Oregon, USA.
Guest Lecturer: ARCH 4/510 "Human-centric environments", Prof. Siobhan François Rockcastle.
Bachelor level course (4th semester, 4 credits, 10 students).

2009–2010 **TUC**, Chania, Greece.
Teaching Assistant: "Introduction to architectural thinking I".
Bachelor level course (1st semester, 4 credits, 80 students).

Student Supervision and Mentorship

Aarhus University, Aarhus, Denmark.

2019 *Master thesis supervision*: Csaba Pákozdi, Department of Engineering.
"Biophilic design and green colour", co-supervision with Prof. Steffen Petersen (Department of Engineering - Indoor Climate and Energy).

EPFL, Lausanne, Switzerland.

2019 *Master thesis supervision*: Joëlle Baehr-Bruyère, Section of Civil Engineering.
"Design of a light-shaping adaptive façade using fiber-reinforced polymer materials", co-supervision with Dr. Anastasios Vasilopoulos (Civil Engineering Institute, EPFL), Prof. Marilyne Andersen (LIPID) and Dr. Jan Wienold (LIPID).

2018 *Semester project supervision*: Thomas Yvan Dériaz, Energy Management and Sustainability Program.
"Influence of space appreciation on visual comfort in MINERGIE buildings", co-supervision with Dr. Luisa Pastore (LIPID).

2018 *Semester project supervision*: Pierre Stéphane Denis Barre, Energy Management and Sustainability Program.
"Influence of subjective impressions on indoor comfort", co-supervision with Dr. Luisa Pastore (LIPID).

2018 *Course project supervision*: Jorge Sanchez Gonzalez, Carlos Megías Núñez, Kiarash Farivar, Ekaterina Svikhnushina, Andreas Maggiori, and Irina Kozlova, Section of Computer Science.
"Human behavior modeling: using Machine Learning to predict subjective responses to daylit interior scenes in virtual reality", in collaboration with Prof. Martin Jaggi and Prof. Rüdiger Urbanke (Institute of Computer and Communication Sciences, EPFL) for the course CS-433 "Machine Learning".

2016 *Semester project supervision*: Karina Borodaï, Section of Architecture.
"Project 24: Light and Emotion", co-supervision with Dr. Giorgia Chinazzo (LIPID) and Dr. Giordano Favi (Section of Mathematics, EPFL).

The Ontario College of Art and Design University, Ontario, Canada.

2018 *Master thesis mentoring*: Manik Perera Gunatilleke, Digital Futures Program.
"Bodies-cities: exploring embodied knowledge of urban sites through interactive virtual reality experiences". Supervisors: Prof. Nick Puckett and Prof. Cindy Poremba (Faculty of Liberal Arts and Sciences, OCAD).

PEER-REVIEWED JOURNAL ARTICLES

2019	**Chamilothori, K.**, Wienold, J. & Andersen, M., *Adequacy of immersive virtual reality for the perception of daylit spaces: comparison of real and virtual environments*, LEUKOS, 15(2-3), 203-226.
2019	**Chamilothori, K.**, Dan-Glauser, E., Rodrigues, J., Wienold, J. & Andersen, M., *Subjective and physiological responses to façade and sunlight pattern geometry in virtual reality*, Building and Environment, 150, 144-155.
-	Chinazzo, G., **Chamilothori, K.**, Wienold, J. & Andersen, M., *Temperature-color interaction: subjective indoor environmental perception and physiological responses in virtual reality*, Journal of the Human Factors and Ergonomics Society (under review).

CONFERENCES WITH PROCEEDINGS

2019	Baehr-Bruyère J., **Chamilothori, K.**, Wienold J., Andersen M., and Vassilopoulos A., *Shaping light to influence occupants' experience of space: a novel kinetic shading system with composite materials*, Proceedings of CISBAT 2019, Lausanne, Switzerland, September 4-6.
2019	Omidfar Sawyer, A., **Chamilothori, K.**, *Influence of subjective impressions of a space on brightness satisfaction: an experimental study in virtual reality*, Proceedings of the Symposium on Simulation for Architecture and Urban Design 2019, Atlanta, GA, USA, April 7-9.
2018	**Chamilothori, K.**, Wienold, J. & Andersen, M., *Façade design and our experience of space: the joint impact of architecture and daylight on human perception and physiological responses*, Proceedings of the Light Symposium 2018 Conference, Stockholm, Sweden, December 5-7.
2018	**Chamilothori, K.**, Dan-Glauser, E., Rodrigues, J., Wienold, J. & Andersen, M., *Perceived interest and heart rate response to façade and daylight patterns in virtual reality.* Proceedings of the Academy of Neuroscience for Architecture, Salk Institute for Biological Studies, La Jolla, CA, USA, September 20-22.
2018	**Chamilothori, K.**, Wienold, J. & Andersen, M., *Methods for using immersive virtual reality for experimental studies in lighting research*, Proceedings of the CIE Expert Tutorial and Workshops on Research Methods for Human Factors in Lighting, Copenhagen, Denmark, August 13-14.
2017	Chinazzo, G., **Chamilothori, K.**, Wienold, J. & Andersen, M., *The effect of short exposure to coloured light on thermal perception: a study using Virtual Reality*, Proceedings of Lux Europa 2017, Ljubljana, Slovenia, September 18-20.
2017	Rockcastle, S., **Chamilothori, K.** & Andersen, M., *Using virtual reality to measure daylight-driven interest in rendered architectural scenes*, Proceedings of Building Simulation 2017, San Francisco, CA, USA, August 7-9.
2016	**Chamilothori, K.**, Wienold, J. & Andersen, M., *Daylight patterns as a means to influence the spatial ambience: a preliminary study*, Proceedings of the 3rd International Congress on Ambiances 2016, Volos, Greece, September 21-24.

2014 **Chamilothori, K.**, Kampitaki A.-M. & Oungrinis K.-A., *Climate-responsive shading systems with integrated shape memory alloys (SMA)*, Proceedings of the 8th Energy Forum on Solar Building Skins, Bressanone, Italy, October 27 – 28.

Poster & Workshop Presentations

2017 **Chamilothori, K.**, Wienold, J. & Andersen, M., *Using immersive virtual reality to investigate the experience of daylit spaces.* Poster at the 7th VELUX Daylight Symposium, Berlin, Germany, May 3-4.

2016 **Chamilothori, K.**, Wienold, J. & Andersen, M., *Immersive scenes with Radiance in a Virtual Reality Headset: comparison of virtual and real environments.* Presentation at the 15th Annual International Radiance Workshop, Padova, Italy, August 29-31.

2015 **Chamilothori, K.**, Wienold, J. & Andersen, M., *Evaluating spatial ambiences through daylight variability, contrast and view.* Poster at the 6th VELUX Daylight Symposium, London, September 2-3.

2013 **Chamilothori, K.**, Kampitaki A.-M. & Oungrinis K.-A., *Memorigami, an origami-inspired shading system using smart materials.* Exhibition at the 9th International Conference on Intelligent Environments, Athens, July 16-19.

Invited Talks & Workshops

2018 *Façade design and our experience of space: the joint impact of architecture and daylight on human perception and physiological responses.* Invited talk, **Light Symposium 2018**, Stockholm, Sweden, December 5th, 2018.

2018 *Façade & daylight patterns and our experience of space.* Invited talk, **Technical University of Crete**, Chania, Greece, May 24th, 2018.

2017 *The potential of virtual reality in the field of lighting.* Invited workshop at the **7th VELUX Daylight Symposium**, Berlin, Germany, May 3rd, 2017.

Demonstrations

2018 *Daylight and facade design: investigations in immersive virtual reality.* Demonstration at the **Light Symposium 2018**, Stockholm, Sweden, December 5th, 2018.

2018 *Workflow and methods for the use of virtual reality in lighting research.* Demonstration at the **CIE Expert Tutorial and Workshop on Research Methods for Human Factors in Lighting**, Copenhagen, Denmark, August 14th, 2018.

2017 *Applications of virtual reality in architecture and lighting research.* Demonstration at the **EPFL ENAC Research Day**, Lausanne, Switzerland, May 23rd, 2017.

Professional Service

2018–present **Reviewer** for the journals LEUKOS and Architectural Science Review.

2018 & 2019 **Scientific Committee Member** for the Symposium on Simulation for Architecture and Urban Design (SimAUD).

Media Coverage

2018	*Lighting and architecture*, K. Muca, R&D Unit WISE, CEBRA Architecture, Aarhus, Denmark (to appear on the CEBRA website).
2018	*VR as a Daylighting Design Tool*, B. Horwitz-Bennett, Net Zero Magazine, vol. 7, no. 4, p. 22.
2017	*The Reality of Virtual Reality*, J. Crockett, Architectural Products, vol. 15, no. 8, pp. 42.
2017	*Lichtforshung*, D.C. Baciu and N. Kahnt, Phoenix, vol. 8, pp. 24-26.
2017	*How VR Is Helping Researchers Understand the Phenomenology Behind Light in Architecture*, T. Musca and R. Stott, ArchDaily Architecture Website, September 17th.
2014	*Memorigami: un prototipo de sistema frangisole adattabile*, C. Orsini, CasaClima Magazine, no. 3, p. 15.

Languages

Greek	Native proficiency.
English	Full professional proficiency.
French	Full professional proficiency.

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