The Effect of Biophilic Glare Control on Occupant Perception: A Laboratory Experiment

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Acknowledgments

Choosing the topic for my graduation project, I reflected on my experiences from the first year of my Master's program and identified my interests and growing awareness. Throughout my education, I have been particularly drawn to aspects concerning the climate and sought to incorporate them into building design. Additionally, I consider myself a practical person who enjoys research and experimental processes.

Discussing my ideas with my first mentor, Alessandra, greatly helped me identify a topic that aligns with my background and preferences, combining my interests in facade design and climate considerations. Furthermore, having known Eleonora from an elective course on occupant comfort and daylighting, I was thrilled to collaborate with her on this project, bringing together the subjects I am passionate about and working with familiar, inspiring mentors. Therefore, I would like first to express my sincere gratitude to my two mentors, Alessandra and Eleonora, for their guidance and collaboration throughout this journey, as well as the supervision of Kynthia, who was truly helpful during the first steps of this thesis and bridged the above subjects with her sensitivity on biophilia aspects.

A sincere thanks to the VideowindoW company and in particular Remco and Francisco who introduced to me their innovative product, taught me how to make the necessary adjustments and manipulate it for experimental purposes, and for their prompt responses to my questions.

I am grateful for the assistance of Green Village and I appreciate our collaboration to realize the experiment.

I extend my deepest appreciation to Pedro and Agnese for their support and willingness to help with the experimental setup, always maintaining a cheerful attitude. My special thanks also go to all 44 participants who contributed their time to help gather the data for this study.

My heartfelt gratitude goes to my family and friends for their love and support during this stage of my life. Special thanks to Akis and Eleni for listening to my concerns and making this journey more pleasant.

Abstract

Building and facade design face the challenge of maximizing daylight penetration while mitigating discomfort glare and addressing additional indoor user requirements and energy loads. Daylight in buildings plays a crucial role in regulating human circadian rhythms and various aspects of psychological functioning, health, and well-being. This is especially relevant in work environments, where improved performance, concentration, alertness, and mood are linked to adequate daylight exposure. Given that people spend most of their time indoors, including in office settings, access to natural light is often limited or obstructed by conventional shading systems. As both daylight and views to the outside benefit worker performance and satisfaction, office building facades frequently feature large window-to-wall ratios to enhance daylight and views. However, this transparency can result in excessive brightness and daylight glare. Various adaptive facade systems have emerged to address these challenges, with different levels of automation and control implemented to optimize performance.

In this thesis, a novel dynamic facade technology, VideowindoW, is discussed and tested as a shading system through an experimental approach in a laboratory setting. This product creates natural patterns aimed at providing glare protection and good indoor environmental quality for occupants. Limited studies have explored the impact of facade patterns on glare perception, satisfaction, and preference, with findings indicating a human preference for natural or irregular geometric patterns related to biophilic theories over more regular and striped patterns. Additional natural elements, including daylight and natural views, significantly enhance the overall architectural experience.

The aim of this work is to present a novel experimental setup in an office setting for evaluating occupant perception under different patterns. The patterns studied include a natural pattern, a striped pattern, and a no-pattern condition. Occupant perception is assessed in terms of (i) glare perception; (ii) daylight satisfaction; (iii) color of daylight satisfaction; (iv) visual comfort; (v) satisfaction with the view out; (vi) acceptance of obstruction of the view out; (vii) pattern aesthetics; and (viii) sunlight pattern aesthetics. Experiments with human participants systematically captured their perceptions and preferences.

The results highlight significant differences in perception regarding glare, view, and aesthetic considerations under different pattern conditions. The natural and no-pattern conditions yielded higher satisfaction levels compared to the striped pattern. Notably, the natural pattern achieved satisfaction levels comparable to a clear, unobstructed scenario and was preferred over the striped pattern. Overall, participants favored the natural pattern, suggesting it enhances both visual comfort and aesthetic satisfaction.

In the realm of facade control and automation, the potential of adaptive shading systems and smart glazing is emphasized. Evaluating innovative products like VideowindoW, which integrates biophilic characteristics with glare control, provides insights into creating visually comfortable environments that align with occupants' preferences and environmental sustainability goals. Several challenges arise in the current application of the system. The office environment offers an opportunity to control the lighting environment for stable occupant positions. Advanced systems that detect occupant presence and modify the content according to window configuration and sun position are required. Additionally, user-friendly interfaces that enable override actions can enhance the acceptance of the product and the experience of the space.

In conclusion, biophilic design plays a crucial role in shaping architectural environments that promote human well-being and sustainability. By leveraging technological advancements and aligning with occupant preferences, future architectural endeavors can innovate and create spaces that harmonize with the natural world. This approach not only enriches the lives of occupants but also fosters a more sustainable relationship with the environment.

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Introduction

1.1. Background

The field of architectural design and especially facade design is linked with multi-criteria requirements. A facade is a dynamic cell that serves as a boundary between the interior and the exterior. On the one hand, it responds to outdoor climate conditions and external loads (Knaack et al. 2007). On the other hand, it aims to provide occupant comfort, health, well-being, and safety regarding the interior of a building.

The main indoor user requirements for occupant comfort include the following: thermal comfort, visual comfort, indoor air quality, and acoustics (Al-horr et al. 2016). Additional requirements can also be incorporated in the group such as personal control and interaction, view, or vibration, expanding its scope to encompass a holistic approach to the occupant experience (Luna-Navarro, Loonen, et al. 2020).

For the purpose of the current research, the focal point is visual comfort with an emphasis on glare, in combination with aspects related to control and interaction. The effect of the view in the visual field is partially addressed as well. However, the state of the art of the project is around the concept of biophilia and biophilic design incorporated in the facade design. Additional points for investigation are related to occupant perception, linked to their behavior and the interface provided. The research encompasses a broad spectrum, exploring how visual comfort, control, and interaction intersect with the biophilic aspect, shaping user experiences within the built environment.

VideowindoW is a startup company, founded in 2019, specializing in construction, real estate, civil infrastructure, entertainment, culture, sports, home, and living (YES!Delft 2019). Dealing with shading solutions in glazing facades, the company created its own product, known as VideowindoW. This modular product is a smart glazing system incorporated in a liquid crystal device and can be applied as an additional layer on the facade. It is equipped with an outdoor light sensor, that collects luminescence data from the exterior and modifies through advanced algorithms a moving biophilic content on glazing while realizing glare control (VideowindoW 2021). The product features align with the focus of the research and will be an integral component of the study, facilitating an in-depth exploration of their impact on the intended outcomes.

1.2. Problem statement

There is a contradictory challenge in facade design in balancing the desire to maximize natural daylight in buildings to enhance people's well-being with the necessity to address glare issues and visual comfort (Lee et al. 2022). Conventional shading systems, while effective in reducing glare, obstruct both daylight penetration and outdoor views.

Problem Statement:

- A novel shading product that controls façade transparency has emerged, which can generate a variety of biophilic patterns and movements, at different speeds and states. However, the impact of this technology on indoor illuminance balance, discomfort glare, and outside view perception remains uncertain. Controlling this technology properly might have a positive impact on occupants' well-being by reducing glare risk, and balancing daylight better, without affecting outdoor views.

1.3. Objective

Research Objective:

- To investigate the potential of integrating biophilic design, specifically through the use of natural patterns on facade components, as a solution to the challenge of balancing daylight access and glare in indoor environments.

Sub-objective:

- Examine whether the inclusion of natural patterns affects occupants' comfort, view satisfaction, and preference for the pattern.

Hypothesis on results:

- It is hypothesized that occupants will show a higher preference for natural patterns, associating them with increased comfort, acceptance of obstruction of view out, and aesthetic appeal.

Boundary conditions:

- The hypothesis assumes that the chosen natural patterns are well-designed and align with established biophilic design principles. Additionally, individual preferences may vary based on factors related to demographics, vision, psychology, present state of the observer, task difficulty, work activity and environmental space.

1.4. Research questions

Research Question:

- Does integrating biophilic patterns on building facades influence occupant perception compared to non-natural patterns or clear conditions?

Background questions:

1. What is the evidence of the impact of biophilic design and patterns on occupants?
2. What are the factors that affect discomfort glare?
3. What are the challenges of automation systems according to occupant perception?

Sub-questions:

1. Does the pattern affect occupants' glare sensation?
2. Does the pattern affect visual comfort and daylight satisfaction?
3. Does the pattern affect satisfaction with the outdoor view?
4. Does the pattern itself affect visual satisfaction in terms of aesthetics?
5. Which pattern is most preferred by participants based on their overall experience and perceived connection with nature?

1.5. Approach and methodology

Three different methodology parts are used for the realization of the presented research:

1. **Theoretical part:** Literature review
2. **Practical part:** Experimental design and execution
3. **Interpretation of data:** Statistical data analysis

First, the Literature Review is mainly focused on the following topics (Google Scholar, TUDelft Repository, and Science Direct are the main search engines):

- Biophilia, biophilic design, biophilic patterns, and evidence of biophilic patterns on occupants
- Visual comfort, glare, lighting design, and standards, strategies for mitigating glare, glare indices, factors that affect glare, experimental design on glare
- Automation systems, user-centric control systems, challenges, and considerations based on evidence of occupant behavior

For the Practical part, a laboratory experiment in an office environment is designed and executed. The experiment is designed according to the literature research. Both objective measurements and subjective assessments will be included and quantitative and qualitative data will be collected.

The third part is an interpretation of the data collected by the experiment and the questionnaires and is a statistical analysis of the results to draw accurate conclusions.

According to the result of the first experiment on a static pattern scenario, there is a potential second experiment on a dynamic glazing scenario. In this case, a second practical part will be designed and executed, driven to additional conclusions.

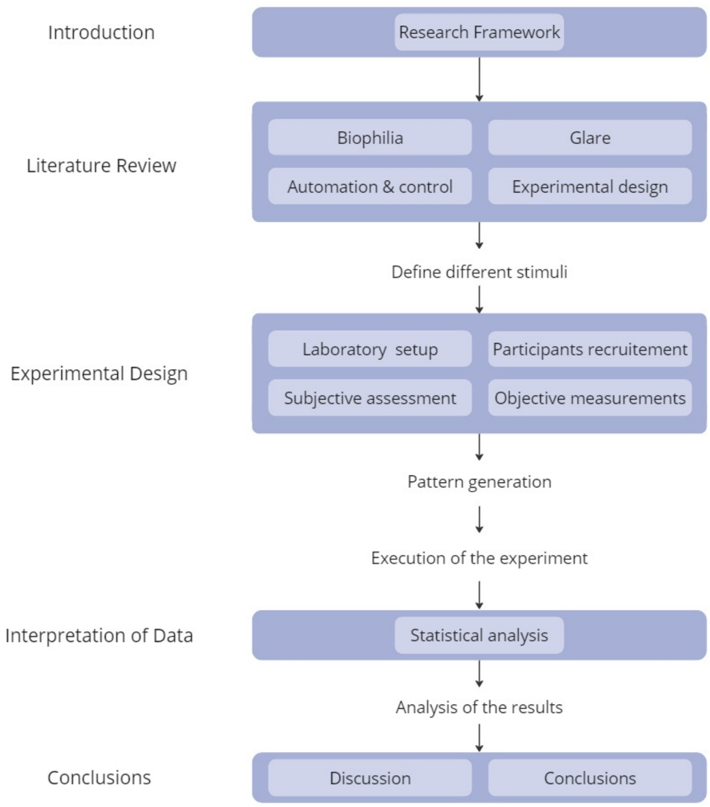


Figure 1.1: Approach and Methodology plan.

1.6. Planning and organization

- **Planning with timeline:** The tasks are arranged in order in the left column, representing some basic steps according to the methodology. The bars on the calendar display the approximate periods needed. The two rounds of experiments are illustrated in orange. The dates may slightly change during execution.

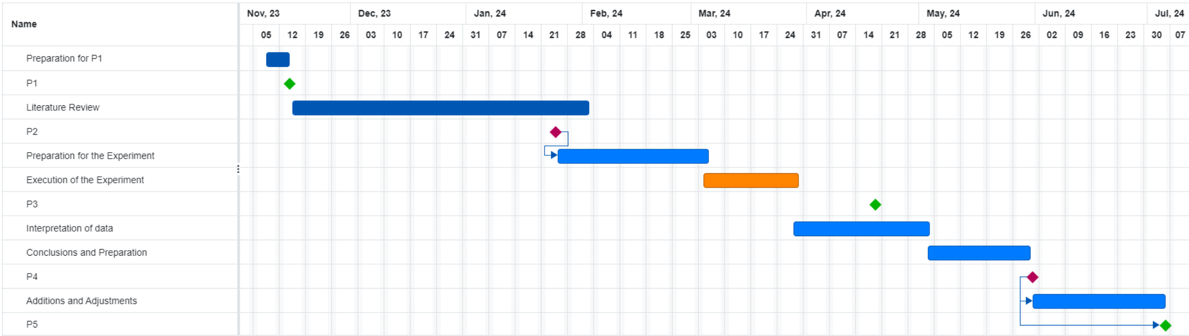


Figure 1.2: Planning in a timeline.

2

Biophilia

2.1. The concept of Biophilia

This section introduces the concept of biophilia. Its profound impact on diverse fields, including psychology, architecture, and environmental studies, has shaped the comprehension of the intricate relationship between humans and nature. For the research, the focus will be on the analysis of human behavior through the lenses of psychological and physiological theories. The application of the biophilia concept in the design of the built environment will be examined, with specific attention given to the gathering of evidence regarding its impact on the health and well-being of occupants.

2.1.1. Defining biophilia

Throughout history, humans have undergone a profound evolutionary journey intimately linked to the natural world. By developing their cognitive abilities, humans managed to thrive, control, and successfully adapt to their environment (S. R. Kellert 2018). These evolutionary responses have become deeply embedded in human biology, cultivating inherent tendencies for connection with the natural and the surrounding environment.

The term 'biophilia' was initially introduced by the German psychologist Erich Fromm and the American biologist Edward O. Wilson. Etymologically, it derives from the two Greek words, 'bio' and 'philia', meaning live and love as affinity (Barbiero et al. 2021). Fromm formulated the biophilic definition in 1973 following its etymology as representing a 'love of life' and expressing a desire to nurture 'growth' in individuals while delving into the fundamental nature of humanity. Fromm aimed to define the psychological inclination towards being attracted to everything alive or vibrant as part of human development, identifying conditions for a biophilic personality (Söderlund 2019).

However, the concept of biophilia is more closely associated with the work of E. O. Wilson, who introduced biophilia as a biological term in 1984, referring to the innate and instinctive characteristic that human beings possess for the natural world. According to Wilson, biophilia can be defined as 'an innate tendency to focus on life and lifelike processes,' coupled with an inherent 'urge to affiliate with other forms of life' (Wilson 1984). According to Wilson, this inherent inclination toward the natural environment is not merely a preference but a fundamental aspect of human biology, exerting influence over various dimensions of human behavior, survival, reproduction, and overall cognitive function (Joye and Block 2011). Nonetheless, the notion of biophilia is rooted in evolutionary history, giving rise to the 'Biophilia hypothesis,' phrased by Wilson and Kellert, which posits that humans are naturally inclined toward seeking, connecting with, and finding consolation in the diversity of life forms (S. Kellert et al. 1993).

The term 'Biophilia' was examined concerning several theories, and a detailed analysis of these associations is presented in the following sections (Figure 2.1).

2.1.2. Psychoevolutionary theories and habitat

Deconstructing the definition of biophilia by Wilson reveals essential points for examination. The emphasis on the natural environment suggests a preference for naturalness in daily life and habitat, and the innate characteristic is intricately connected to the fundamental nature of humanity. Both are linked with the cognitive abilities and the brain function of humanity (Wilson 1984). The desire for affiliation is somewhat linked to the aforementioned aspects but represents a more complex concept (Joye and Block 2011).

A first exploration into the decision-making process reveals a direct correlation with a preference for naturalness. Within this decision-making process, there is an inclination to favor natural products or substances over artificially produced equivalents. This tendency is identified as the 'naturalness bias', reflecting a cognitive process that operates without adhering to a specific rule (Li et al. 2012). There are two main grounds attributed to this bias. One perspective involves an 'instrumental' foundation, wherein individuals hold a belief in the 'functional superiority' of natural products due to their efficacy, health benefits, enhanced safety, superior taste, and minimal environmental impact. On the other hand, the 'ideational' basis supports the 'moral or aesthetic superiority' of naturalness solely based on its natural state, emphasizing its precedence over humanity and its association with a sense of justice (Haans 2014).

While the two foundations are discussed independently, it is important to acknowledge that one may arise as a consequence of the other, and vice versa (Haans 2014). Despite this potential interdependence, the ideational aspect is closely connected with biophilia regarding its evolutionary character and it is often influenced by cultural notions and preferences. In this case, cultural beliefs in natural superiority can force the process of decision-making to an already made decision. Another possibility to alter this action is the idea of the 'connectedness to nature', a natural affinity or bond with the environment. This indicates that people prioritize the well-being of the environment as a whole, have a proactive stance toward preserving the natural world, and that individuals who are more closely interconnected with nature are likely to exhibit these preferences more strongly. It is noteworthy to highlight that these theories do not contradict each other. Instead, in their theoretical formulations, they function as assumptions with a solid foundation but may exhibit inconsistencies in certain specifics.

From another approach, until now, the evolutionary journey of humans has been discussed in connection with various aspects of biophilia. The emotional and psychological bond between humans and the natural world has drawn attention in the field of environmental psychology, giving rise to Roger Ulrich's psychoevolutionary framework (Joye 2007). This theoretical model suggests that our emotional responses to the environment are immediate and not subject to conscious control by cognitive processes. From this perspective, emotional reactions are fast, automatic, and unconscious, enabling individuals to quickly form positive or negative sentiments about their surroundings. The argument claims that these rapid emotional responses have evolutionary origins and serve an adaptive function by prompting immediate actions that contribute to the well-being and survival of the organism. Specifically, our human ancestors, in their quest for survival, encountered diverse challenges, risks, and predators, as well as opportunities for exploration and reproduction in various environments.

Focusing more on the direct habitat of the human being, the various natural settings encountered by individuals can be identified as landscapes containing distinctive structural characteristics. Jay Appleton formulates the 'prospect refuge theory' explaining that people's inclinations for landscapes are associated with the environmental attributes of prospect and refuge (Joye 2007), (S. R. Kellert 2018). Prospect involves settings that offer a broad view of the surroundings, facilitating the perception of distant features and opportunities. On the other hand, refuge pertains to environments that provide shelter and a sense of security. Together, these attributes reflect evolutionary preferences, with prospect addressing the need for awareness of distant aspects, while refuge caters to the desire for safety and protection in spatial experiences. Aligned with the prospect and refuge theory, the innate human preference for landscapes similar to savannas, characterized by open grassy areas and scattered trees, emphasizes a desire for environments offering visual openness and natural elements (Joye 2007).

On the other hand, Ulrich outlined certain visual elements describing the setting in his framework that evoke positive emotional responses, adding visual and aesthetic criteria (Ulrich 1983). These factors involve the acknowledgment of visual complexity, specifically favoring mid-level complexity marked by prominent features or noticeable patterns. Additionally, there is a preference for moderate to high depth within the visual field, a uniform ground surface texture facilitating ease of movement, a 'deflected vista', and a notable absence or minimal existence of perceived threats. The inclusion of calm water elements and vegetative components further amplifies the positive response, augmenting an elevated sense of appreciation within the observed environment.

In an alternative perspective, Kaplans outlines two primary domains associated with four attributes of natural environments that have a positive impact on individuals (Kaplan et al. 1989), (Joye 2007). These domains involve "understanding," representing the desire to comprehend one's surroundings, and "exploration," signifying the need to broaden horizons, bridging the gap between mere understanding and gaining a more in-depth awareness of the surroundings. The four attributes are complexity, coherence, legibility, and mystery. Complexity, in scenic evaluation, refers to the richness and intricacy of a visual scene, encompassing diverse visual elements and suggesting numerous aspects to explore and consider. Coherence, refers to the orderly organization of visual elements, facilitating a sense of order and directing attention within a scene. Legibility involves the ease with which the elements of a cityscape can be recognized and organized into a coherent pattern, emphasizing the importance of orientation. Finally, mystery involves the potential to uncover more information within a scene, encouraging exploration by suggesting that further details are concealed beyond the initial viewpoint, often achieved through a partial obstruction or changes in the environment.

2.1.3. Restoration and recovery theories

The inherent biophilic inclination, deeply rooted in human biology, serves as the framework for comprehending the restoration and recovery dimensions inherent in biophilia. Delving into the interrelated dimensions of stress mitigation and attention restoration, this section explores the vital role that biophilia plays in enhancing well-being and offering a pathway to recovery from the challenges of the modern world.

According to Kaplan's Attention Restoration Theory (ART), directed attention fatigue occurs when individuals undergo mental exhaustion due to prolonged engagement in tasks that demand focused and directed attention (Kaplan et al. 1989). This condition is characterized by a diminished capacity to maintain concentration, leading to cognitive fatigue and increased vulnerability to stress and bad temper (Joye 2007). ART posits that exposure to natural environments serves as a potent means to alleviate directed attention fatigue. The intrinsic qualities of nature, including its capacity to evoke fascination and enable effortless engagement, play a pivotal role in restoring cognitive resources. This restoration process is crucial in counteracting the undesirable effects of prolonged directed attention, offering valuable insights for interventions aimed at enhancing cognitive well-being and performance.

Ulrich's Stress Reduction Theory proposes that exposure to nature serves an adaptive function, providing individuals with a restorative break from stress (Ulrich 1991). This restoration is essential for recharging energy levels needed for subsequent activities, such as acquiring food or water. The adaptive response to restoration involves positive cognitive states like attention and interest, accompanied by feelings of liking, decreased negative emotions like fear, and a shift in physiological arousal from high to moderate levels. In essence, Ulrich's theory proposes that engaging with nature facilitates a cognitive shift towards a positive state, emotional well-being, and a more balanced physiological state.

Contemporary society, especially in urban settings, witnesses an increasing detachment from nature, primarily driven by technological and sedentary lifestyles that prioritize indoor activities (S. R. Kellert 2018). This disconnection stands in opposition to increasing evidence supporting the significant influence of nature on human health and well-being. The challenge lies in strategically incorporating nature experiences into built environments. The biophilic design aims to create habitat environments that acknowledge humans as biological entities, emphasizing the imperative of integrating nature for enhanced health, productivity, and overall well-being in the places of residence, work, and habitation.

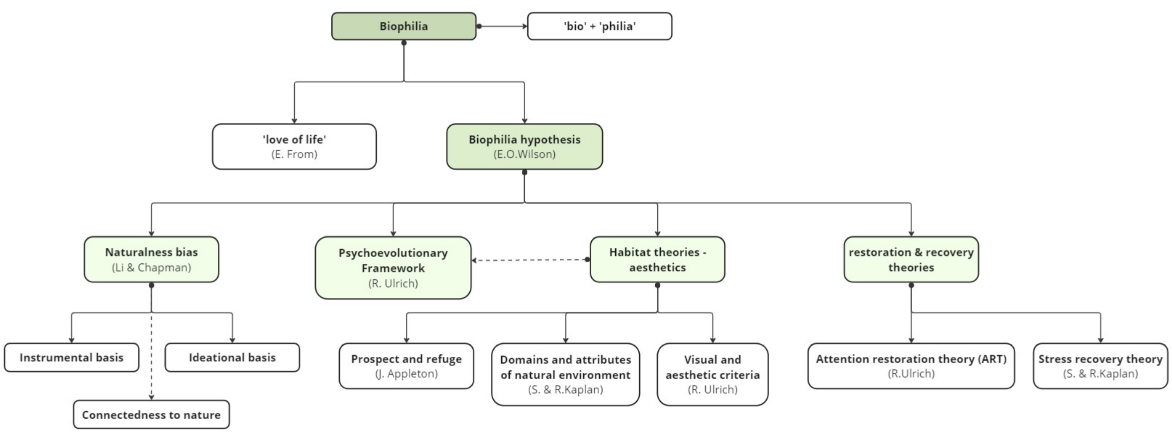


Figure 2.1: Review of biophilia concept related theories.

2.2. Biophilic design

This section explores the application of biophilic principles, expanding upon the conceptual foundation established in the previous section. After developing a comprehensive understanding of biophilia's core concepts and related theories, attention is shifted toward their practical integration in the built environment. This part explores the implementation of biophilic principles in architectural concepts and facade elements, connecting theoretical concepts and practical design applications, and illustrating how biophilic ideas are translated into physical environments that significantly impact human experiences.

2.2.1. Biophilic design principles and biophilic experience

Biophilic design, an essential part of architecture, focuses on creating a strong connection between occupants and the natural environment, based on values and principles. By incorporating elements linked to a direct connection with nature, an indirect one, and a connection related to spatial conditions, individuals can experience various biophilic attributes and derive benefits from them. The concept of biophilic design, introduced in 2001, encompasses various interpretations and values, setting the stage for an exploration of diverse practices that integrate nature into architectural designs (Zhong et al. 2022), (Söderlund 2019).

S. Kellert's categorization of values offers a comprehensive and systematically tested framework derived from long-term empirical research. He specifically outlines 10 values that illustrate the roles and benefits of biophilia (Table 2.1) (Ross et al. 2018). These values incorporate a diverse range of human bonding with the environment that formed a solid basis for the practices that followed.

Table 2.1: Kellert's biophilic values (Ross et al. 2018).

Value	**Description**	**Roles and Benefits**
Moralistic	Ethical considerations for nature	Reliance on multiple connections with the natural world
Humanistic	Emotional bond with nature	Bonding, nurturance, cooperation
Utilitarian	Practical and material use of nature	Comfort, security, efficiency
Scientific-Ecologistic	Systematic study of nature	Cognition, problem-solving, critical thinking
Naturalistic	Direct experience of nature	Contact with the natural world sustains body, mind, and spirit, stress reduction by natural elements in the built environment, creativity and productivity
Aesthetic	Physical appeal and beauty of nature	Curiosity, intellectual development, imagination, creativity, stress reduction, improve emotional well-being
Negativistic	Fear and aversion from nature	Coping, protection, security, awe, appreciation for powers greater than human
Spiritual	Spiritual reverence for nature	Meaning, purpose, feelings of kinship and relation, reverential feeling to old structures
Dominionistic	Mastery and physical control over nature	Mastery skills, self-confidence, self-esteem, strong dopamine or pleasure responses
Symbolic	Use of nature in language and thought	Communication, language, design, healing and recovery

According to the critical review of Zhong et al., there is a timeline from 2001 until 2020 when different theories and practices were developed focusing on characteristics of biophilic design (Zhong et al. 2022). The term was quite active, particularly in 2008 and the years that followed, and used from different perspectives to describe similar approaches. Most of them are addressed together in detail in the later book guide on biophilic design by Kellert et al. (S. R. Kellert et al. 2013) and individual work of the practitioners (Figure 2.2). The connections with the biophilic definitions and theories discussed in the previous chapter are readily apparent. Therefore, in chronological order, in 2001, Heerwagen and Hase introduced seven features of biophilic buildings. In 2008, Kellert categorized 72 characteristics of biophilic design providing a detailed explanation for a deeper understanding of the biophilic design concept. Concurrently, in the same year, Heerwagen,

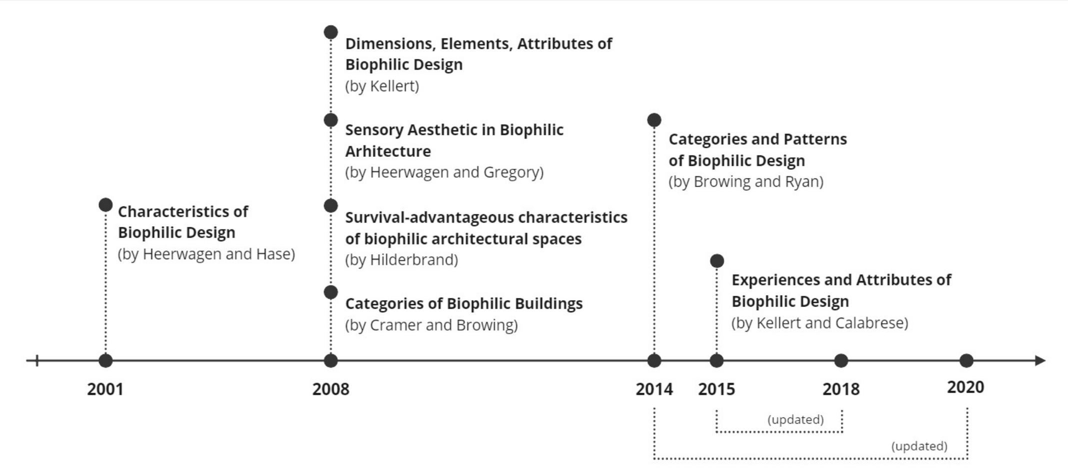


Figure 2.2: Timeline of biophilic theories and practices (Zhong et al. 2022).

Gregory, and Hildebrand focused on basic aesthetic and psychoevolutionary aspects. Simultaneously, three main categories were established by Cramer and Browning, which were analyzed further in 2014 and 2020. In subsequent years, particularly in 2014 and 2020 Browing in collaboration with Ryan, expanded his work by referring to specific elements. Finally, in 2015 and 2018, Kellert narrowed down his earlier work and together with Calabrese, delved into the three types of biophilic experience and their corresponding characteristics.

Among the various practices, certain commonalities emerge despite differences in depth and detail (see Appendix Figure A.1). For instance, the most predominant feature that is used by all the practitioners is the prospect and refuge, a psychoevolutionary issue that was already introduced at that time. Fear is also employed by more than one practitioner, partially connected to the preceding theory. Another recurrent element is the use of a variety of sensory stimuli, akin to the emotional value and the definition of biophilia as affiliation. The aesthetic factor is also strong and is described by the theories on habitat analysis, referring to the organized complexity, enticement and mystery. Generally, visual connections with nature often involve repeated references to natural elements like light and water, as well as physical or mimetic representations addressed as biomimicry and biomorphic shapes, forms, natural geometries, and patterns.

Analyzing Kellert's latest work, which serves as a synthesis of previous research, three different experiences can be observed, a 'direct' one, an 'indirect', and an 'experience of space and place'. Each experience is characterized by different attributes that can be seen in Table 2.2 (S. R. Kellert 2018). The direct experience involves real exposure to natural elements, such as vegetation, water, lighting, or weather conditions. The indirect experience is based on representations and symbolic elements of nature, illustrated in images, materials, shapes, patterns, and features that tend to mimic biological and natural behaviors. The last experience is centered on the built environment and its ecological design, emphasizing the overall feeling of the environmental condition, described similarly to previous theories as security, aesthetics, emotional values, and transition. Overall, these experiences are sensed by human beings through their senses, namely sight, sound, touch, smell, and taste. The visual can be considered the most necessary one to identify dangers and opportunities in a setting.

2.2.2. Application in architecture and facades

Nature has long served as a source of inspiration throughout the history of architecture even before the introduction of the biophilic term. In recent years, however, there has been a pronounced shift towards employing biophilic design strategies. This shift is driven by the imperative to address climate change, enhance the health and well-being of occupants, and foster circularity and resilience in architectural practices. The biophilic design in architecture can be described by different strategies incorporating fundamental aspects of natural elements, shapes, and structural landscapes into the built environment, everything that is related to the aforementioned biophilic principles according to the theories and practices.

Various architectural types related to biophilia have been developed and applied, moving away from the uniformity of modern architecture (Joye 2007). Examples include Biomorhic and Zoomorphic structure designs by Santiago Calatrava and Antoni Gaudi, both drawing from natural forces. Organic Architecture, as

Table 2.2: Biophilic experience and attributes (S. R. Kellert 2018).

1. Direct experience of nature	2. Indirect experience of nature	3. Experience of space and place
Light	Images	Prospect and refuge
Air	Materials	Organized complexity
Water	Texture	Mobility
Plants	Color	Transitional spaces
Animals	Shapes and forms	Place
Landscapes	Information richness	Integrating parts to create wholes
Weather	Change, age and the patina of life	
Views	Natural geometries	
Fire	Simulated natural light and air	
	Biomimicry	

seen in Frank Lloyd Wright's work, seamlessly integrates with natural surroundings. These approaches incorporate symbolic elements, embedding natural content into the structure and evoking emotions and experiences already discussed in previous sections. Several examples will be examined (Figure 2.4).

Gaudi's Sagrada Familia, in Barcelona, is a characteristic example of biophilic design principles both in the exterior and interior space (Gaudi n.d.). Focusing on the latter, a direct biophilic experience using the natural element of light can be observed. The play of natural light through intricately designed stained glass windows creates an immersive and dynamic environment. Resembling the dappled light patterns found in natural settings, these windows infuse the space with vibrant colors, fostering a connection to the outdoors. The interplay of light and shadows within the Sagrada Familia's interior evokes the calming and rejuvenating qualities associated with natural environments, enhancing the overall biophilic experience for occupants.

Calatrava's Oriente Station in Lisboa incorporates biophilic design providing an indirect experience of nature (Calatrava 1998). This is achieved with its 'forest of trees' concept, using steel and glass structures to mimic a natural landscape. The biomorphic shapes and extensive use of glass create an aesthetically pleasing and transparent space, resembling natural patterns. The station's layout and axial connections align with biophilic principles, providing passengers with a sensory and immersive experience. Calatrava's comprehensive approach, including urban planning, integrates Oriente Station into the broader urban environment, showcasing a thoughtful inclusion of biophilic elements in architectural design.

Fallingwater, a house designed by Frank Lloyd Wright in Pennsylvania, embodies biophilic design principles through a meticulous integration of built structures with natural elements (Fallingwater 1935). This provides a direct biophilic experience, an indirect one, and an of space and place. Situated above a waterfall, the design seamlessly incorporates the natural element of water into the design and principles of the prospect and refuge theory, providing occupants with both expansive views (prospect) of the surrounding forest and intimate spaces (refuge) within the built environment. The use of natural materials like stone and wood strengthens the connection to the outdoors, creating a biophilic harmony. Additionally, the cantilevered terraces and large windows strategically frame and capture the dynamic play of light and shadow, mimicking natural variations and creating an immersive experience that aligns with biophilic design principles.

Biophilic design strategies are broad and depend on the various scales to which biophilic design can be applied in architecture (S. R. Kellert et al. 2013). They can appear on the building level and expand to the urban scale reaching the block, street, neighborhood, community, or region level Figure 2.3. For the current research, the focus is on the building level and precisely on the facade component.

The Bosco Verticale in Milan, designed by architect Stefano Boeri, exemplifies biophilic design principles in its innovative facade (Boeri 2014). Comprising two residential towers, the building features an extensive array of trees and plants on its balconies, creating a vertical forest. This integration of greenery not only enhances the aesthetic appeal but also contributes to environmental sustainability, providing natural shading, air purification, and biodiversity in an urban setting. The design fosters a harmonious coexistence between the built environment and nature, offering residents a direct connection to greenery and the natural world within an urban context.

The biomorphic facade of Suites Avenue by Toyo Ito in Barcelona exemplifies biophilic design by incorporating organic, nature-inspired forms into the architectural structure (Ito 2005). The facade's wavy and arched resemble natural elements, creating a visually stimulating and harmonious connection to the surrounding environment. This biomorphic design approach enhances occupant well-being by evoking associations with the organic geometrical patterns found in nature. Additionally, the play of light and shadow on the biomor-

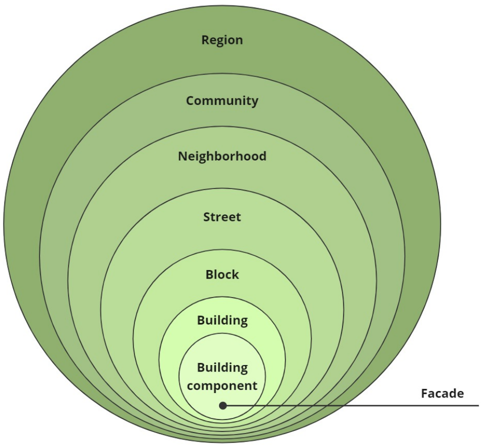


Figure 2.3: Biophilic design in scales.

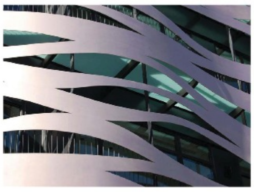
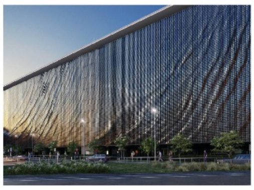
	Direct experience of nature	Indirect experience of nature	Experience of space & place
Building level	 Antoni Gaudi, La Sagrada Familia	 Santiago Calatrava, Oriente Station	 Frank Lloyd Wright, Falling water
Facade component	 Stefano Boeri, Bosco Verticale	 Toyo Yto, Suites Avenue	 Ned Kahn, Brisbane Airport

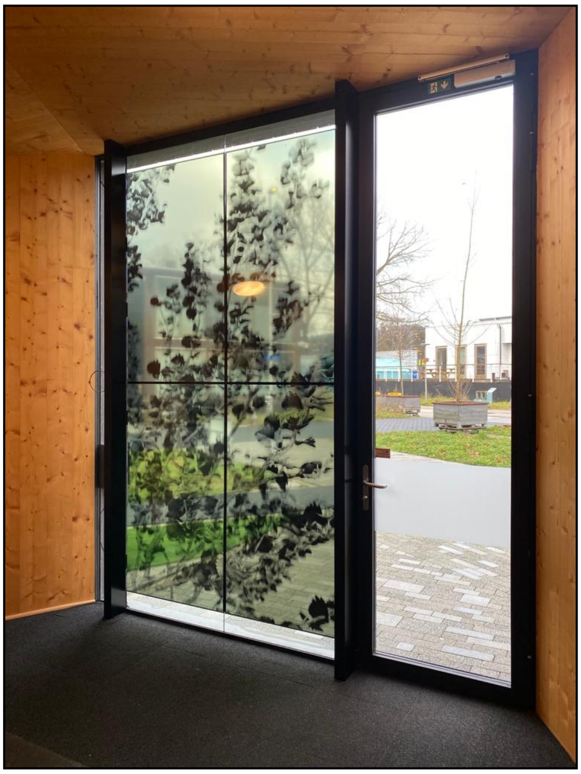
Figure 2.4: Biophilic design applications in building and facade level.

phic facade contributes to a dynamic and ever-changing visual experience, fostering a sense of connection to the natural world within the built environment.

The kinetic facade of the Brisbane Domestic Terminal Airport Carpark, designed by Ned Kahn, embodies biophilic design principles through its dynamic and interactive elements (Kayıhan 2018). Composed of thousands of small, reflective metal panels, the facade responds to environmental factors such as wind, creating a visually captivating play of movement and light. This dynamic quality mirrors natural phenomena like leaves rustling in the wind, establishing a connection between the built environment and the ever-changing aspects of the natural world. The facade's kinetic features contribute to a sense of vitality and engage occupants with the surrounding environment, enhancing the overall experiential and aesthetic qualities of the architectural space.

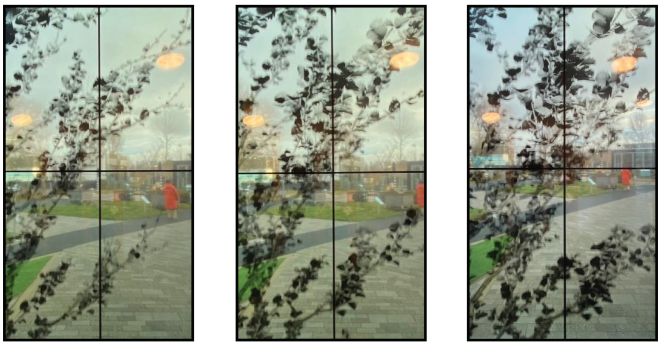
2.3. Biophilic characterization of the VideowindoW product

The VideowindoW product incorporates some characteristics of biophilic design. The most important features include the relation of the tree pattern with natural geometry and fractals and the dynamic effect of motion and light that create a visually enriching architectural experience of the space. Below each characteristic is analyzed separately.



(a) Light Penetration through the product

(b) Fractal-based geometry



(c) Motion capture

Figure 2.5: Biophilic characteristics of the VideowindoW product.

Natural Geometry and Fractals: The tree pattern, generated by an AI system, aligns with the principles of natural geometry, particularly in terms of hierarchically organized scales and fractals (Figure 2.5b). In both nature and the built environment, geometric patterns often show a hierarchy, with elements progressing from a broad base to progressively narrower, higher levels in a mathematically proportionate manner (S. R. Kellert 2018). This feature is evident in most trees, where the trunk forms a broad base supporting narrower and higher branches. The tree pattern also embraces the concept of fractals, which are repeated patterns or shapes that change predictably. Fractal, derived from the Latin "fractus" meaning broken, exhibits a unique property known as self-similarity, where rough patterns repeat across different scales. Unlike traditional geometry with integer dimensions, fractals have a non-integer dimension, ranging between 1 and 2 for plane fractals and between 2 and 3 for spatial fractals (Joye 2007). In the tree pattern, you can also see fractal patterns in the leaves, being a bit different but still very similar. Like fractals found in nature, the tree pattern exhibits repeating patterns that, when observed at different scales, reveal layers of symmetry, creating a sense of wholeness.

Light: The dynamic biophilic pattern on the facade contributes to the architectural environment by adjusting light transmittance based on outdoor conditions, aligning with fundamental aspects of human existence (Figure 2.5a). Natural light plays a pivotal role in shaping people's spatial and temporal responses, influencing their orientation within surroundings and fostering a connection to daylight patterns and seasonal changes (S. R. Kellert et al. 2013). Human adaptation to variations in light conditions, including circadian rhythms, is crucial for well-being, comfort, and productivity. The dynamic adjustment of light by the biophilic pattern ensures a harmonious integration of these natural fluctuations, facilitating ease of movement, spatial familiarity, and overall positive experiences. This intentional manipulation of light, beyond increasing exposure, reflects biophilic design strategies. The pattern's ability to modulate light intensity, diffuse light, and create shadows contributes to a creatively displayed natural light, stimulating occupants' interest, awareness, and knowledge of the space.

Motion: The motion embedded in the tree pattern emulates an additional layer of nature (Figure 2.5c). In the natural world, constant movement is evident (S. R. Kellert et al. 2013). The intentional movement of the biophilic pattern reflects the dynamic qualities seen in nature, adding an appealing aspect to the visual environment. The responsive motion, resembling the gentle sway of tree branches in the wind, brings a lifelike element to the built environment. Similar to the natural interaction of light and shadow, the pattern's movement generates a captivating mix of visual elements, enhancing the dynamic brightness similar to the ever-changing scenes in natural surroundings. This deliberate integration of motion in the biophilic pattern aims to create an authentic and visually pleasing experience in the architectural and facade setting. This feature of motion not only aligns with biophilic principles but also introduces a sense of vitality and connection to the outdoor environment.

2.4. Evidence on impact of biophilic design on occupants

This part focuses on a comprehensive exploration of the impact of biophilic design on occupants' experiences, drawing from empirical evidence derived in both artificial and natural environments. Together these studies contribute to a holistic understanding of how biophilic design influences individuals.

2.4.1. Results of studies tested in an artificial environment

Various studies explored the impact of biophilic design on occupants within artificial settings. The findings from Haans, Tuaycharoen, Abboushi, and Camilothori shed light on preferences, discomfort glare, fractal patterns, and façade geometry, collectively contributing to a better understanding of how biophilic elements influence occupant experiences.

Haans (2014) explored different types of light to analyze people's attitudes toward natural and non-natural sources in various settings both natural and artificial. Of 11 light types that were examined, daylight was considered more natural, than light emitted by a daylight harvester, followed by light from a daylight simulator and other artificial sources. The perception of what was considered 'natural' was contingent on both the source and the degree of transformation and occupants were capable of attributing this term in a meaningful manner for distinguishing natural and non-natural sources. At the same time, natural was preferred by them and was believed to be beneficial in terms of health, concentration, and aesthetics, which led them to a general positive point of view. So, natural is differentiated, is preferred, and is beneficial.

In a laboratory experiment, Tuaycharoen et al. (2005) investigated the effect of different images projected onto small screens on discomfort glare. His findings revealed that the image content especially natural scenes can reduce discomfort glare tolerance, contrary to urban scenes. Additionally, the presence of natural elements such as water or ground has an impact on this behavior. Therefore, natural content can reduce discomfort from glare.

Abboushi, Elzeyadi, Taylor, et al. (2019) examined the visual interest, preference, and mood in a lecture room with projected patterns and renders with patterns (Figure 2.6). Both a higher visual interest and a higher preference were linked with fractal choices over Euclidean patterns. More specifically, an emphasis was given to the dimension of fractals with mid-complexity fractals being higher on preference levels and being linked with restoration theories. This finding was altered in a further experiment on projected renders with patterns, where occupants showed a preference for higher dimensions in fractal patterns. Thus, natural patterns like fractals are considered more interesting and preferable.

Research by Chamilothori, Chinazzo, et al. (2019) was focused on the virtual reality environment and subjective and psychological aspects related to the facade geometry. Three different facade types were rendered according to physical radiance data, an irregular, a regular, and a facade scenario with blinds, all of them having the same opening percentage of the window area (Figure 2.7). According to the subjective responses from occupants, the irregular pattern was considered more pleasant, interesting, and exciting than the other options. Physiological responses led to cardiac deceleration and were linked with recovery theories. In another experiment, 8 facade patterns (Figure 2.8) were tested according to their influence on occupants in terms of the sky, space activity, and cultural factors again in the virtual environment (Chamilothori, J. Wienold, et al. 2022). From the three factors tested, only cultural preferences showed significant differences in the levels of excitement between the two nationalities that were checked. The facade geometry was proven to determine the experience of the space especially in the example of two patterns with slight differences where measurable features such as the bright level, amount of space, and level of satisfaction were affected. Consequently, the two studies indicate the predominant effect of facade geometry on occupant perception.

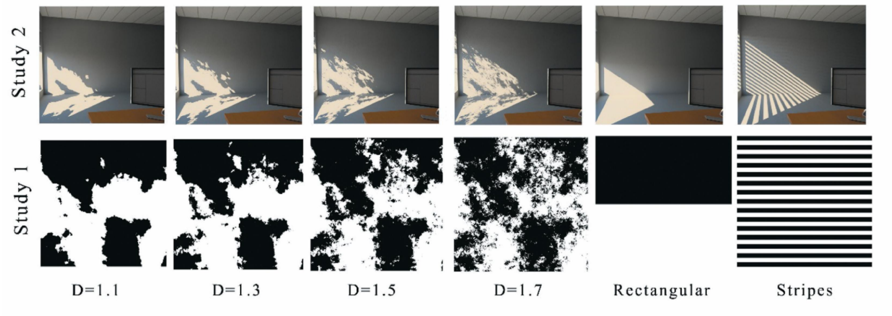


Figure 2.6: Projected patterns and renders of projected patterns (Abboushi, Elzeyadi, Taylor, et al. 2019).

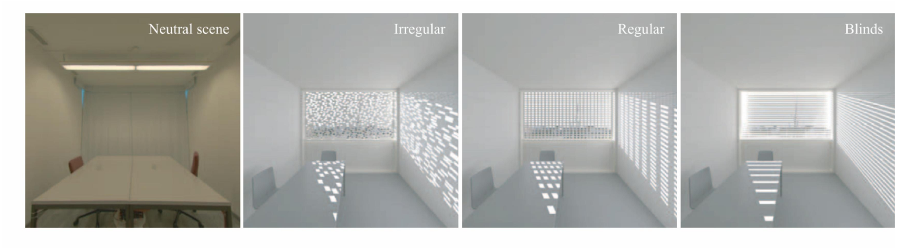


Figure 2.7: Patterns in virtual environment (VR) (Chamilothori, Chinazzo, et al. 2019).

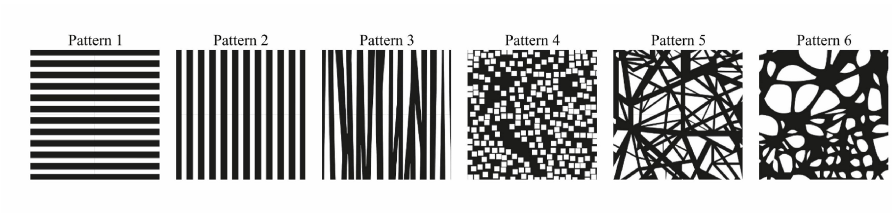


Figure 2.8: Patterns tested in virtual environment (VR) (Chamilothori, J. Wienold, et al. 2022).

2.4.2. Results of studies tested in a natural environment

On the other hand, the impact of biophilic design is analyzed according to experiments realized in a natural environment. Two studies, Abboushi's investigation, and Tuaycharoen's research provide valuable insights into the intersection of biophilic design and natural surroundings.

Abboushi, Elzeyadi, Wymelenberg, et al. (2021) conducted a study evaluating visual comfort, visual interest, and quality of the view under three different conditions. The conditions included clear windows, windows with fractal patterns, and windows with striped patterns, tested in a real office environment (Figure 2.9). Unexpectedly, contrary to their expectations, the study found that there were no significant differences in visual comfort and visual interest between these conditions. Nevertheless, an interesting observation emerged when the outdoor views were present. In particular, the patterns, fractals, and stripes, were perceived as distractions, decreasing the visual interest in the outdoor views and the overall image. This distraction was related to a psychological theory, known as 'masking', according to which a reduction in the clarity of one element (in this instance, the outdoor scenery) is caused by another element or covering (fractal or striped pattern). Additionally, the concept of 'outdoor view reconstructability' appears, and refers to the capacity of individuals to recreate areas of a view that are blocked mentally. That is maybe why the clear condition demonstrated higher view quality, indicating that simplicity in window design may enhance the overall quality of the outdoor view. The study observed that this ability was reduced under both patterns compared to the clear condition. The research also detected that visual interest peaked at higher distances and view quality was influenced by the desk arrangement.

Tuaycharoen et al. (2007) research focused on the relationship between the window view and its content with discomfort glare. The study revealed insights into how the characteristics of a view influence occupants' perception of glare discomfort. A well-lit window with an interesting view was linked with reduced discomfort compared to a window with an equal average level of brightness but a less interesting view. Views were more interesting when having natural content. Additionally, the research highlighted that a view with a broad luminance range is more prone to causing glare compared to one with similar average brightness but less variation. The way light intensity was spread across space significantly influenced how individuals perceive discomfort caused by glare. The findings supported the idea that visual comfort is related to aesthetic criteria.

Figure 2.9: Window patterns tested: fractal pattern D = 1.7 (left), clear condition (middle), and striped pattern D = 1 (right) (Abboushi, Elzeyadi, Wymelenberg, et al. 2021).

2.5. Conclusions

Biophilia, the inherent connection to nature, significantly influences human behavior and well-being, shaping preferences, decisions, and emotional responses toward the natural world. Biophilic design, integrating natural elements into architecture, serves as a valuable tool for enhancing human comfort and promoting environmental sustainability. Throughout the evolution of biophilic design, exemplified by various architectural projects, a consistent emphasis on integrating natural elements, sensory stimuli, and aesthetic values is observed. The VideowindoW product effectively embodies biophilic design principles, offering a potentially enriching and harmonious architectural experience aligned with humans' innate biophilic tendencies.

Empirical evidence from both artificial and natural environments consistently supports the positive impact of biophilic design on occupant well-being. Natural elements such as light, fractal patterns, and irregular geometries significantly influence occupants' comfort, satisfaction, and preference. Incorporating biophilic design principles into architectural projects not only enhances aesthetic appeal but also contributes to better health, reduced stress, and increased productivity among occupants. However, a recent study also reveals that occupant perception concerning visual aspects was not influenced under different pattern scenarios including a biophilic pattern, which addresses a research gap in the field and suggests further exploration.

Despite the last findings, integrating biophilic principles with advanced technologies holds promise for creating more engaging, comfortable, and sustainable built environments. This is particularly relevant to the project objectives and the following chapters, which focus on visual comfort, glare control, and automated systems. By exploring how biophilic design principles can mitigate glare and enhance visual comfort, optimizing innovative technologies like the VideowindoW can create environments prioritizing human well-being and environmental management.

In summary, the study of biophilia underscores the significant influence of the connection with nature on architectural design. Further research and innovation at the intersection of biophilia and technology offer opportunities to develop an architecture that not only enhances daily lives but also fosters a more sustainable relationship with the natural environment.

3
Visual comfort

3.1. Human vision and light perception:

Understanding human vision and light perception is essential for optimizing visual comfort in architectural design, as it provides fundamental insights into how light interacts with the human eye and influences the overall visual experience. The human eye functions as a sensory organ integral to the sensory nervous system that allows vision. It is connected to the brain and responds to visible light, facilitating the utilization of visual information for various purposes. This complex mechanism enables humans to observe their surroundings and perceive variations of light, color, and brightness. (Baker et al. 2014) (SLL 2009).

Anatomy and components of the human eye:

The anatomical structure of the eye consists of various interconnected components (Figure 3.1). The cornea, a transparent front layer, and the sclera, the visible white part, form the external eye. Acting as a window, the cornea, together with the pupil, regulates light entry, controlled by the iris, a colorful ring surrounding the pupil, that is responsible for the eye color. The crystalline lens, positioned behind the pupil, adjusts the light focus on the retina, located at the eye's back. Accommodation, a process facilitated by the lens's elastic nature, enables the eye to focus on objects at different distances.

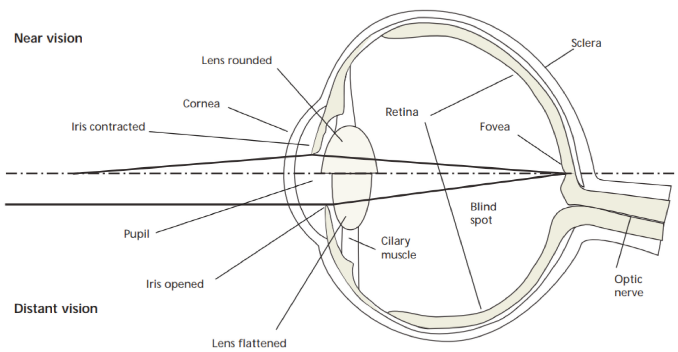


Figure 3.1: Eye anatomy (SLL 2009).

Photoreceptor cells:

The retina consists of two photoreceptor cells, the rods and cones (Figure 3.2). Rods are responsible for low-light and dim conditions, whereas cones function optimally in bright light and are responsible for facilitating color vision. After photoreceptor cells in the retina capture light, they send signals through the optic nerve to the brain's visual processing centers. This crucial pathway is essential for relaying visual information, and initiating intricate neural processes in the visual cortex. The brain processes and interprets these signals, leading to our perception of the visual environment.

Color perception and visual spectrum:

Light is electromagnetic radiation characterized by wavelengths. Within the solar spectrum, visible light falls within the wavelength range of 0.38 to 0.78 nm (Figure 3.3). Cones in the retina respond to specific

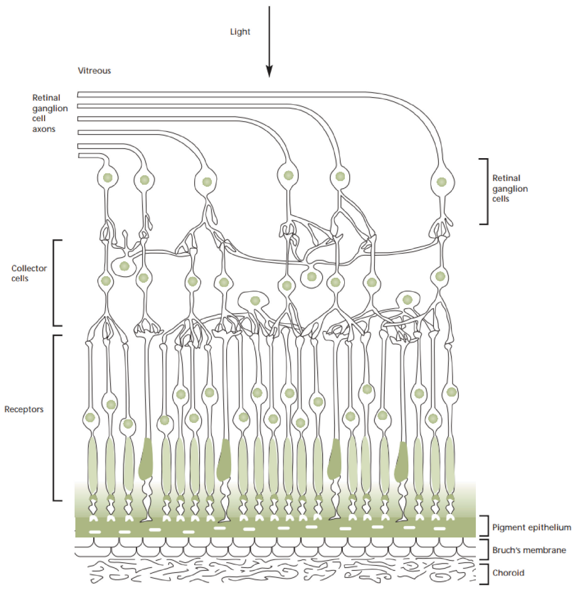


Figure 3.2: Photoreceptor cells (SLL 2009).

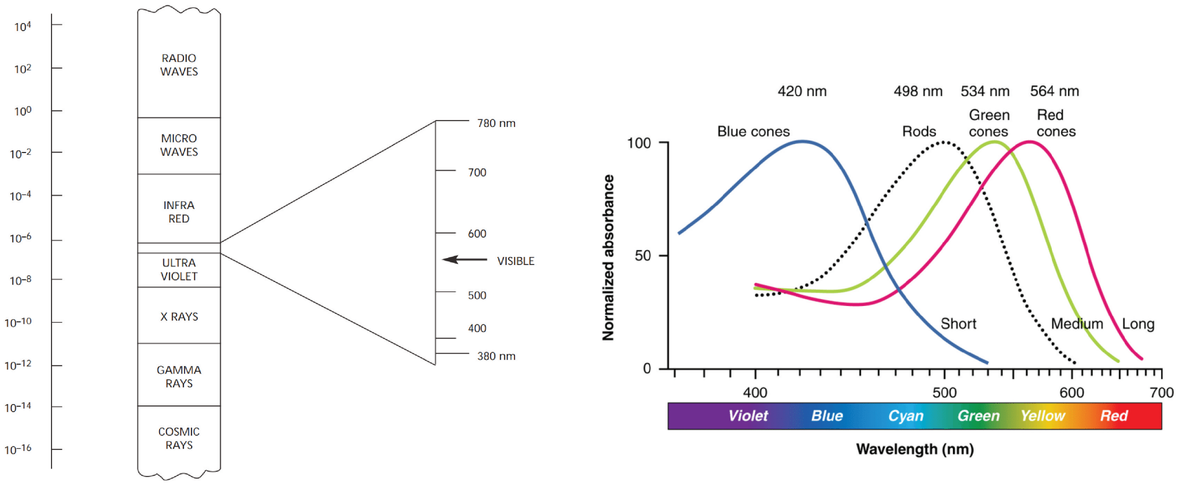


Figure 3.3: Electromagnetic spectrum and visible light (left), eye sensitivity (right) (SLL 2009).

segments of this visual spectrum, allowing the discrimination of various colors. The eye's peak sensitivity to light gradually decreases from its peak around 0.555 nm (yellowish-green) towards the boundary values. Short-wavelength cones are sensitive to violets and blues, medium-wavelength cones to greens and yellows, and long-wavelength cones to oranges and reds. The brain processes signals from these cones, creating our perception of color. The visual spectrum spans a continuum of colors, from violet to red, with each hue corresponding to a specific wavelength.

Brightness perception and luminance:

The brain's perception of light intensity, or brightness, is a complex process influenced by the concept of luminance. Luminance is a photometric unit that quantifies the intensity of visible light emitted or reflected from a surface per unit area. It is expressed in candelas per square meter (cd/m^2). This metric takes into account the spectral sensitivity of the human eye and is essential for understanding how the human visual system perceives the brightness, darkness, and contrast of an object or a scene.

Illuminance:

Illuminance refers to the amount of luminous flux falling on a surface area, measured in lux (lx). It characterizes the brightness of a space or object as perceived by the human eye. Illuminance takes into consideration both the intensity and distribution of light within a given area. This metric plays a pivotal role in lighting design, influencing visual comfort, task visibility, and overall environmental aesthetics.

Field of view:

The field of view encompasses the entire extent of the observable world that can be seen at any given moment without changing the direction of gaze. Central vision, concentrated around the fovea centralis, is responsible for detailed and focused sight. This area is critical for tasks requiring high acuity, such as reading or recognizing faces. It covers approximately 1-2 degrees of visual angle. In contrast, peripheral vision covers a wider expanse but lacks the same level of detail as central vision. The ergorama, representing the most comfortable range of vision is considered within a 60-degree angle of the FOV and is a subset of the panorama. Panorama involves the complete visual field approximately within a 120-degree angle, while ergorama specifically denotes the comfortable region where the eyes can move with ease, minimizing strain and optimizing visual efficiency.

Visual acuity:

Visual acuity refers to the clarity or sharpness of vision. It is commonly measured by the ability to discern details of a visual stimulus at a specific distance. The Snellen chart, for example, is frequently used to assess visual acuity, where the ability to identify progressively smaller letters or symbols indicates higher acuity. This measurement is an essential aspect of evaluating overall visual performance and identifying potential vision impairments.

3.2. Daylight and well-being

Circadian rhythms are innate, biological cycles that regulate various physiological and behavioral processes over a roughly 24-hour period. (Bommel et al. 2004). Carefully calibrated circadian rhythms ensure the synchronization of bodily functions with different day phases. For instance, exposure to strong morning light pauses melatonin production by the pineal gland, influencing organs like the brain with circadian activity cycles (Baker et al. 2014). Melatonin release at night induces sleepiness, moderates the endocrine system to reduce stress, and regulates functions facilitating sleep. Beyond visual tasks, daylight influences overall lighting quality in workplaces (Kantermann et al. 2013). Recognizing health and well-being benefits not only aids individual workers but also enhances work performance, concentration, alertness, and mood.

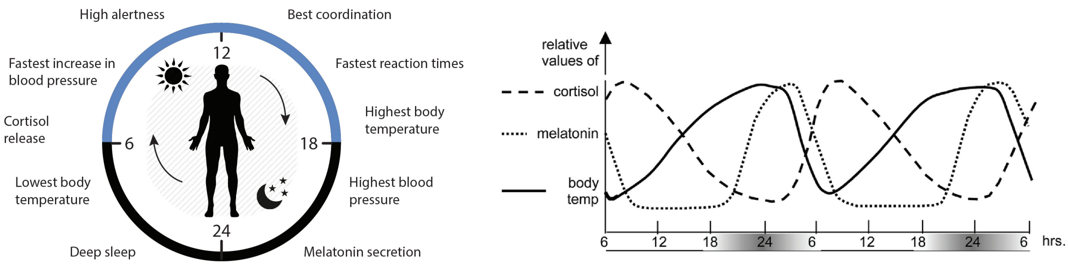


Figure 3.4: Circadian rhythms (left), melatonin, cortisol and body temperature throughout the day and night (right) (Kantermann et al. 2013).

Hence, the action of daylight effectively speeds up and aligns the body's circadian rhythms. Acute effects, representing a 'non-image-forming' pathway (Kort 2019), alongside the 'image-forming' pathway related to the visual aspect, contribute to psychological aspects such as social behavior, performance, well-being, and mental health (Figure 3.5). Consequently, light controls both human physiology and psychology.

3.3. Visual comfort and Glare

Visual comfort occurs with the absence of visual discomfort. Many factors are responsible for causing visual discomfort, such as insufficient light, illuminance non-uniformity, glare, veiling factors, shadows, or flickers, translated in challenges in visual tasks, inadequate or excessive stimulation, distractions, and perceptual confusion (SLL 2009). For this research, the focus is on glare and specifically on discomfort glare, its indices, and the influencing factors.

3.3.1. Definition and types

The CEN 2011 definition of glare is a "condition of vision in which there is discomfort (discomfort glare) or a reduction in the ability to see details or objects (disability glare), caused by an unsuitable distribution or

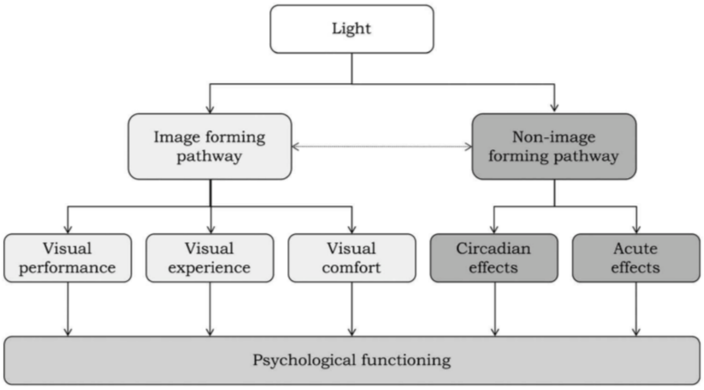


Figure 3.5: Light pathway and psychological functioning (Kort 2019).

range of luminance, or to extreme contrasts" (Clotilde Pierson et al. 2018). There are five types of glare in total (SLL 2009), which are listed below:

- **Saturation glare:** Extended exposure to intense luminance in the visual field, causing discomfort and prompting eye protection.
- **Adaptation glare:** Abrupt exposure to heightened luminance, causing temporary oversensitivity, mitigated by visual adaptation to the new conditions and facilitated by transitional zones.
- **Disability glare:** Intense light to low-illuminance scenes, creating a luminous veil that diminishes contrast and desaturates adjacent retinal images. It occurs with both point and large-area sources.
- **Discomfort glare:** Visual discomfort in response to bright light sources, luminaires, or windows.
- **Overhead glare:** high illuminance sources above the head, arising from reflections on eyebrows, glasses, and facial characteristics.

In interior spaces, glare occurs either in the form of disability glare or discomfort glare. Discomfort glare is specifically emphasized as directly relevant to the exploration of visual comfort. As defined by the International Commission on Illumination (CIE), discomfort glare is 'glare that causes discomfort without necessarily impairing the vision of objects'.

3.3.2. Indices and metrics of glare

Indices of visual comfort and glare play a pivotal role in evaluating the quality of lighting environments within built spaces. Visual comfort indices combine diverse metrics, considering factors such as luminance levels, contrast ratios, and glare potential. According to a review on visual comfort indices (Carlucci et al. 2015), the ones for glare are listed below:

1. Luminance (L)
2. Luminance ratio
3. British Glare Index (BGI)
4. Visual Comfort Probability (VCP)
5. CIE Glare Index (CGI)
6. Discomfort Glare index (DGI)
7. New Discomfort Glare Index (DGIn)
8. Unified Glare Rating (UGR)
9. **Discomfort Glare Probability (DGP)**

10. Simplifications of DGP (Wienold, Hviid)

11. Enhanced simplified

12. Enhanced Simplified DGP (eDGPs)

13. Predicted Glare Sensation Vote (PGVS)

14. J-Index

15. Comparison of glare sensation scales

According to the study, in glare evaluation, the absence of standardized metrics poses a challenge, as diverse formulas assess factors causing glare without a unified theoretical consensus on discomfort glare. Existing metrics overlook correction for cultural differences and glare source exposure duration. Notably, Discomfort Glare Probability (DGP), or Daylight Glare Probability (DGP) when applied to daylight, emerges as a key metric for addressing absolute glare issues. Its strength lies in its strong correlation with user response, consideration of vertical eye illuminance, and expression of glare degree based on the percentage of observers finding luminous conditions uncomfortable. However, it is important to consider that DGP in early design proves challenging due to its need for well-defined scenes, spatial rendering requirements, and limitations for multi-objective optimizations. Thus, the equation for DGP is the following (Jan Wienold and Christoffersen 2006):

$$DGP = 5.87 \times 10^{-5} \times E_v + 9.18 \times 10^{-2} \times \log\left(1 + \sum_i \frac{\mathrm{L}_{s,i}^2 \omega_{s,i}}{E_v^{1.87} Pi^2}\right) + 0.16 \tag{3.1}$$

Where:
E_v : the vertical eye illuminance [lux]
$\mathrm{L}_{s,i}$: the luminance of the glare source(s) [cd/m²]
$\omega_{s,i}$: the solid angle of the glare source(s)
P_i : the position index relative to the glare source(s)

Jan Wienold (2007) introduced a simplified glare assessment metric called the Daylight Glare Probability simplified (DGPs). This metric relies solely on the vertical eye illuminance (Ev), as it was found to correlate well with perceived glare. DGPs offer a streamlined approach by omitting consideration of specific glare sources and using a single-point calculation, significantly reducing computation time compared to other glare metrics based on luminance. It can be categorized as a saturation glare metric and is better applicable in situations where direct sunlight or its specular reflection does not reach the observer's eye.

$$DGPs = 6.22 \times 10^{-5} \times E_v + 0.184 \tag{3.2}$$

3.3.3. Glare in building standards

EN 17037:2018: Daylight in Buildings: It is a European Standard that provides guidelines and requirements for daylighting in buildings regarding daylight provision, view out, exposure to sunlight, and glare (NEN 2018). Regarding glare, a strong emphasis is given to DGP. This standard introduces DGP as a quantitative measure to evaluate the likelihood of discomfort glare during activities such as reading, writing, or utilizing display devices. By defining criteria for glare protection, it sets threshold values for DGP, ensuring that discomfort glare remains within acceptable limits for a specified portion of the reference usage time. These thresholds are designed to be integrated into subjective assessments, allowing individuals to express their perceptions of glare through the Daylight Glare Sensation Vote (DGSV) methods on a subjective scale.

Table 3.1: DGP threshold values for glare protection.

Criterion	DGP
Glare is mostly not-perceived	DGP ≤ 0.35
Glare is perceived but mostly not disturbing	0.35 < DGP ≤ 0.40
Glare is perceived and often disturbing	0.40 < DGP ≤ 0.45
Glare is perceived and mostly intolerable	DGP ≥ 0.45

EN 12464-1:2011 (The Indoor Lighting Standard): It is a European Standard that provides guidelines for creating effective lighting conditions in work environments (Ensto Lighting 2011). The standard focuses on ensuring visual comfort and efficiency, covering various aspects of lighting, including the glare control. It lays out specific criteria and recommendations to minimize discomfort glare in workplaces, emphasizing the importance of maintaining lighting conditions that enhance the visual comfort of occupants. The standard provides practical guidance for designing and implementing lighting systems to create optimal working conditions. This includes considerations for illuminance levels, uniformity, color rendering, and measures to prevent glare. To quantify and control discomfort glare, the standard introduces specific metrics, with the Unified Glare Rating (UGR) being a prominent example. It establishes limits on the UGR, ensuring that discomfort glare is maintained within acceptable levels for diverse visual tasks. The table demonstrates some examples.

Table 3.2: Examples of lighting requirements for spaces, areas, tasks, and activities

Space Type	**Illuminance [lx]**	**UGR Index**	**Uniformity** $U_0\left(\frac{E_{\mathbf{min}}}{E_m}\right)$	R_a **index**	**Notes**
Stairways, escalators, travelators	100	25	0.4	40	-
Technical facilities	200	25	0.4	60	-
Storage spaces	100	25	0.4	60	200 lx if work is continuous
Offices and writing	500	19	0.6	80	-
Check-out areas	500	19	0.6	80	-
Waiting rooms	200	22	0.4	80	-
Kitchens	500	22	0.6	80	Separate adjustment zone for restaurant kitchens
Parking areas	75	-	0.4	40	Illuminance from floor level
Classrooms	300	19	0.6	80	Lighting should be adjustable
Auditoriums	500	19	0.6	80	Lighting should be adjustable

WELL standard criteria: The WELL standard offers guidelines designed to minimize disruptions to the body's natural circadian rhythm, boost productivity, foster quality sleep, and ensure optimal visual acuity (International WELL Building Institute n.d.). Three criteria are focused on glare.

- The Solar Glare Control focuses on reducing glare caused by direct sunlight, utilizing tactics like blocking or reflecting sunlight away from occupants.
- The Low-Glare Workstation Design addresses visual discomfort by strategically positioning computer monitors to avoid glare and luminance contrast, creating a more comfortable workspace.
- The Electric Light Glare Control emphasizes minimizing direct and overhead glare through specific criteria regulating the luminous intensity of lighting fixtures, contributing to an overall glare-conscious environment.

3.4. Factors that affect discomfort glare

3.4.1. A review on factors

A comprehensive review including field and laboratory experiments, review studies, and surveys has identified factors influencing glare and assessed the extent of their impact (Clotilde Pierson et al. 2018). These factors are further categorized into three main groups based on the context of their relation: lighting, context, and observer.

The first category is related to lighting. As evident in discomfort glare indices, four physical quantities are relevant to discomfort glare: the luminance of the glare source, the adaptation level (considered in terms of vertical eye illuminance or background luminance), the solid angle of the glare source, and the position index (a correction factor associated with the observer's line of vision). These factors are intricately linked to the lighting environment and the interaction between the observer and the glare source and are illustrated in the Figure 3.6.

The second category describes factors that characterize the environment or the experiment. According to the influence indicator, the most critical ones are the spectrum and color temperature related to glazings that filter an amount of the daylight spectrum and result in a colored effect of daylight. Also, the rating scales on questionnaires can function as biases for the participants, who also appear to be more tolerant of glare in the field than in the laboratory environment. Additionally, some other features such as the attractiveness of the view outside, the position and direction, or the temperature are still indecisive if they influence glare perception.

Participants can be an influence not only in terms of their feedback but also as observers. There are many features tested describing general, vision, or present state characteristics features that are tested and can affect the results such as the cultural background, the contrast sensitivity, or the level of fatigue, however, some of them appear not to have an effect or have a slight effect.

3.4.2. Additional evidence

Recent studies examined the aforementioned factors or additional sources of influence, validating previous results, or leading to unexpected ones. The studies include features such as the color spectrum, the time of the day, the outside view, the socioenvironmental content, and ocular behavior. These factors represent the 'more likely', 'somewhat likely', and 'inconclusive' influence factors according to the previous review.

A study conducted an experiment to assess occupants' glare perception when exposed to blue-tinted electrochromic glazing and color-neutral glazing, examining the impact of the light spectrum (Jain et al. 2023). With 20 participants, the research highlighted a significant influence of the glare source spectrum on individuals' perception of glare in daylight conditions. Despite both types of glazing having comparable light transmittance, participants showed greater tolerance for glare with the clear window compared to the electrochromic one. This pattern persisted even when glare metrics predicted higher values for the former condition.

In a different study, individuals offered subjective feedback to evaluate and measure the effects of glare at various times of the day, proposing adaptable set points for glare control (Bian et al. 2020). The results affirmed the fluctuation of glare impact throughout the day. Additionally, the research validated the use of DGP thresholds for Glare Sensation Vote (GSV) scales and suggested precise Vertical Illuminance set points for morning, midday, and afternoon periods.

Furthermore, there was one study focusing more on occupant satisfaction with two different control strategies, Venetian blinds with slats closed or in a cut-off angle (Karlsen et al. 2015). However, the focus concerned visual comfort and glare, and according to the results, the view out influenced the participants' choice preference between the two strategies and indicated that glare tolerance to a certain extent could be accepted with the availability of a view outside.

In a large-scale field experiment involving 401 participants (211 utilized), which assessed discomfort glare from daylight in office spaces across four countries (Chile, Belgium, Japan, Switzerland), the socioenvironmental influence factor was examined (C. Pierson et al. 2022). This factor encompassed the climate, habitat, and culture of the participants' surroundings, and the study took place during the same timeframe, with desks positioned within 5 meters of the window. Surprisingly, the results did not reveal a significant influence, contrary to expectations based on prior research.

In an experiment aimed at identifying a novel glare indicator, ocular behavior was examined in a laboratory with an office environment setting (Garretón et al. 2016). The study assessed eye gaze direction, the extent of opening, and pupil size in relation to vertical eye illuminance (Ev). The results indicated a noteworthy impact of the degree of opening on glare, aligning with the Glare Sensation Vote (GSV) and Discomfort Glare Probability (DGP), suggesting its potential as an influential indicator. Additionally, significant results were observed for pupil size.

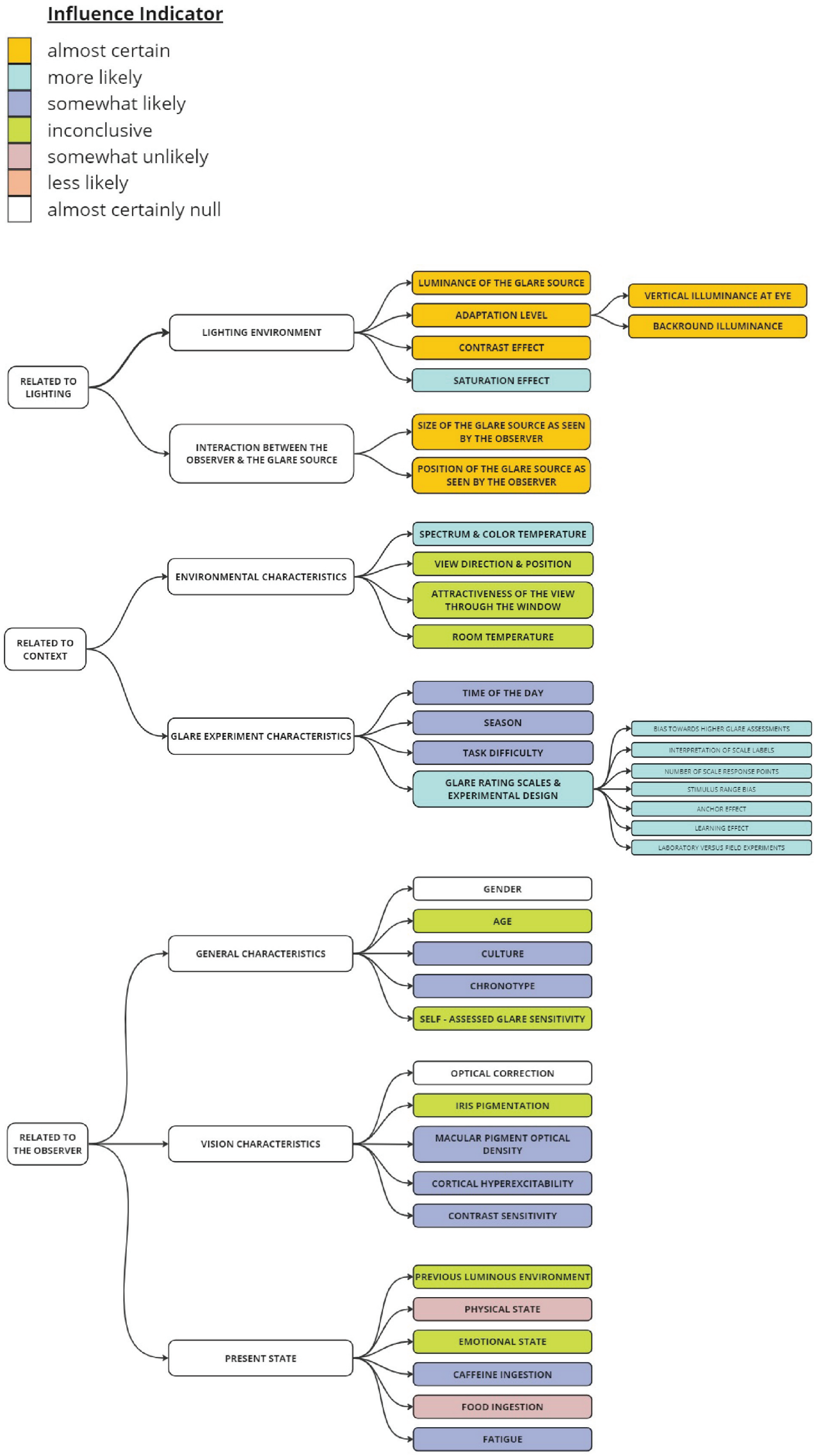


Figure 3.6: Factors influencing discomfort glare perception from daylight (Clotilde Pierson et al. 2018),(Illustration by the author.

3.5. Conclusions

In this chapter, the intricate relationship between human vision, light perception, and visual comfort, with a specific focus on discomfort glare was explored. Understanding the anatomical and physiological mechanisms of the human eye, including its sensitivity to different wavelengths and its ability to perceive brightness and color, is fundamental in designing environments that promote visual comfort. The role of daylight is critical, not only in supporting visual tasks but also in regulating circadian rhythms, which influence sleep, well-being, and overall productivity. Daylight's impact on visual comfort highlights the importance of proper lighting design in enhancing workplace performance and mood.

Visual comfort is achieved by mitigating factors that cause visual discomfort, such as insufficient light, non-uniform illuminance, and, notably, glare. Discomfort glare is defined as glare that causes discomfort without necessarily impairing vision and is the central theme of this project regarding visual comfort. Various metrics for evaluating glare like DGP have been used to evaluate glare due to their correlation with user perception and their practical application. Furthermore, various building standards provide guidelines for minimizing glare in buildings, underscoring the importance of these metrics in ensuring visual comfort and their crucial role in designing environments that enhance both visual comfort and overall well-being.

Factors influencing discomfort glare were categorized into lighting, context, and observer-related factors. Key lighting-related factors include the luminance of the glare source, the adaptation level, the solid angle of the glare source, and the position index relative to the observer's line of vision, and most of them are included in the glare indices. Context-related factors involve either environmental characteristics or glare experiment features, which are control factors and should be taken into account to be specified or fixed in the experimental design. Observer-related factors encompass general and vision characteristics and the present state of the observer and can be present in introductory questionnaires. All these factors are tools to be used in the experimental design, through measurements, design, and questionnaires.

This chapter sets the stage for the subsequent exploration of biophilic design's impact on glare perception, particularly focusing on the VideowindoW product, which integrates biophilic characteristics and glare control. The upcoming chapter explores the automation and control of facades, further enhancing the understanding of the optimization of glare control solutions to improve occupant perception and comfort. This integrated approach aims to create visually comfortable environments that harness the benefits of biophilic design and advanced automation technologies.

4

Automation and Facade Control

4.1. Challenges of design for daylight and glazing systems

Facade design in modern architecture plays a crucial role in determining the overall comfort, energy efficiency, and privacy of a building. The growing preference for glazed facades and the frequently large to window-to-wall ratios introduces several challenges that architects and engineers must address to create optimal living and working environments (Schweizer et al. 2007), (Aries et al. 2010). These challenges include balancing visual and thermal comfort, optimizing daylight usage, minimizing energy consumption, ensuring privacy, and managing views. Each of these aspects must be carefully considered collectively and integrated into the design to achieve a harmonious and functional building envelope.

Visual comfort and daylight: Balancing visual comfort and daylight in facade design is critical yet challenging. Extensive use of glass can lead to excessive glare, causing discomfort and reducing occupant productivity. In these cases the role of shading systems is crucial (Evola et al. 2017). Achieving uniform daylight distribution is also difficult, as areas near windows can become overly bright while deeper interior spaces remain dim (Hosseini S. 2019). Effective integration with artificial lighting is essential to ensure consistent visual comfort throughout the day, balancing natural and artificial light. Additionally, maintaining view quality without excessive brightness is important to provide pleasant and comfortable working or living environments.

Thermal comfort: Maintaining thermal comfort in buildings with glazed facades presents several challenges. Large glass areas can result in significant solar heat gain, increasing cooling loads during summer months. Conversely, in colder climates, these facades can lead to substantial heat loss, raising heating demands. Thermal bridging, caused by poorly insulated glazing frames, can create points of unwanted heat transfer, compromising comfort and efficiency (Theodosiou et al. 2019). Effective facade design must balance indoor temperatures to ensure comfort despite external weather conditions, requiring advanced materials and innovative solutions.

Energy efficiency issues: Energy consumption in buildings globally accounts for one-third of the total energy used (Bui et al. 2020). Especially in glazed facades is a critical concern, as inefficient glazing can significantly increase the energy required for heating and cooling, which is linked with the daylight and the thermal gains or losses. Poor daylight integration necessitates greater use of artificial lighting, further raising energy consumption. The dynamic interaction between the building envelope and internal systems impacts overall energy efficiency, making it essential to design facades that optimize passive solar heating in winter and shading in summer. Achieving sustainable design goals while maintaining visual and thermal comfort demands careful selection of materials and technologies.

View out and privacy: Providing occupants with visual access to the external environment is essential in architectural design, particularly concerning glazed facades. Although generous window sizes offer panoramic vistas, it's imperative to balance this with considerations of excessive lighting and privacy which creates a conflict with the obstruction of the view. Consequently, shading mechanisms and strategic positioning of windows become crucial to mitigate potential discomfort and offer opportunities for viewing outside in a balanced way that maintains privacy. Effective placement and orientation of windows should prioritize favorable views while shielding occupants from undesirable sights. Furthermore, advancements in shading technologies, such as dynamic systems that adjust their state to provide various shading solutions, can significantly enhance the quality of views while effectively regulating light and heat transmission into the building.

4.2. Shading systems and technologies

Facade designers face several challenges in creating an efficient shading system that optimally balances daylight utilization and external views while minimizing discomfort and reducing energy consumption. The concept of an adaptive façade, characterized by various definitions and terminologies, emerges as a response to the limitations of fixed or static conventional shading systems (Tabadkani et al. 2021). Adaptive façades, unlike their rigid counterparts, possess the capability to adjust dynamically to alterations in both indoor and outdoor environmental conditions. Furthermore, facades have a critical role as a physical barrier and interface between the interior and exterior, being exposed to unpredictable meteorological variations such as solar radiation, precipitation, wind, and extreme temperatures (Knaack et al. 2007). These factors significantly influence the indoor comfort experienced by occupants, highlighting the necessity for responsive and adaptable facade solutions. The main typologies of adaptive facades can be seen in the figure and are the following: active, passive, biomimetic, kinetic, intelligent, interactive, movable, responsive, smart, and switchable.

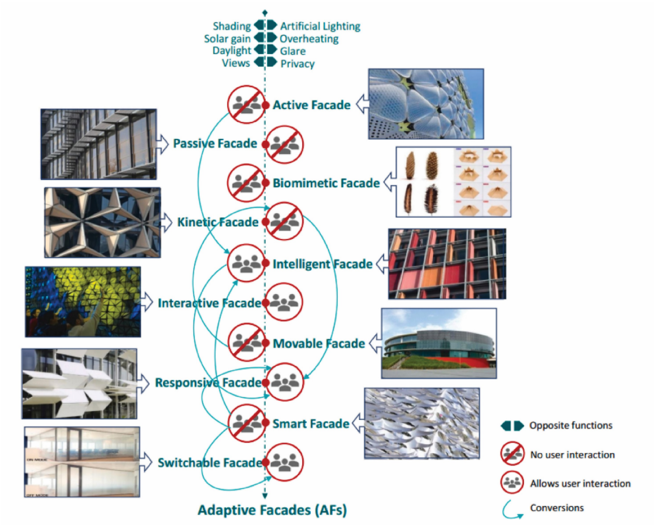


Figure 4.1: Adaptive facade typology (Tabadkani et al. 2021).

Regarding smart glazing systems, known as smart windows, these shading systems are technologies that exhibit dynamic optical properties in response to external stimuli such as voltage, light, or heat, transitioning from translucent to transparent (Ghosh et al. 2018), (Figure 4.2). These systems play a crucial role in managing light transmission to enhance occupants' visual comfort while also contributing to energy load management. Three key technologies, Suspended Particle Devices (SPDs), Electrochromic (EC) devices, and Liquid Crystal Displays (LCDs), offer adaptive control features for responsive adjustments (Dakheel et al. 2017). These systems effectively control transmitted solar radiation during both transparent and opaque phases.

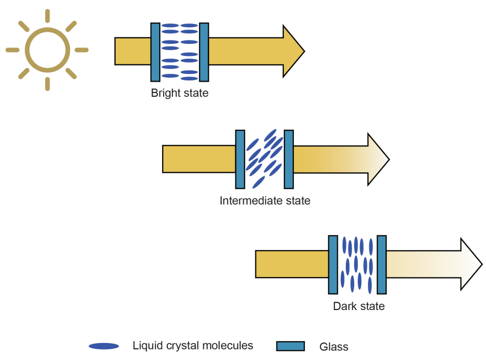


Figure 4.2: Transparent and translucent states of Liquid crystal glazing

Adaptive shading systems fall into two main categories: the conversion of conventional systems like motorized blinds or roller shades and non-conventional, more complex systems. Three main steps describe the performance of these systems (Tabadkani et al. 2021) (Figure 4.3):

1. **Data collection:** gathering information on outdoor and indoor environmental conditions and occupancy patterns, aligning with human comfort and building performance goals
2. **Data processing:** data processing and control through computational tools to ensure effective operation, actively adjusting through feedback loops or using smart materials for self-adjustment
3. **Responsive actions:** physical and non-physical responses based on received energies, encompassing interactions within physical domains, responsive time scales related to human comfort, adaptation scales at macro and micro levels, spatial scales influencing performance, and the visibility scale affecting building appearance

Figure 4.3: Facade performance steps.

In the case of dynamic adaptive facades, different types of actuation systems occur (Figure 4.4). On the contrary, static facades present no actuation systems (Luna-Navarro, Loonen, et al. 2020). The Figure 4.5 illustrates the intricate dynamics of occupant-façade interaction within a building environment. It captures the interrelation between key elements such as the occupant, building structure, façade design, control logic, and the surrounding indoor and outdoor environments.

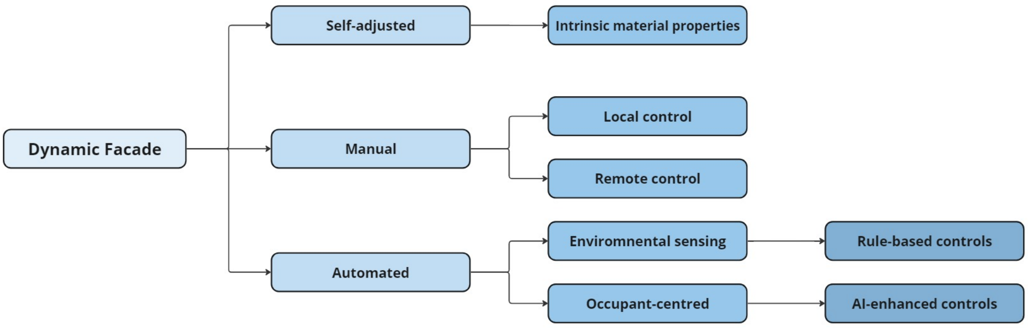


Figure 4.4: Actuation system of dynamic facade (Luna-Navarro, Loonen, et al. 2020).

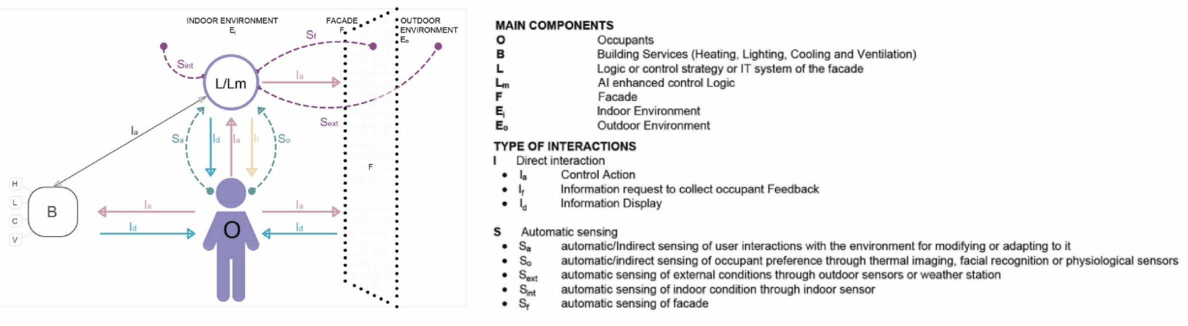


Figure 4.5: Occupant Facade Interaction (Luna-Navarro, Loonen, et al. 2020).

4.3. Challenges of automated systems

On the one hand, automated dynamic facades can contribute to energy efficiency, keep a sufficient level of indoor environmental quality, and give feedback to the occupants by warning them about the current situation (Day et al. 2019). On the other hand, their performance is often hindered by challenges related to occupant acceptance of these automated control strategies.

A study investigated four scenarios involving automated roller shades and tested occupant perception and reaction (Bakker et al. 2014). The scenarios varied in terms of movement frequency and the distances (in cm) of potential adjustments. One scenario involved shading adjustments based on daylight conditions. Each scenario was tested twice, with the second trial allowing an override option. The results revealed that while disturbance levels were not high, less frequent and distinct adjustments were perceived as less distracting than smooth ones. Additionally, participants using the override option expressed greater satisfaction with the availability of an outside view, underscoring the significance of personal control and achieving a balance between daylight, view, and glare control.

In another investigation, a Venetian blinds system with automatic features was investigated, allowing users the options of manual override or complete switch-off of the automated mode (Meerbeek et al. 2014). Users made numerous adjustments, primarily opting for manual control and rejecting the automatic system when choosing the switch-off option. This behavior was linked to users' preferences for daylight presence, access to views, and a general sense of control over the system, which are more inclined to manually adjust blinds and reject automatic adjustments. Surprisingly, even with the manual override, occupants manually controlling the shading were not more satisfied with indoor conditions than others, suggesting that neither the control mode nor the extent of their control influenced the comfort level. This indicated that those who believe in their ability to adjust blinds for desired effects are also more likely to opt for manual adjustments.

One experiment tested motorized roller shades and dimmable electric lights to capture the interaction between different systems and human behavior (Sadeghi et al. 2016). The different settings included a manual control system with a wall switch option, a manual with a web-based system, a fully automated system controlled by daylight conditions, and an automated one with an option of override through a remote controller. Accessible controls for lighting and shading in offices led to higher daylight utilization, reducing reliance on electric lighting and consequently energy consumption. The results also indicated that occupants preferred personalized indoor climates, and there was a correlation between their perceived control and acceptance of various visual conditions.

A field experiment, conducted in single or two-person offices, investigated the manual operation of electric lighting alongside automated external Venetian blinds with an override option (Voss 2003). The study found that electric lighting was frequently activated upon users' arrival, with a weaker correlation for intermediate events. Lower switch-off probabilities were linked to dimmed, indirect lighting. Users manually adjusted blinds to enhance illumination, and while they rarely opposed automated openings, frequent manual corrections were observed during automatic blind lowering, influenced by incident solar gains.

In a recent example, a field study examined occupant satisfaction according to multiple criteria in two facade conditions (Luna-Navarro, Lori, et al. 2023). These included a dynamic automated facade with blinds with an override option and a manually controlled one. The study emphasized the dynamic influence of the façade on indoor conditions and occupant satisfaction, varying throughout the day and across the floor plan, with a higher impact closer to the façade and the need for a comprehensive, multi-domain perspective to identify potential areas for improvement. A notable, example was that the success of the automated control strategy depended not only on satisfaction with outdoor views but also on factors like thermal comfort and glare mitigation.

According to a review of the impact of automated facades on occupants, the investigation delved into occupant responses concerning behavior, satisfaction, acceptance of control logic, and perception of indoor environmental conditions (de-la-Barra et al. 2022). The majority of studies concentrated on single-office layouts, leaving a gap in data for open-plan offices. However, the results showed that personal factors impacted occupant behavior, but many studies overlooked attitudes and personal significance. Occupant interaction with automated facades was crucial, driven by individual environmental requirements. Facade technology types affected satisfaction, with differences noticeable when compromising one environmental domain for another. Barriers exist, including the need for common methods to study personal factors, understanding multi-domain comfort preferences, and exploring learning and personalized control. That is why, further research should consider different climates and conditions, emphasizing the necessity of user-centric automated facade solutions.

4.4. VideowindoW product information

The biophilic glare control facade product was installed as a retrofit solution for the Nonohouse building at Green Village, Delft, in collaboration with VideowindoW and TU Delft. This product, designed to enhance visual comfort while incorporating biophilic design principles, is an additional component integrated into the existing southeast-oriented glazing of the building's facade (Figure 4.6).

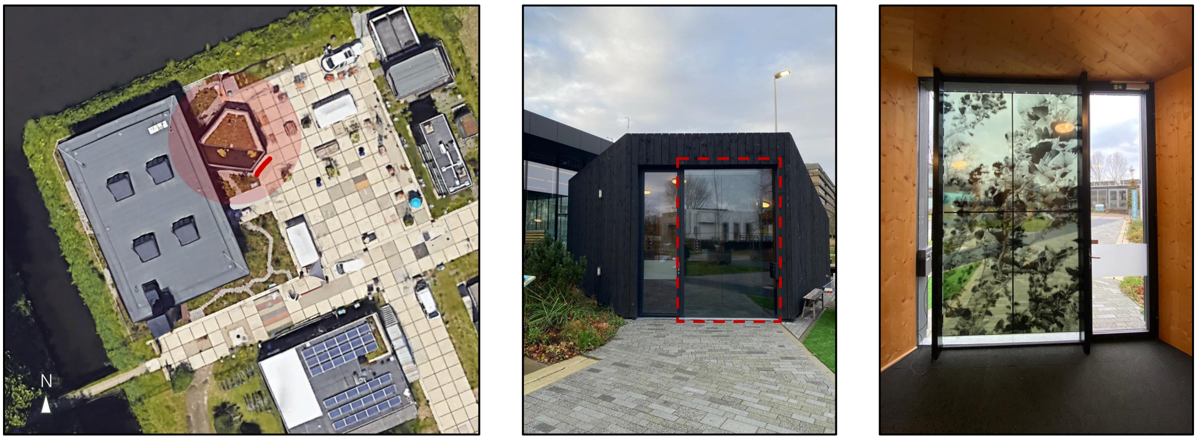


Figure 4.6: Location at the Green Village (left), dedicated part of the facade from outside (middle) and inside view (right).

4.4.1. Build up

The build-up of the product is illustrated in Figure 4.7. More specifically:

- **Dimensions:** 1755mm x 2890mm x 200 mm
- **Facade components** (Starting from the inside to the outside):
  - **Laminated safety glass (66.2, thickness: 12.76mm):**
    Two glass plates (each 6mm thick)
    Two transparent PVB films (total thickness: 0.76 mm) in between
  - **VideowindoW Screen (thickness: 3mm):**
    Four screens 65" Full HD modules – LCD modules and TFT modules
    Resolution of 1922*1083 pixels with pixel size of 0.74 mm*0.74 mm
  - **Existing glass**
  - **Additional supporting components and controller**

4.4.2. Control

VideowindoW has provided access to its online platform for possible adjustments to the pattern. Additionally, a remote controller has been installed for the ease of system control (Figure 4.8). The parameters include adjustments according to the features:

- **Content:** A diverse range of content options includes artwork, natural scenery, commercial advertising, information, and gaming. For the purposes of this research, a tree representation was chosen to align with biophilic design principles and glare control objectives.
- **Size:** The scale of the tree pattern can be adjusted with the effect of zooming in and zooming out.
- **Growth:** The density of the tree branches and the coverage of the facade can be controlled, simulating the natural growth of a tree.

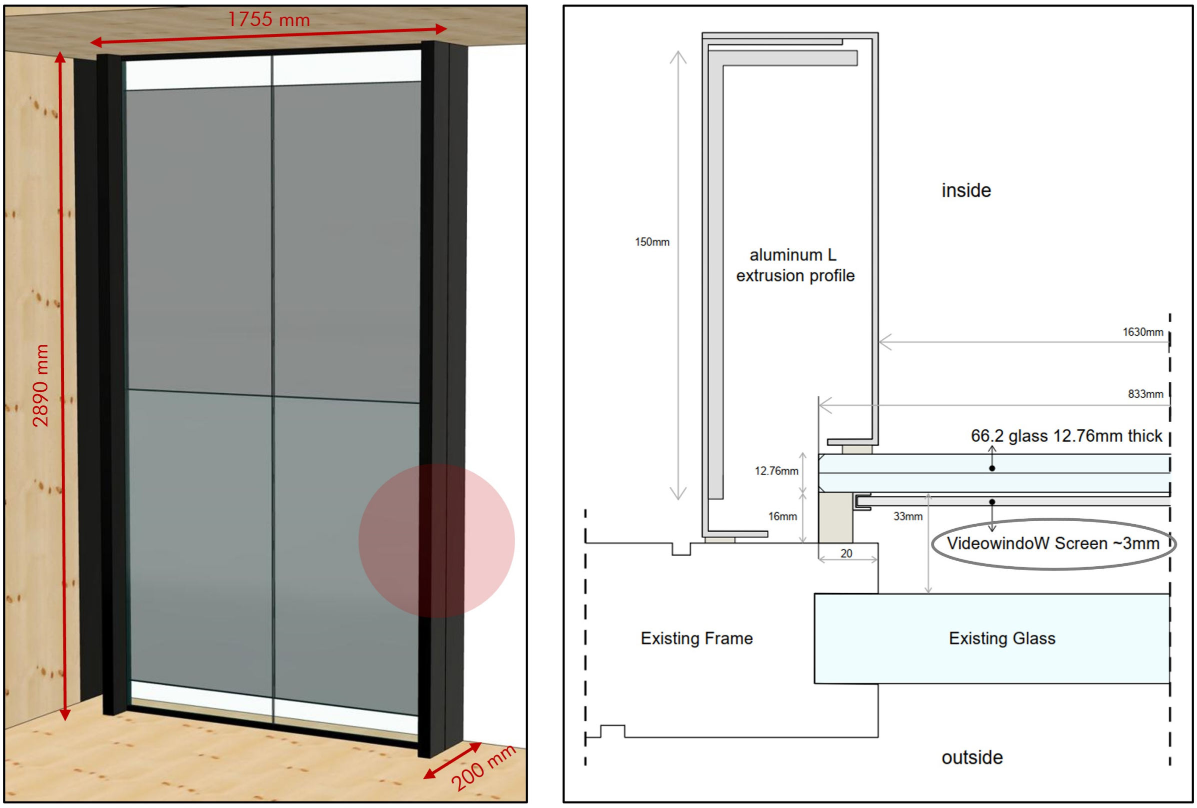


Figure 4.7: Build-up of the product.

- **Contrast:** The visibility of the pattern can be adjusted by altering contrast levels. The higher or lower contrasts are produced by darkening the grayish-shaded patterns and creating soft shadows or deep shadows with strong highlights.
- **Wind motion:** The tree pattern can exhibit simulated constant movement to mimic the effect of wind. By increasing this motion, the effect is similar to a more windy occasion.
- **Rotation speed:** The dynamic tree produces a video that is similar to one produced by a camera capturing the tree in a rotation mode. This speed can be adjusted in a range of low to high speed.
- **Dimming:** The facade product incorporates a dimming feature to control light penetration and glare, due to a dimming-darkening effect. There is a range from minimum to maximum glare protection, corresponding to minimum and maximum dimming effects.

Actuation system: The adaptive performance of the biophilic facade is driven by the following automated steps (Figure 4.9):

1. **Data collection from the outdoor sensor:** Outdoor environmental data, including lux values ranging from 0 to 100,000, are collected from sensors positioned on the facade pointing outside to capture both direct and diffused light.
2. **Data processing by supporting components:** Collected data are processed by the system to modify the content accordingly.
3. **Data processing by the AI system:** An AI algorithm adjusts light transmittance levels to achieve desired conditions and generates the corresponding dynamic facade pattern.
4. **Responsive action and pattern appearance:** The modified pattern is displayed physically on the LCD modules.

Figure 4.8: Adjustable parameters through the remote controller (left) and throuh the website access (right).

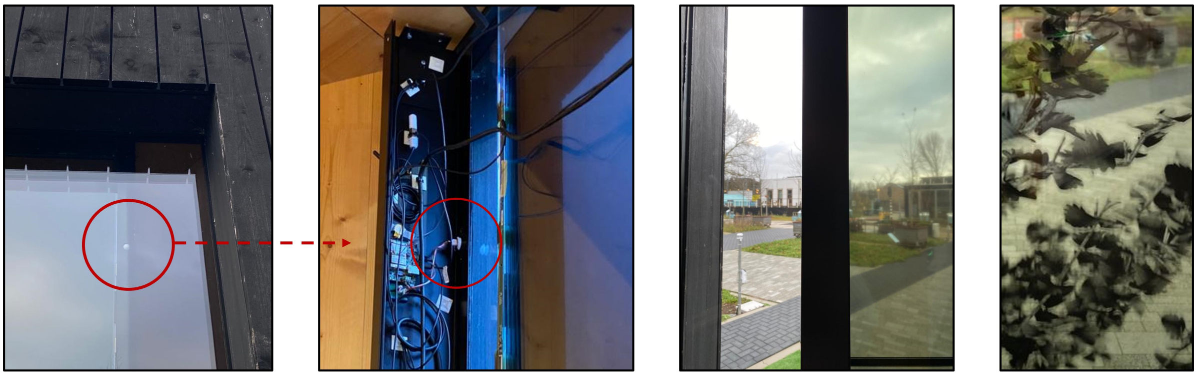


Figure 4.9: Actuation system in steps: data collection from the outdoor sensor (left), data processing through additional components and AI system (middle), responsive action and pattern presence (right).

4.5. Conclusions

The design of facades that effectively balance daylight utilization, external views, occupant comfort, and energy efficiency presents complex challenges in modern architecture. The integration of adaptive facades, which dynamically respond to changing environmental conditions, offers a viable solution to the constraints of static shading systems. These adaptive facades, encompassing a wide variety of typologies such as kinetic or switchable, are vital for maintaining indoor environmental quality in response to varying meteorological conditions.

While automated dynamic facades can significantly enhance energy efficiency and indoor environmental quality, their success is often limited by occupant acceptance. People's preferences and how they interact with these automated systems are key. Studies show that while people like having control even if they don't improve their comfort levels, they also want systems that work automatically. The preference for daylight and view-out poses additional challenges. Finding the right balance between manual control and automation is crucial.

Smart glazing systems, including Suspended Particle Devices (SPDs), Electrochromic (EC) devices, and Liquid Crystal Displays (LCDs), play a crucial role in modulating light transmission and managing energy loads. The operation of adaptive shading systems involves collecting data about the environment, analyzing it, and then making adjustments to the facade to keep occupants comfortable and save energy. These recent systems are promising for addressing challenges and potentially improving the human experience and future research should focus on these opportunities.

An upcoming experiment in this project will test VideowindoW, a biophilic glare control product that exemplifies these adaptive principles. The study aims to evaluate the product's performance, its alignment with user preferences, and overall acceptance.

5
Experimental Method

5.1. Experimental design

The design of an experimental environment is fundamental to conducting glare assessments and testing various scenarios. Such an environment could either be a section of a real space or a laboratory setup emulating real-life conditions and activities (Konstantzos et al. 2017). The office setting is commonly used in experiments related to visual comfort and glare where the position of the observer remains fixed. Most of the time, the space is a single-occupancy office where occupants perform common office tasks, since multi-occupancy spaces appear more complex (Shafavi et al. 2020). Depending on the research objectives, the experimental setup may involve none, one or more participants and its configuration can vary accordingly. In experiments concerning glare, the presence of a light source can vary. This source may contain natural daylight, artificial lighting, or a combination of them, simulating diverse environmental conditions, and exploring different levels of glare.

For the current experiment, a single-occupancy laboratory setting is applied and glare is captured under daylight different lighting conditions deriving from daylight.

5.1.1. Aim and methodology

Aim: This experiment aims to compare the impact of static biophilic patterns on building facades with non-natural patterns and homogeneous-clear conditions on occupant perception.

Methodology: Both quantitative and qualitative data are collected. Quantitative data are collected through environmental measurements using specialized equipment, while qualitative data are gathered through user perception assessments via questionnaires. The experiment is conducted at the Nonohouse building located within the Green Village, where three glazing settings are tested: a tree pattern, a striped pattern, and a no-pattern condition.

The procedure involves recruiting volunteers to perform reading tasks and fill out questionnaires while measuring the environmental conditions.

Interesting points: Key aspects of interest include the following:

- **Glare perception with/without the pattern:** Comparison of participants' sensation to glare under different glazing settings, assessing whether the presence of biophilic patterns affects glare perception.
- **Visual comfort and daylight satisfaction:** Examination of participants' satisfaction of the visual daylight environment when exposed to different pattern scenarios.
- **Satisfaction with the view with/without the pattern:** Evaluation of participants' subjective perception of the satisfaction with the outdoor view and acceptance of obstruction under varying glazing settings.
- **Satisfaction with the overall aesthetics:** Assessment of participants' satisfaction with the overall aesthetic appeal of the facade under different pattern conditions.
- **Overall pattern preference and association with natural connection:** Report user preferences and biophilic impact.

Variables

- **Dependent:** Glare perception/ Visual Comfort/ Daylight satisfaction/ Color of daylight satisfaction/ Satisfaction with the view out/ Acceptance of obstruction of view/ Pattern aesthetics/ Sunlight pattern aesthetics

- **Independent:** pattern scenario (natural pattern/non-natural pattern/no-pattern condition presence), dimming effect (transparent or opaque state), pattern characteristics (size, contrast), DGP, light transmittance, vertical illuminance at the eye, background illuminance, contrast

- **Cofounding:** general characteristics (age, gender, cultural background), vision characteristics (optical correction, spectacles - lenses), present state of the observer (fatigue, physical state, emotional state, caffeine), experimental design, time of the day, season, view direction and position, task difficulty, weather conditions, temperature, environmental distractions, attractiveness of the view through the window

Different stimuli

- **Tree pattern:** biophilic pattern

- **Striped pattern:** regular pattern

- **No-pattern:** homogeneous-clear condition

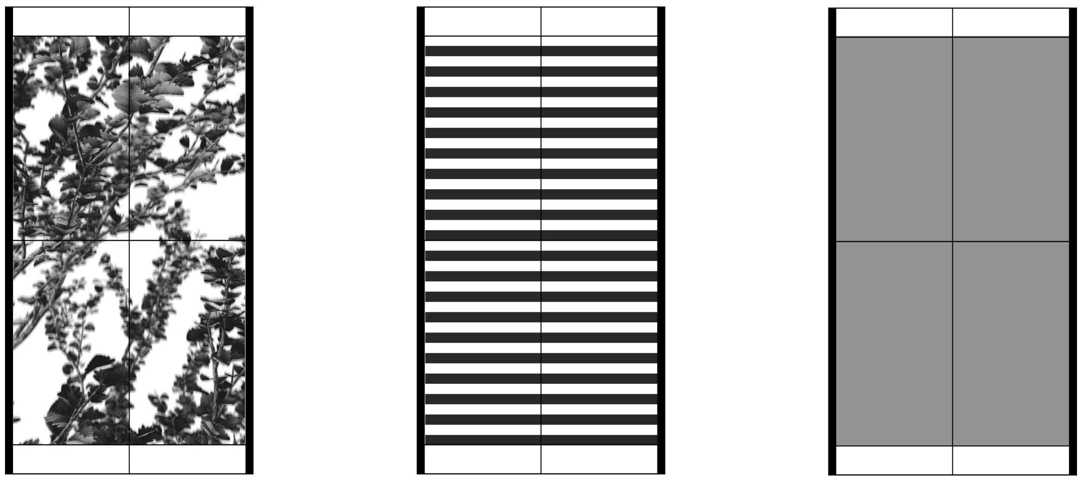


Figure 5.1: Different stimuli, tree pattern (left), striped pattern (middle), clear condition (right).

5.1.2. General information

The environmental conditions and context of the experimental design are summarized in Table 5.1. The lab was situated at the Green Village in Delft, with coordinates of latitude 51.99° N and longitude 4.37° E. Its internal dimensions followed a trapezoidal plan, measuring 3.2 meters along one parallel side, 2.05 meters along the other parallel side, with a shorter side of 2.2 meters and a longer side of 2.3 meters. The ceiling height was 3.2 m. The lab featured a southeast-facing window measuring 1.76 meters in width and 2.89 meters in height, where the VideowindoW system was installed as an additional component.

The experiment took place during the spring period, specifically in March 2024, with sky conditions ranging from overcast to clear. Participants were asked to choose one of two available sessions according to their preference and the day availability:

- Session (A): 9:00-10:30

- Session (B): 10:30-12:00

Table 5.1: General information of the experiment regarding the environmental conditions and context.

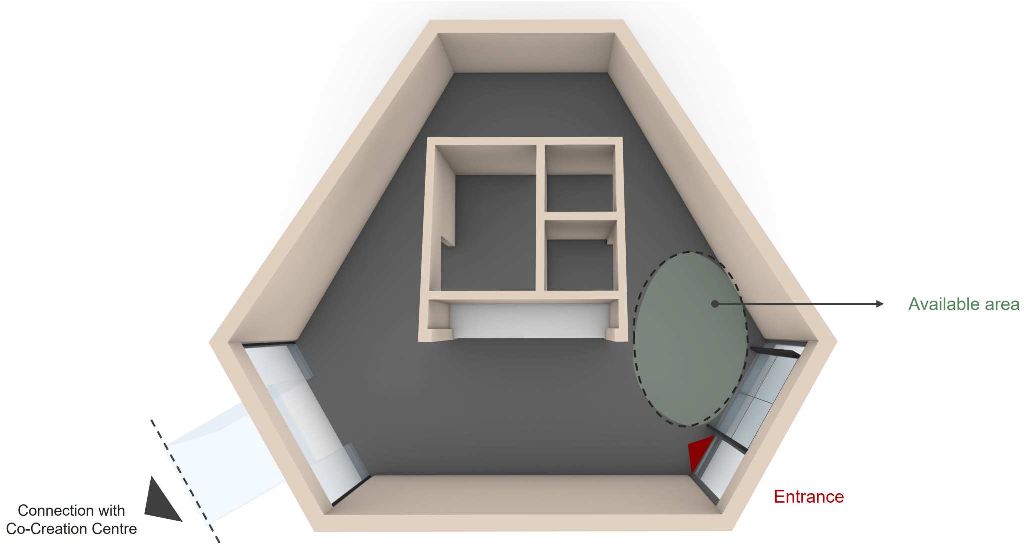
Environmental conditions and context	**Description**
Location	Southwest Netherlands, Delft, Green Village (latitude: 51.99° N, longitude: 4.37° E)
Orientation	Southeast
Sky conditions	Overcast to Clear
Season	Spring - March 2024
Time of the day	9:00-12:00
External scene	Low-density built area with scarce vegetation Paving with green parts, ground-floor buildings, trees, sky
Equipment	Camera with fish-eye lens Illuminance meters Thermometers Workstation
Indices	Daylight Glare Probability (DGP)
Test sessions	1 for each participant 2 participants per day (9:00-10:30 and 10:30 - 12:00)
Shading settings	A. Tree pattern B. Striped pattern C. No-pattern
Randomization of stimuli order	Latin Square Design 3*3 (ABC, BCA, CAB)
Visual tasks	Reading tasks of participants' preference
Glare assessment	4-point GSV
Participants	Master and Ph.D. Students, Green Village employees

During each session, participants were exposed to three different stimuli: a tree pattern, a striped pattern, and a no-pattern condition. These stimuli were applied as shading settings for the experiment. Participants engaged in reading tasks of their preference while exposed to these stimuli and were instructed to fill out questionnaires including glare assessments. Simultaneously, environmental conditions were being measured.

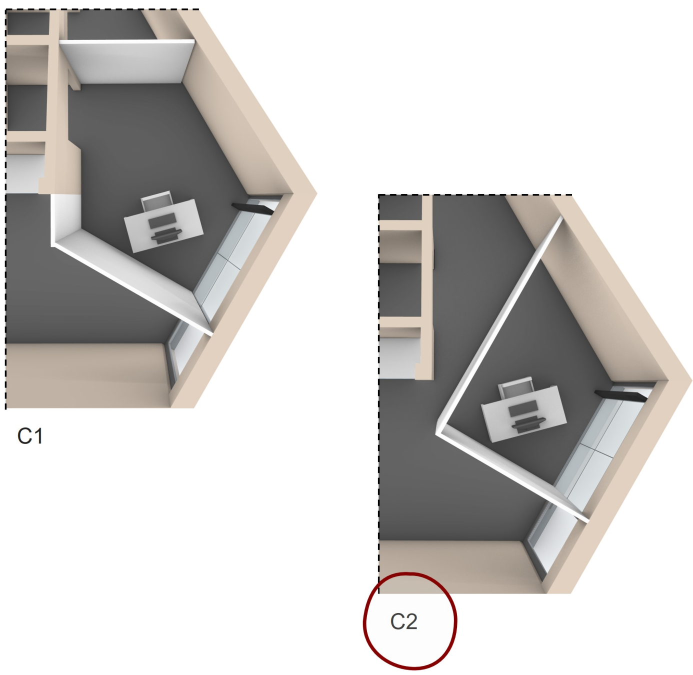
5.1.3. Room layout

The experiment was conducted at the Nonohouse building at the Green Village. The building functions not only as a test location for researchers and entrepreneurs in collaboration with the TU Delft but also as an annex and reception area for the Co-Creation Center, where kitchen and toilet services are installed. As a result, was actively in use during the experimental period, posing logical challenges regarding the lab space and layout constraints. Close coordination with the Green Village management was essential to design the experiment effectively.

The facade product was already installed on the southeast facade of the Nonohouse, adjacent to the entrance, covering nearly the entire facade (Figure 5.2a). To accommodate necessary circulation space and utilize the area in front of the facade for the placement of the experimental workstation, two potential partitioning scenarios were considered (Figure 5.2b). After careful consideration and negotiation with all parties involved, the second case that allowed continued access to building amenities was selected.



(a) Room layout and availability of space.



(b) Room layout, possible partitions and option selected.

Figure 5.2: Room layout and configurations.

The final design for the partitions consisted of a continuous, flexible railing and a curtain that extended from the ceiling to the floor, capable of complying with the shape of the inclined ceiling (Figure 5.3). The choice of a black curtain was deliberate to minimize reflections and diffuse daylight. To ensure complete closure of the space and prevent disruption from movements such as opening the entrance door or people moving around, velcro tape was strategically placed at critical points along the curtain.

The room layout necessitated the exclusion of artificial lighting within the lab room and provided a controlled environment solely dependent on natural daylight conditions (Figure 5.4). This approach ensured the avoidance of lighting reflections and interference, enhancing the experimental conditions for accurate data collection and analysis. Additionally, the vertical opening with clear glazing that remained open upon enclosure of the space (as depicted in Figure 5.2b) was covered with thick black paper. An informational poster was placed adjacent to the curtain to inform Green Village employees and visitors about the ongoing experiment, kindly asking for silence.

Figure 5.3: Curtain design (left) and velcro tape strategically placed to ensure complete enclosure of the lab space (right).

Figure 5.4: Exclusion of artificial lighting inside the lab space, curtain markings on the ceiling indicate the placement of the curtain railing.

5.1.4. Equipment and set-up

The experimental procedure involved the identification of the relationship between personal glare assessments and objective environmental quantities. Several measurements of the luminous environments were captured while the participants were voting their glare sensation. These included: vertical illuminance at the eye (Ev), the luminance map of the FOV through the high dynamic range images ($HDRIs$), horizontal illuminance on the desk plane (Eh), and vertical illuminance on the facade outside. Other measurements included the room temperature (RT) and relative humidity (RH). The selected measurements correspond to the most frequent type of measurements in visual comfort and glare assessments (Shafavi et al. 2020). Outdoor sky condition was characterized using the Copernicus Atmosphere Monitoring Service (CAMS) radiation service (**camsRadiation**). The experimental set-up of the lab with the position of each instrument can be seen in Figure 5.5. Subsequently, the measurements that were collected according to the equipment and other features are listed at the Table 5.2 below:

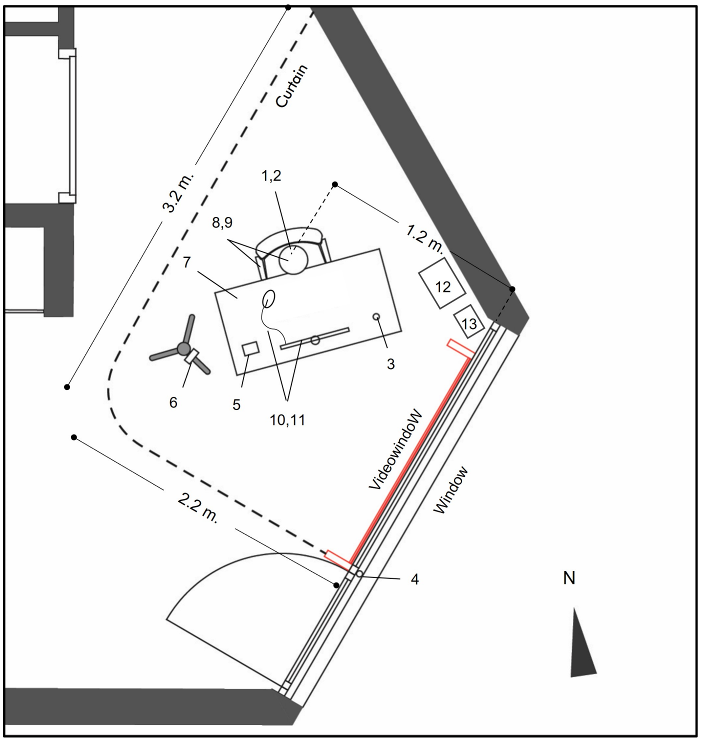
Table 5.2: Equipment used, data collection, placement and frequency of measurements.

Equipment	**Data to collect**	**Measurements**	**Placement**	**Purpose**	**Frequency**
Digital camera (Canon EOS 70D and Sigma fisheye lens)	HDRI images	Jpeg, CR2 files	Tripod placed at the position of the observer	Evalglare processing	manually captured, 2 times for each scenario
Illuminance meter(Konica Minolta)	Illuminance levels [lux]	Vertical illuminance at eye (Ev)	Mounted on the camera, close to the lens	Validation of vertical illuminance readings from the camera	manually collected, before and after the camera images
Illuminance meter (Li-cor)	Illuminance levels [lux]	Horizontal illuminance (Eh) and Vertical illuminance on the facade (Evf)	Desk and Facade	Monitoring indoor lighting and outdoor climate conditions outside	automatically every 1 second
Temperature data logger (Hobo)	Temperature [°C], Illuminance levels [lux], Relative humidity [%]	Room temperature	Desk and Tripod	Balancing room temperature factor	automatically every 15 seconds
Workstation (desk, chair, monitor, mouse)	-	-	45 degrees, 1.2 meters distance between the window and the occupant head	Clarify the position of the occupant for the performance of the visual tasks	-

A 45-degree clockwise arrangement of the workstation was chosen instead of positioning the desk parallel or perpendicular to the window. This decision was based on findings from previous studies, which indicated that such an arrangement would help minimize unwanted head movements, particularly during glare assessments (Kent et al. 2017). These adjustments aimed to reduce the tendency for participants to look directly at the window instead of focusing on the monitor and creating a higher probability of glare even if the diagonal configuration is not common in offices (Karlsen et al. 2015).

Most of the measurements were taken automatically as arranged. The illuminance sensors were placed either vertically or horizontally according to their purpose. One was placed outside vertically to the facade to monitor the climate conditions outside and inside horizontally on the desk to monitor the lighting conditions inside. One hobo was placed vertically close to the occupant's head on a tripod to collect mainly the thermal results and the second one horizontally on the desk to validate the readings from the illuminance sensor.

The manual measurements consisted of the camera series of images and the illuminance meter mounted on the camera in a tripod, as shown in Figure 5.6. These measurements were collected from the observer's position, pointing towards the visual display unit and capturing their visual experience. The tripod was placed every time according to markings at the same position. Its height was fixed at 1.2 m. at the average height of subjects when sited. The illuminance meter was used for calibrating the camera readings and the vertical illuminance was collected before and after each series of images. The software qDslrDashboard was used to



Equipment legend:

1. Canon EOS 70D camera
2. Konica Minolta illuminance meter
3. Li-cor illuminance meter
4. Li-cor illuminance meter
5. Hobo
6. Hobo
7. Workstation
8. Desk chair
9. Subject's head
10. Mouse
11. Monitor
12. Laptop connected to monitor
13. Alpha-log

Figure 5.5: Equipment and set-up in the room layout.

manipulate the series of features through the experimenter's laptop (Hubai 2024).

The CCD camera was a Canon EOS 70D equipped with a 4.5 mm F2.8 EX DC HSM Circular Sigma fish-eye Lens. CCD camera images offer a means to extract luminance values from scene pixels, representing different measurement points within the captured scene. 9 pictures were collected from each measurement. A shutter of 1", 8 fnumber, 100 iso and 0 EV were selected as features.

Figure 5.6: Photometric measurements: glare monitoring setup located at the occupant position including a tripod with camera and illuminance meter (1,2), horizontal illuminance (3) (left), vertical illuminance on the facade (right).

The internal view of the lab with the experimental set up is shown in Figure 5.6.

Figure 5.7: Internal view of the lab.

5.1.5. Sun simulation and test sessions

The experiment was scheduled for the spring period, specifically in March. The season and time of the day factors were specified to be controlled. The presence of direct sunlight on the facade was essential to examine varying levels of glare and to ensure equal testing conditions.

To specify the test sessions effectively and take advantage of the biggest time range of the sun's presence according to the orientation of the building, a simulation was conducted. This simulation captured the sun's position across various points on a horizontal plane. Detailed designs of the lab space, the Nonohouse building, and the surrounding area of the Green Village were designed in a Rhino 3D model (see Appendix A.4). Climate Studio was used as a plug-in for the facilitation of daylight simulations. The window was intentionally designed to be clear, as the pattern effect was not a primary concern for this simulation.

The horizontal plane was placed at the height of the eye level when sitting at 1.2 meters, representing the experience of the participants (Figure 5.8). The density of measurement points on this plane was adjusted according to room partitions and minimized to ensure a sufficient range of options. The workstation's position was selected based on a pie diagram displayed on the plane. All points were evaluated in this specific direction throughout March. The selected point offered the widest time range and did not constrain workstation placement in relation to the partitions.

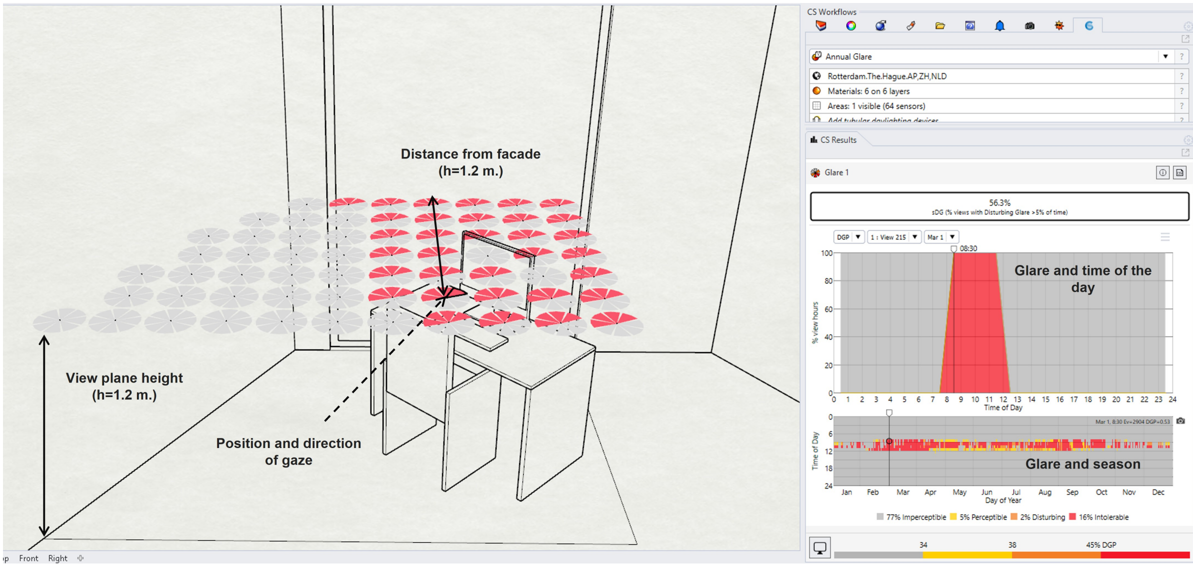


Figure 5.8: Horizontal plane at the eye level when sitting in Climate studio sun simulation to determine the workstation position. The pie elements represent the different directions according to the measurement points.

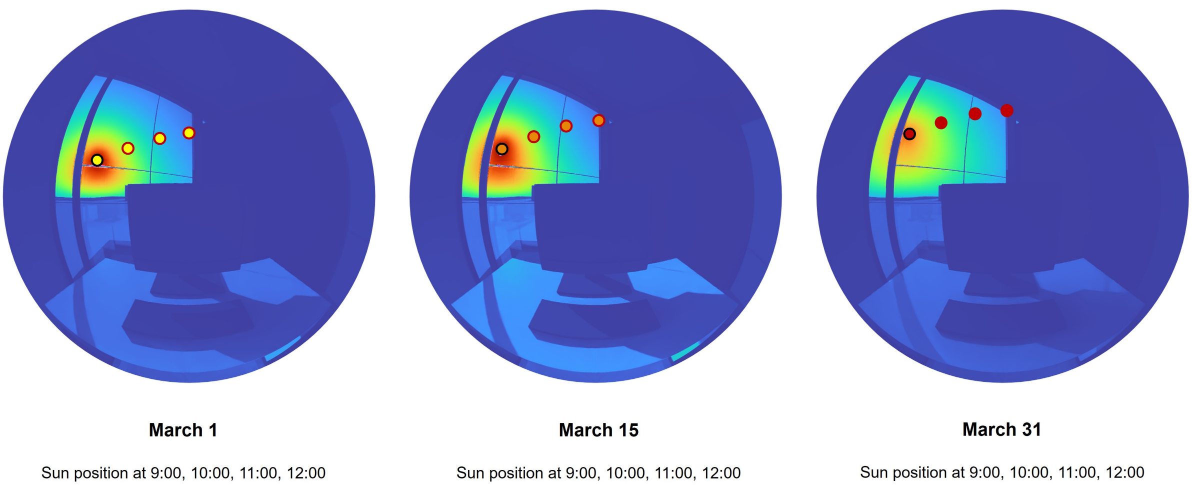


Figure 5.9: Fisheye representation of the sun position on the facade for March 1st, 15th and 31st at 9:00, 10:00, 11:00, 12:00.

The sun was captured and marked for critical dates during March, including March 1st, 15th and 31st. The time that the sun was present during the month was covering the period from 9:00 to 12:00. The sun's hourly position within this timeframe is depicted in Figure 5.9. An overall view of the sun's positions and its visible area on the facade is illustrated in also in Figure 5.10. Consequently, test sessions were scheduled between 9:00-10:30 and 10:30-12:00, allowing for two sessions daily. This scheduling was crucial for accommodating the required number of participants within the restricted timeframe.

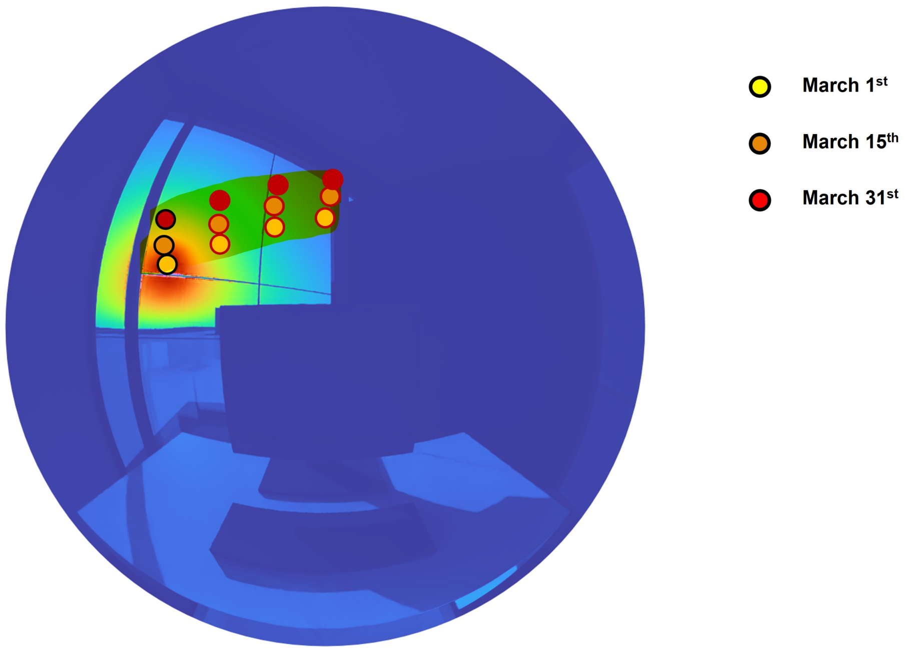


Figure 5.10: Area of sun position on the facade during March.

5.1.6. Pattern selection and generation

(A) Tree pattern

For the experiment's purpose, static patterns were decided to be examined. Every participant had to be exposed to the same patterns. The facade product was designed by the company featuring a dynamic motion effect of a tree pattern. However, there was a possibility of capturing certain static images from their website platform while the facade exhibited the dynamic effect. The steps included (Figure 5.11):

- Selecting a screenshot from real-time data.
- Saving the file as PNG image.
- Loading it as a demo through the website on the facade.

Since the tree was not generated for the current experiment's aim but based on outdoor data and the company's confidential design principles, it was crucial to select it based on certain parameters. Therefore, the simulation for the sun's position was repeated, incorporating an additional grid of the window on the model. By deconstructing the fisheye image, the sun's position became visible on the grid, facilitating further decisions. Twenty variations of the tree pattern were captured using the aforementioned steps and examined on the grid (Figure 5.12, Appendix A.5). The selected variation exhibited improved branch placement based on the area of direct sunlight on the facade from the simulation and demonstrated better distribution of branches and uniformity.

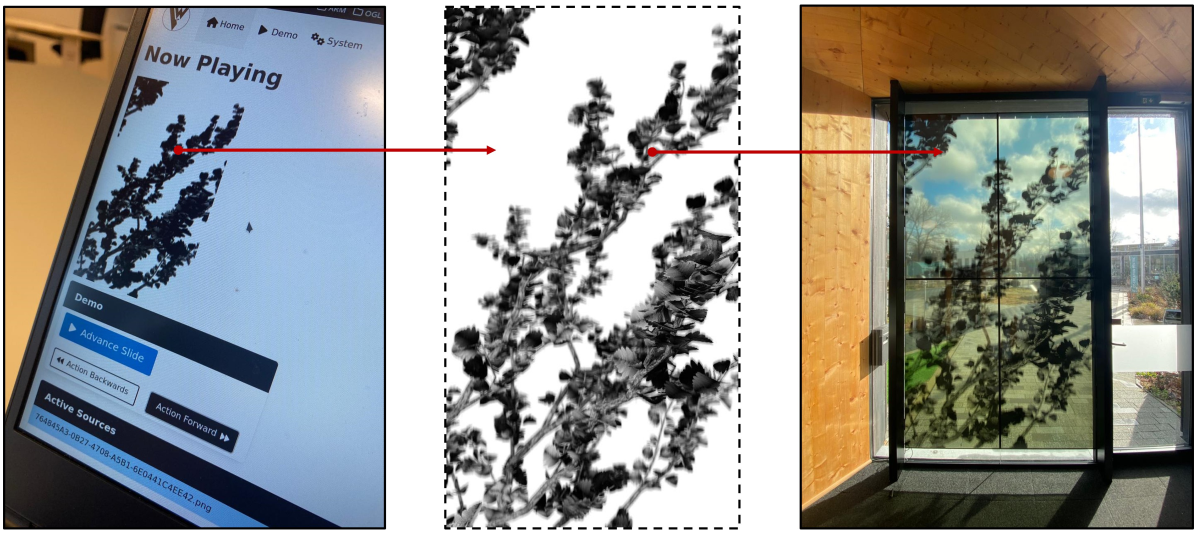


Figure 5.11: Static pattern generation from the website in steps: selecting a screenshot from real-time data (left), saving the file as PNG image (middle), loading it as a demo on the facade (right).

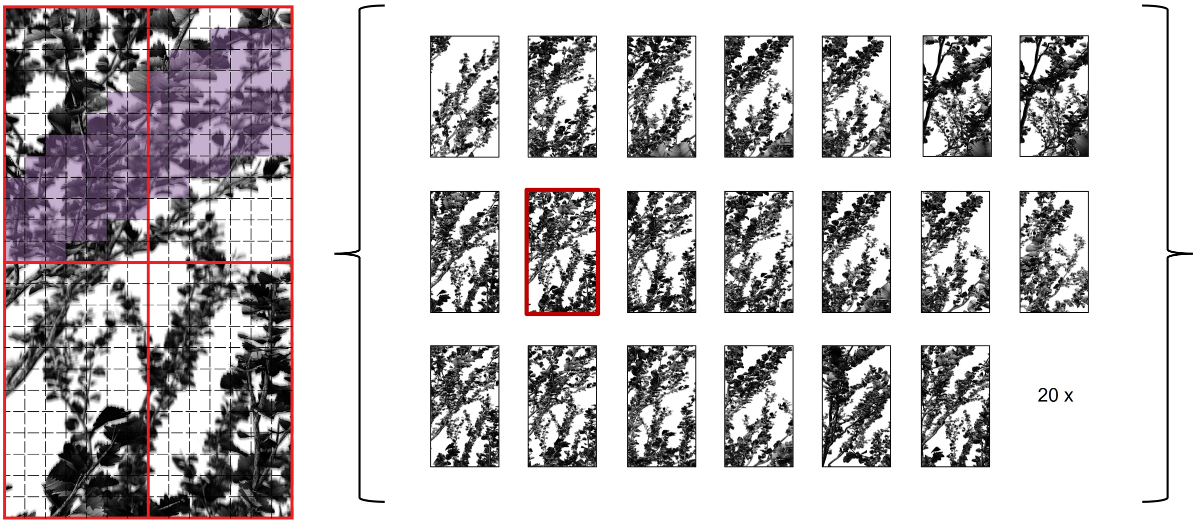


Figure 5.12: 20 evaluated variations of the tree pattern captured by the system and tested in the façade grid for better branch placement and distribution.

(B) Striped pattern

According to the literature review on experiments regarding occupants' responses to biophilic design, the alternatives to biophilic patterns included striped patterns, either vertical or horizontal, or more irregular patterns (Figure 5.13). For the current experiment, regular stripes were used in order to avoid biophilic design attributes associated with natural geometry, such as curved elements or other irregularities. Additionally, horizontal stripes were preferred over vertical ones to test the resemblance with conventional shading systems.

(C) No-pattern

Following previous experiments, a clear condition was chosen as a third choice. Nevertheless, instead of opting for total clear glazing, a no-pattern or homogeneous condition was created to maintain the same average transparency as the previous patterns. This approach enabled the inclusion of a no-pattern shading scenario, thereby mitigating biases and establishing a potential comparable case.

(D) None

A fourth condition was generated, including a transparent outcome on the facade, simulating the facade product being switched off. This facilitated the experimental procedure, as a neutral initial state was chosen for introduction to the lab, which was also utilized at the end.

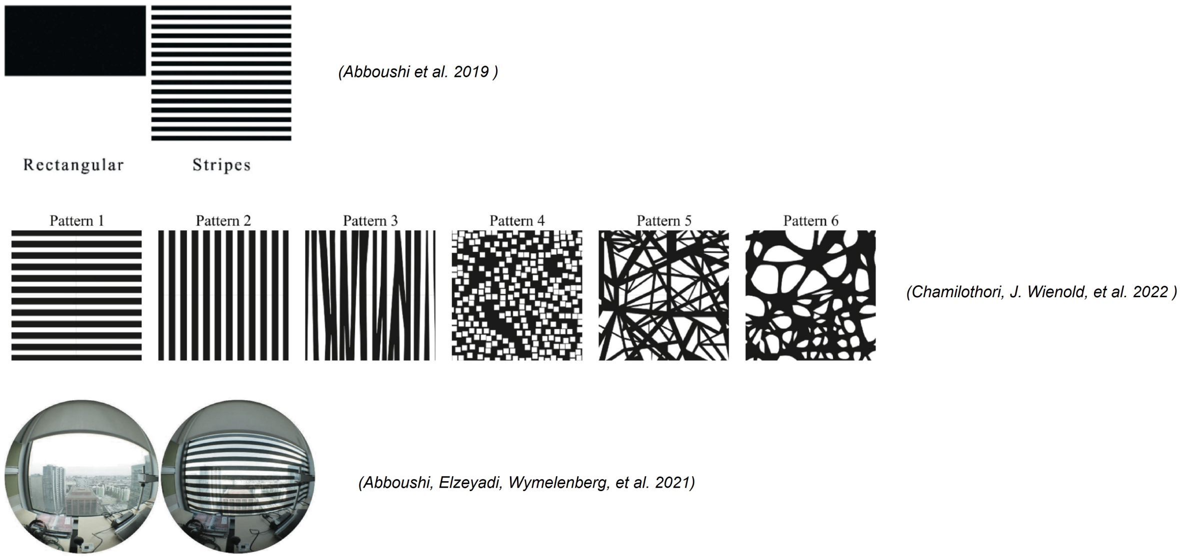


Figure 5.13: Options for non-biophilic pattern according to the literature review.

Comparable stimuli generation

When each PNG was loaded onto the facade, its shading value was interpreted as a level of transmittance. Employing a Python script, the average shading value could be computed on a scale where 0 represented black and 255 represented white (see Appendix A.6). The average shading value of the selected tree pattern was determined to be 135, corresponding to an average transparency level of 53%. Utilizing this value, the striped and no-pattern options were generated to have the same average shading value and transparency (Figure 5.14). The different shading values corresponding to transparency levels except total transparent (white) and their frequency are shown in Appendix A.7.

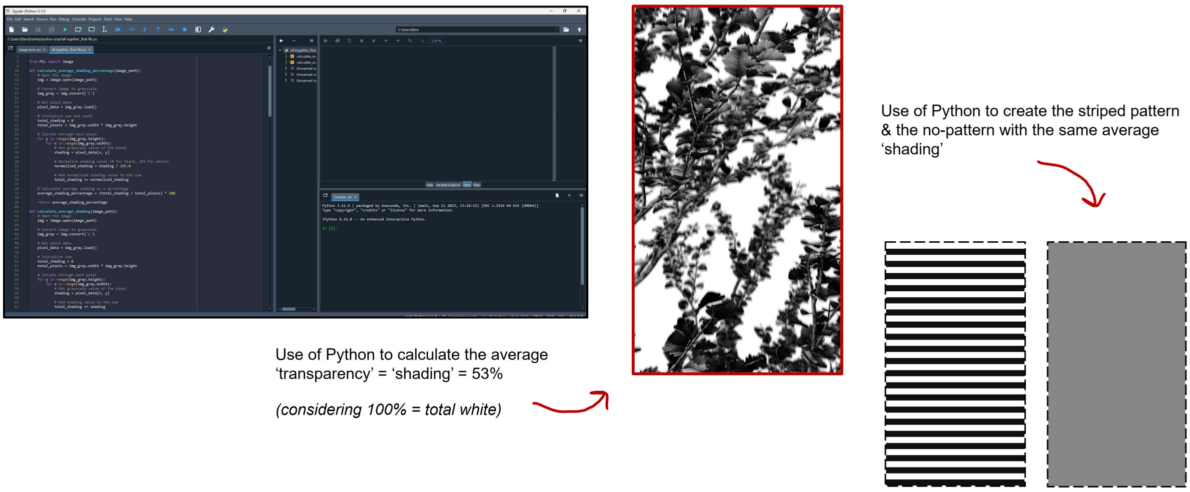
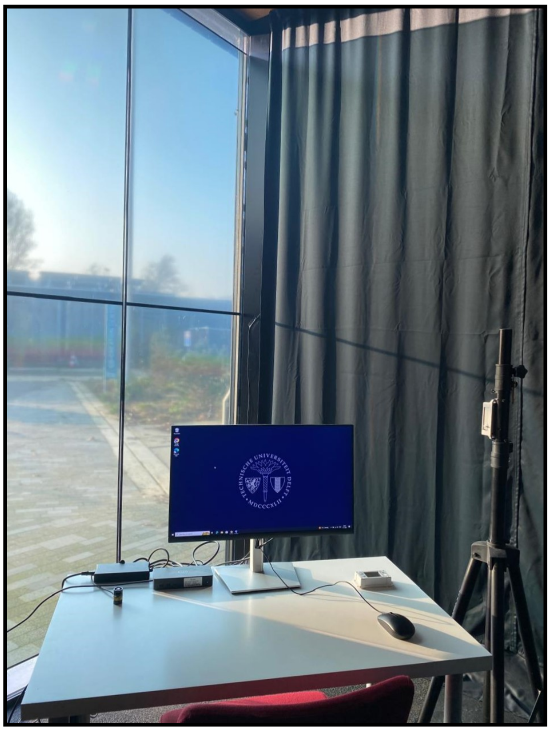


Figure 5.14: Use of python script for creating comparable stimuli

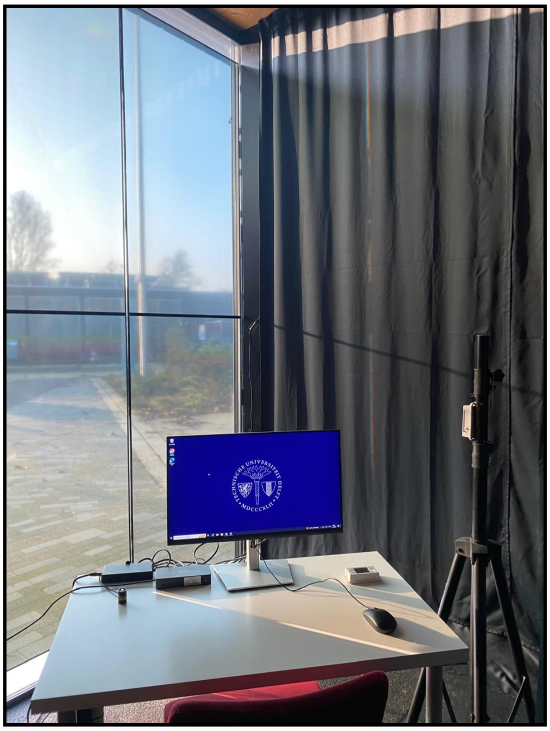
The four generated patterns that were used in the experimental procedure are depicted in Figure 5.15, applied in the window technology.

(a) Tree pattern

(b) Striped pattern



(c) No-pattern



(d) None

Figure 5.15: Pattern scenarios tested.

5.1.7. Procedure

The experimental procedure requested subjects to participate in one of the two test sessions available every day during March according to the schedule. The two slots available were determined based on the sun simulation, with sessions scheduled either from 9:00 to 10:30 (Session A) or from 10:30 to 12:00 (Session B). Each experiment had a duration of 1.5 hours. The order of presentation for the three stimuli was randomized using a 3x3 Latin Square Randomization method. This ensured that each pattern was equally exposed across all possible presentation orders (Figure 5.16).

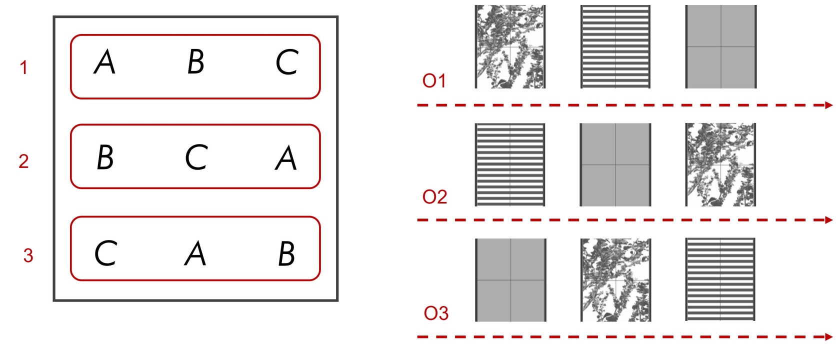


Figure 5.16: 3x3 Latin Square Randomization of presentation order of stimuli.

The procedure and every step linked to its duration are depicted in the Figure 5.17. Before the arrival of the participant, the facade was adjusted to a clear condition state. The initial 25 minutes were dedicated to the introduction and explanation of the experiment by the experimenter, including the completion of the consent form and the first questionnaire covering demographics and the observer's present state including the experience of the space. The participant entered the experimental space during the explanation and the experiment officially started after the signing of the consent form, when all preparations were completed and the curtain was closed. During the introductory part, the participant was exposed to the switched-off effect of the facade (D).

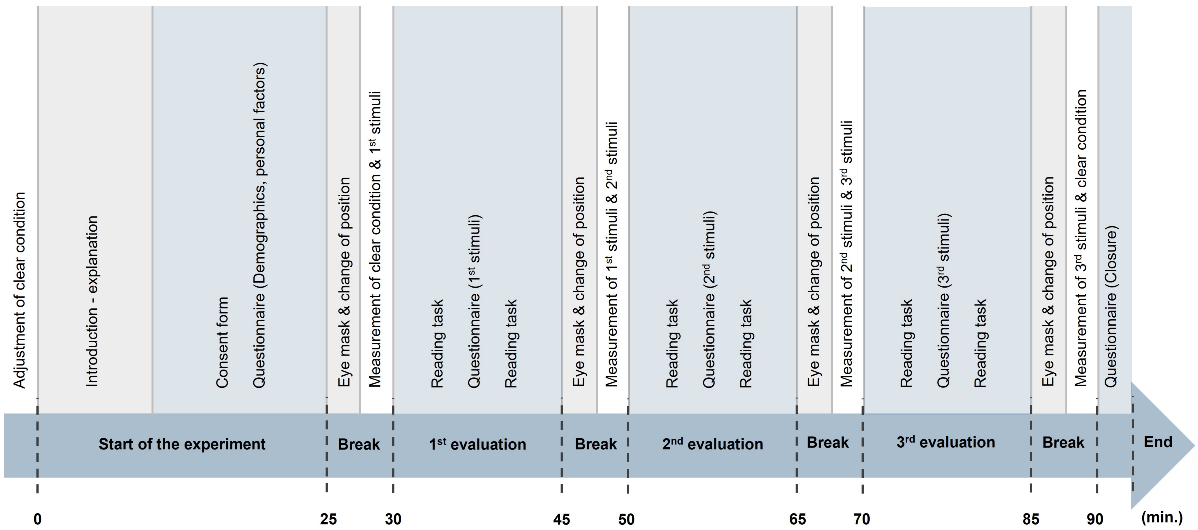


Figure 5.17: Experimental procedure including introduction, 3 main evaluations representing each pattern scenario and break time in between for the necessary measurements.

Three evaluations were conducted, each representing a different facade setting. Each facade setting was exposed to the participants for 15 minutes. Before and after each evaluation, measurements of the previous condition and the subsequent one were conducted using the camera and the illuminance meter mounted on it. Since the camera, placed on a tripod, was positioned for each measurement at the participant's location, the participant was instructed to change their position before the experimenter entered the space. Detailed instructions were provided both at the start of the experiment and before each measurement to assist the participant. Additionally, the participant was instructed to wear an eye mask and cover their eyes before the experimenter entered the lab space each time. This measure aimed to mitigate the influence of outdoor lighting conditions when the curtain opened and to neutralize the human eye, ensuring consistent starting conditions for each pattern. This approach also minimized the influence of the experimenter during the measurement procedure and their presence in the room. The break time, including the change of position of the observer and the measurements by the experimenter, lasted for 5 minutes each time.

During the evaluations, the participant engaged in reading tasks of their preference, either online or using their USB stick with their files as recommended. Midway through the 15-minute exposure to each pattern, the participant was prompted by the experimenter behind the curtain to complete a questionnaire for that specific evaluation.

After the final measurement, the participant was instructed to complete the last questionnaire, which included closure questions and comments. For Session B, the clear condition was already set, and the same procedure was repeated, with only the presentation of the stimuli being altered as mentioned earlier.

Consequently, the tasks of the experimenter included changing the facade settings, collecting measurements with the camera, and providing instructions to the participant (Figure 5.18). Conversely, the participant's tasks involved performing reading tasks, wearing the face mask and changing position or filling out questionnaires as instructed (Figure 5.19).

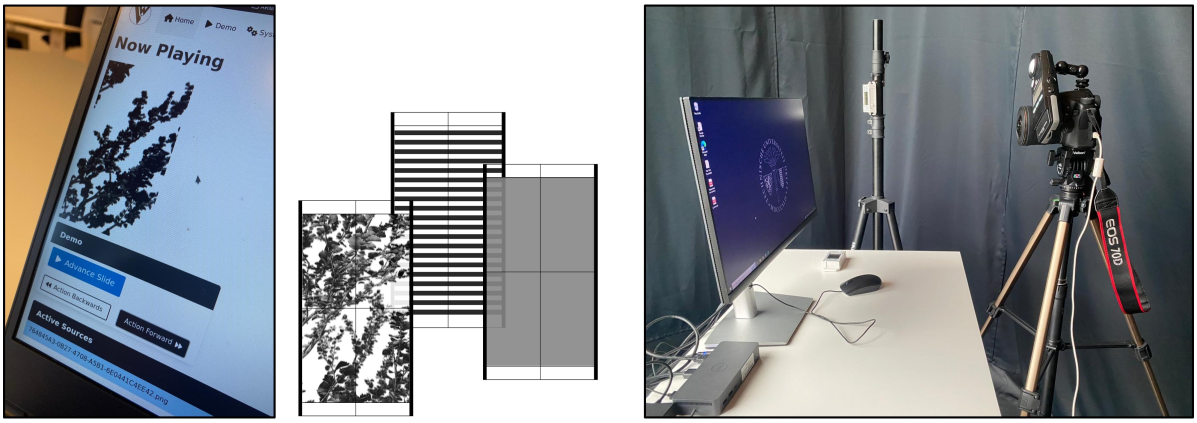


Figure 5.18: Experimenter tasks: changing the facade display (left) and collecting the measurements (right).

Figure 5.19: Participant tasks: performing the reading tasks (left), wearing the ey mask and changing position (middle), filling the questionnaires (right).

5.1.8. Participants

The G-Power analysis software tool was utilized to determine the total sample size required (Faul et al. 2024), (Figure 5.20). An effect size expected to be observed in the study, based on previous research, was estimated as small to medium, with a size of 0.25 considered. A significance level (alpha) of the common value 0.05 was entered, and a power (1-beta) of 0.95 was utilized, indicating that the study is well-powered to detect meaningful effects. The required number of participants was calculated to be 43 in total.

F tests – ANOVA: Repeated measures, within factors

Analysis:	A priori: Compute required sample size		
Input:	Effect size f	=	0.25
	α err prob	=	0.05
	Power (1–β err prob)	=	0.95
	Number of groups	=	1
	Number of measurements	=	3
	Corr among rep measures	=	0.5
	Nonsphericity correction ϵ	=	1
Output:	Noncentrality parameter λ	=	16.1250000
	Critical F	=	3.1051566
	Numerator df	=	2.0000000
	Denominator df	=	84.0000000
	Total sample size	=	43
	Actual power	=	0.9514057

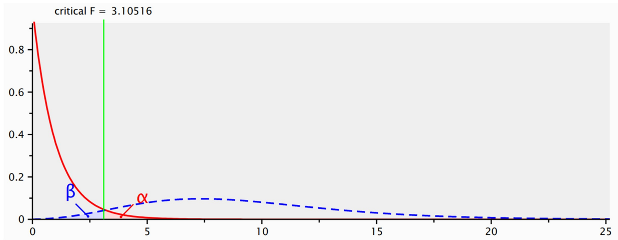


Figure 5.20: G-power analysis for determination of the number of population needed.

Participation in this study was voluntary. Subjects were recruited via a survey in Qualtrics software which was distributed through email or in person (Qualtrics 2024). The invitation for participation began with an explanation of the experiment, providing location and contact details for further communication or questions (Figure 5.21). Participants were informed about the reading tasks to be performed in an office setting and were advised to bring files of interest on a USB memory stick. They were informed that internet access would be provided, and they were instructed to use a workstation monitor to read and fill out questionnaires. The participants who expressed interest filled their name, and email and selected a slot according to their availability. Qualtrics display logic was manipulated to prevent scheduling overlaps, and participants were directly assigned to their preferred session. An automatic reply containing their assigned slot and location details for assistance was sent to their email immediately after survey submission.

The dates on which participants were scheduled can be viewed in Appendix A.9. Certain days in March were excluded from the survey due to the space being occupied for other activities, as indicated by the Green Village schedule. In total, 44 subjects were recruited for this project, including 37 Master's students, 4 PhD students, and 3 Green Village employees.

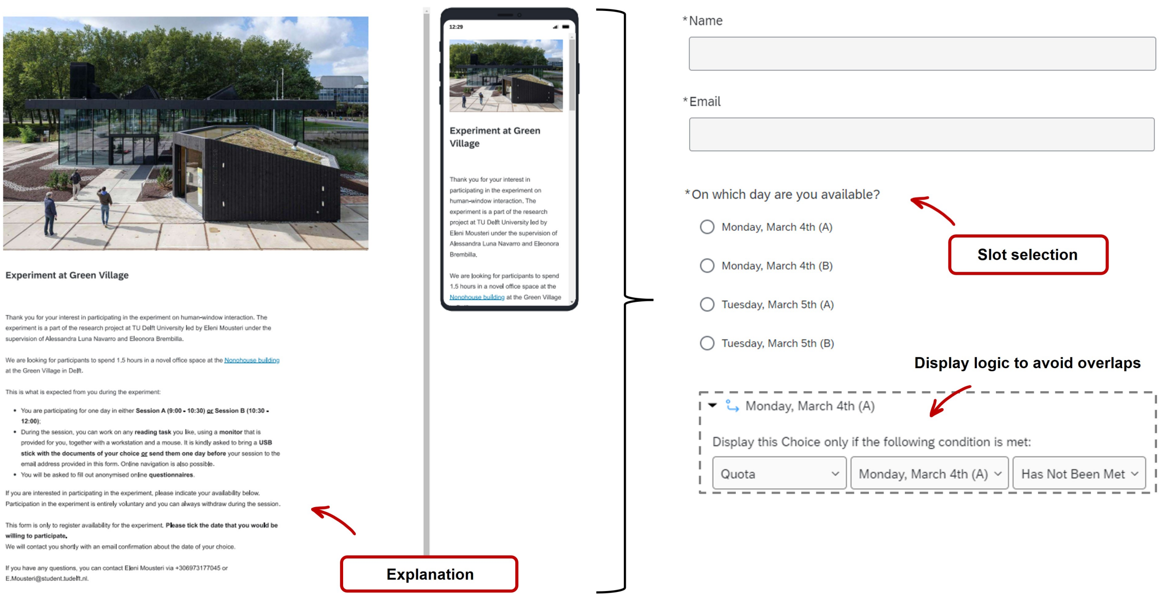


Figure 5.21: Invitation for participation in Qualtrics form.

5.1.9. Questionnaires

Three types of questionnaires were incorporated into the experimental procedure: an introductory questionnaire, an evaluation questionnaire for each pattern, and a closure questionnaire (Appendix A.11 - A.15).

The introductory questionnaire was completed before the evaluations, requesting information from participants regarding general characteristics (gender, age, cultural background), vision attributes (optical correction, contrast sensitivity, color blindness), their present state (sleep quality, stress level, fatigue level, caffeine intake), and their experience within the space (view satisfaction, visual satisfaction, room temperature feeling). Response formats varied according to the nature of the questions.

The evaluation phase comprised three questionnaires repeated for each of the three patterns presented to participants. Questions addressed the following aspects: glare perception, daylight satisfaction, color of daylight satisfaction, visual comfort, view out satisfaction, acceptance of obstruction of view, pattern aesthetics, sunlight pattern aesthetics, room temperature feeling, and perceptions related to biophilic design and psychology. Glare assessment was conducted using a 4-point Glare Sensation Vote (GSV) scale, while other questions utilized a 5-point Likert scale, except for temperature feeling, which employed the ASHRAE 7-point scale. These questions represented the dependent variables of the experiment and can be seen in Table 5.3.

Table 5.3: Questionnaire for dependent variables and scales used.

Variables	Question	Scale
Glare perception	At present, the level of glare I feel is:	4-point scale (imperceptible, noticeable, uncomfortable, intolerable)
Daylight satisfaction	I am satisfied with the amount of daylight entering the room.	5-point Likert scale (strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, strongly agree)
Color of daylight satisfaction	I am satisfied with the color of daylight through the window.	
Visual comfort	I find the visual environment of the office comfortable for working.	
View out satisfaction	I am satisfied with the view through the window.	
Acceptance of obstruction of view	I don't find the pattern/dimming effect on the glazing to be an obstruction to the outdoor view.	
Pattern aesthetics	I like the pattern/dimming effect on the glazing in terms of aesthetics.	
Sunlight pattern aesthetics	I find the sunlight patterns created by the pattern/dimming on the glazing to be visually interesting.	
Room temperature feeling	How do you feel in the room at the moment?	7-point ASHRAE thermal sensation scale

The closure questionnaire included two additional questions and a section for comments. These questions focused on participants' preferences for the patterns, particularly regarding their favorite choice and the pattern perceived to foster a connection with nature.

5.2. Conclusions

The Experimental Method chapter provides a detailed framework for examining how biophilic design affects occupant perception in architectural settings. The experiment's design, variables, room setup, equipment, and procedures are all carefully outlined to ensure scientific rigor.

The experiment focuses on key variables related to occupant perception. The dependent variables include glare perception, daylight satisfaction, color of daylight satisfaction, visual comfort, view out satisfaction, acceptance of obstruction of view, pattern aesthetics, sunlight pattern aesthetics, and room temperature feeling. The independent variables encompass the presence of different patterns, dimming effects, pattern characteristics, and environmental conditions. Confounding variables such as participant demographics, vision characteristics, and environmental distractions were also considered to maintain the study's validity.

The experiment took place in the Green Village laboratory, where the room was designed to support various glazing settings and accurate environmental measurements. Specialized equipment and sensors were used to collect real-time data on environmental conditions and occupant responses.

Further, careful consideration was accorded to the determination of the season and time of day for conducting the experiment and selecting the workstation placement inside the lab. By selecting the spring period and scheduling sessions during morning hours, the study sought to optimize daylight exposure and take advantage of the short timeframe available.

Careful consideration was attributed to the selection and generation of patterns employed in the experiment. Through a systematic approach integrating insights from biophilic design principles and sun position studies, static biophilic patterns were carefully selected to emulate both natural elements and irregular and no-pattern conditions to test different aspects. The patterns were comparable in terms of average light transparency.

During the experimental procedure, participants engaged in reading tasks under different glazing settings while completing questionnaires. This approach aimed to gather comprehensive data on occupant responses to varying environmental conditions.

By documenting each step rigorously, from variable selection to participant engagement, the chapter provides a robust framework for investigating the relationship between biophilic design and occupant perception.

6
Results

6.1. Sky classification

The characterization of sky conditions is crucial for understanding the external climate dynamics during experiments and correlating them with the facade and indoor environmental data. The sky was characterized using data from the Copernicus Atmosphere Monitoring Service (CAMS), providing measurements of horizontal diffuse irradiance (DHI) and horizontal global irradiance (GHI) (SODA 2024). These measurements allowed for the calculation of the sky ratio, following the methodology outlined by Chung (1992), where the sky ratio represents the ratio of DHI to GHI.

The exact location of the Nonohouse building was pinpointed on a map, and the temporal variable was set at 1-minute intervals, then aggregated into 15-minute ranges to represent each pattern exposure time (Figure 6.1). For Session A, data collection occurred during the time intervals of 9:30-9:45, 9:50-10:05, and 10:10-10:25. For Session B, data collection took place from 11:00-11:15, 11:20-11:35, and 11:40-11:55. Data were collected daily and subsequently merged into a unified file for analysis.

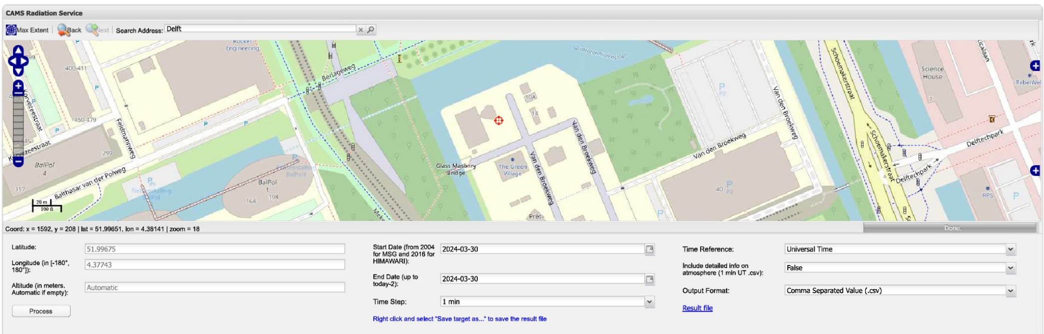


Figure 6.1: Location and time step selection for Copernicus Atmosphere Monitoring Service (CAMS).

Based on the sky ratio, the sky is classified into three categories:

- clear = sky ratio < 0.3
- partly cloudy = 0.3 < sky ratio < 0.8
- overcast = sky ratio > 0.8

The sky condition was classified for each pattern exposure and can be observed in A.17, A.18. It was also verified by the experimenter's notes for the climate condition each day. Figure 6.2 illustrates the comparison between the different patterns. Overall, 59% of the total sessions were characterized by cloudy sky, 16% by partly cloudy, and 25 % by clear sky. Notable differences in the total amounts of each type of sky condition for each pattern are not evident. This suggests minimal variations in sky conditions during the short duration

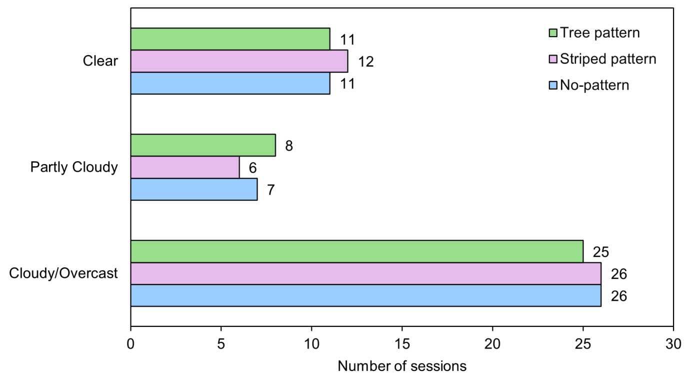


Figure 6.2: Classification of sky conditions (Clear, Partly Cloudy, Cloudy/Overcast) and the corresponding total number of sessions for each window pattern (Tree pattern, Striped pattern, No-pattern).

of the experiment and consistency between the scenarios. Most examples, as also depicted in the appendices, indicate relatively stable sky conditions, with similar sky ratios observed between patterns on each day. However, a few days exhibited certain variations, attributed to unstable cloud coverage.

It is noteworthy that for the results depicted in Figure 6.2, the average ratio signifies an overall sky condition. However, as emphasized in the appendices, when inspecting each minute separately, the overall measurements correspond to more than one classification and are highlighted. Therefore, in some instances, the sky may appear predominantly clear, while simultaneously exhibiting partial cloudiness, or vice versa, and the same can be observed with overcast and partially cloudy conditions. On stable days, a total of 23 whole sessions out of 44 consistently displayed overcast or cloudy skies across all patterns, while 8 sessions exhibited clear skies, and 2 sessions showed partly cloudy conditions. In the remaining 11 sessions, the sky classification fell into more than one category, indicating significant sky variations.

6.2. Image processing

During the experiment, one set of measurements involved capturing a series of images using a digital camera equipped with a fisheye lens. These measurements aimed to generate a luminance map, illustrating the visual environment of the participant and acquiring the Discomfort Glare Probability (DGP) values. The images were saved in both JPEG and CR2 formats from the camera.

The subsequent steps included utilizing Lmk Labsoft software to process the CR2 images and create one HDR image for each series of CR2 files (TechnoTeam Bildverarbeitung GmbH 2024), (Figure 6.3). Following this, the Radiance Converter software was employed to convert the HDR images into PF files containing radiance data. Finally, the PIC files generated from the PF files were processed using Evalglare in Ubuntu, an open-source operating system on Linux, for further analysis (Canonical Ltd. 2024), (Appendix A.10). The analytical measurements were recorded in notes transferred to an Excel file, including the DGP, while colored JPG images were generated to visually depict the sources of glare.

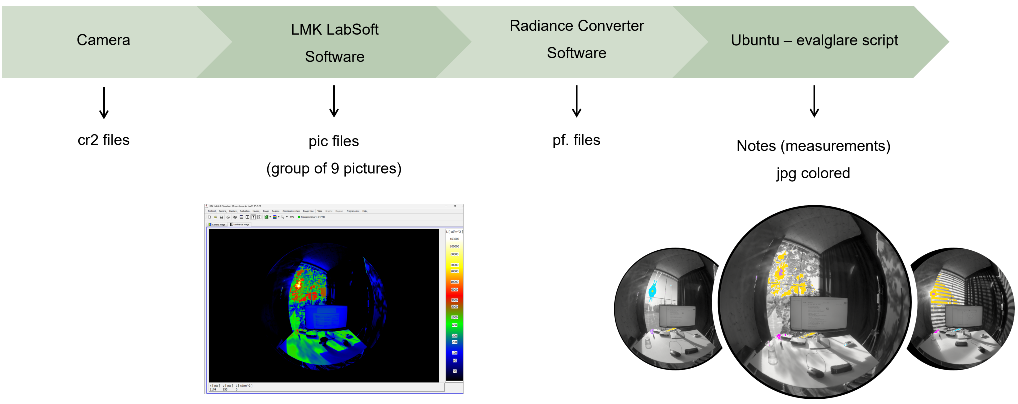


Figure 6.3: Image processing in steps.

Throughout the image processing, errors occurred related to pixel overflow in the Labsoft software and the final DGP values. These errors were identified by comparing the vertical illuminance derived from the script in the notes with the one that was measured as an average from the manual measurements taken before and after the camera series measurements:

$$\frac{Ev_{average} - Ev_{camera}}{Ev_{average}}$$

The discrepancies in vertical illuminance were found to be higher than +/- 25%, which is not acceptable as a result. This significant variance indicates inaccuracies in the image processing workflow, necessitating further investigation and correction to ensure reliable and accurate glare analysis.

To address these issues initially, a simplified approach was taken by utilizing the simplified DGP method (Equation 3.2), which relies solely on vertical illuminance from manual measurements. This method allowed for a more straightforward and direct calculation of DGP, ensuring that the results were not affected by the processing errors encountered with the automated image-based method. By using the vertical illuminance values obtained manually, a more accurate assessment of discomfort glare could be made, serving as a reliable reference for further detailed analysis. Before applying this method, the Konica Minolta sensor that collected the manual measurements of vertical illuminance was checked for its accuracy with one Li-cor sensor. The former was mounted on the camera and the latter was attached to the camera lens. The results were almost identical, indicating that the equipment worked properly. The sky condition was overcast to partially cloudy.

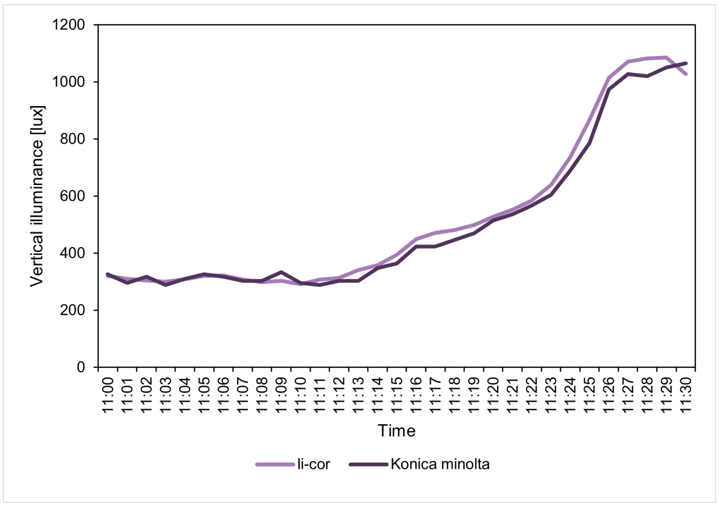


Figure 6.4: Validation of illuminance sensors, overlap in vertical illuminance monitored by li-cor and Konica Minolta sensors.

However, this method only accounts for saturation glare, excluding the possible contrast glare present. Therefore, a second attempt was made to comply with the following directions (Abreu Vieira Viula 2022):

- If the DGP error derived from the camera was within the ±25% error range, the value was marked as correct and used in the measurements.
- If the DGP value was outside the acceptable error range, and the manual vertical illuminance was higher than the same value derived from the camera, the picture was calibrated by adding the manually measured illuminance value in the Ubuntu evalglare script.
- Lastly, if the manual measurement was lower than the camera-derived value, the measurement was discarded.

Utilizing the described methodology, a total of 264 measurements were meticulously analyzed. Out of these, 191 were deemed accurate according to predefined criteria. To enhance precision, 67 measurements required adjustments through script modifications, while 10 were excluded due to discrepancies or irregularities.

In Figure 6.5, a comparison between manually measured illuminance values and those obtained from camera-based measurements is presented. Interestingly, the excluded measurements primarily displayed exceptionally low illuminance levels, whereas the corrected measurements tended to converge around lower values, approximately 2000 lux. This suggests a possible limitation or threshold within the evalglare algorithm.

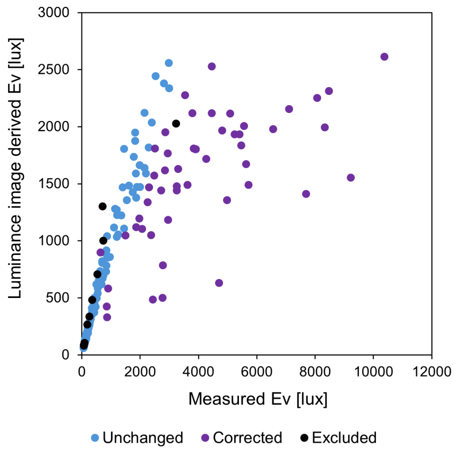


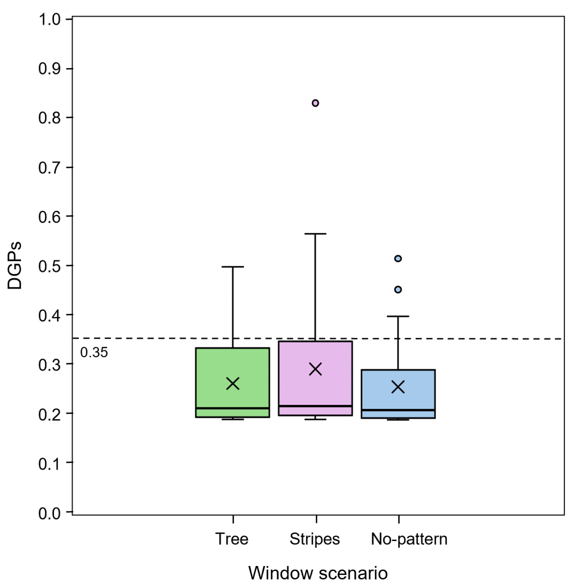
Figure 6.5: Luminance derived from the camera versus luminance derived by the manual measurements.

These findings set the stage for a thorough examination of the dataset, ensuring careful analysis of both sets of results to maintain consistency and reliability.

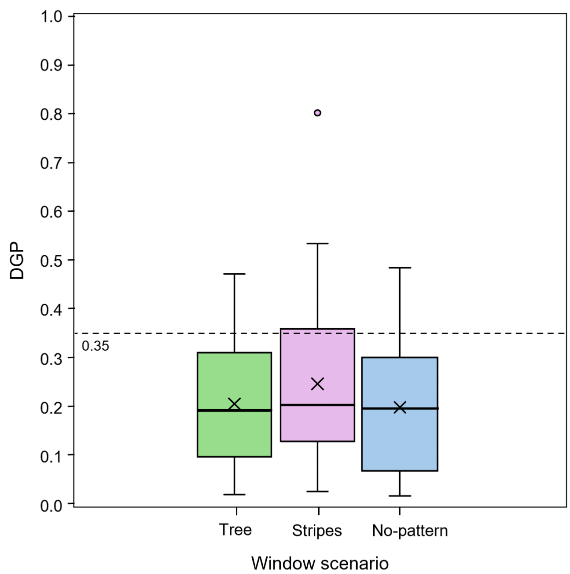
6.3. Glare in objective and subjective data

Objective measurements

The box plots depict the combined average Daylight Glare Probability (DGP) measurements for each pattern, integrating data collected both before and after exposure (Figure 6.6). Both image processing methodologies were used to plot the results and check for the data's consistency. Overall, the results show consistency.



(a) Simplified DGPs



(b) DGP edited

Figure 6.6: Box plots illustrating Daylight Glare Probability (DGP) measurements across various scenarios. The dotted line at 0.35 indicates the threshold for imperceptible glare, where values below this line are considered imperceptible.

The results indicate minimal disparities in the graphical representation along the different patterns. The consistent median DGPs values across all three patterns, standing at 0.21, underscore a uniform central tendency in the measurements, suggesting predominantly imperceptible glare. The same happens at the DGP that was edited, where the median value is close to 0.20 for all cases. Moreover, the mean values fall into the imperceptible categories, represented in both methods inside the range of 0.20 to 0.30. These observations also align with the characterized sky condition, which, as previously noted, was predominantly cloudy in approximately half of the total sessions.

The interquartile range (IQR) serves to delineate the spread of the middle 50% of the data. Notably, the IQR appears slightly broader for the Stripes pattern in comparison to the Tree and No-pattern conditions in the first case, implying a marginally heightened variability in DGP values for the Striped pattern. The situation is a bit different in the second method, where the No-pattern appears to have a slightly broader spread. However, the differences are minimal, indicating a similar spread of data across the scenarios.

This is further validated by the observation of maximum DGP values, notably peaking at 0.83 for Stripes, trailed by 0.66 for Tree, and 0.52 for No-pattern or at 0.80, 0.47, and 0.48 accordingly in the edited version. These heightened DGP levels, especially in the Stripes pattern suggest either elevated discomfort glare levels or the potential presence of outliers. This phenomenon may be attributed to the design and performance intricacies of the pattern. The Stripes pattern, characterized by its dark and transparent segments, underlines the likelihood of experiencing heightened discomfort glare when exposed to sunlight, resulting in the representation of extreme values as outliers.

Conversely, the No-pattern condition, featuring a uniform shading-transparency gradient, also exhibits outliers for the DGPs values, although in a more predictable and balanced manner, clustered close to the whiskers. The Tree pattern presents a scenario in between the other two, with a modest number of outliers, potentially attributed to inherent variations in the distribution of tree branches, despite efforts to maintain uniformity. These distributions are illustrated in a more balanced manner in the edited DGP where, these values are represented inside the whiskers without the presence of outliers.

Each box plot displays a skewness towards lower DGP values, suggesting a prevalence of lower discomfort glare instances. This inclination is once more linked to the prevailing sky condition, reinforcing the statement of minimal glare occurrences.

Overall, the striking resemblance among the plots signifies a consistency of the results by the two methods and a congruity in the performance of the facade patterns concerning glare.

Subjective questionnaires

The subjective evaluation of glare perception, obtained through participant questionnaires, offers valuable insights into the human experience of luminance discomfort within the experimental setting. Analysis of the questionnaire responses reveals distinct patterns in participants' subjective assessments of glare across different facade settings. Participants attributed varying levels of perceptual discomfort to each pattern, as evidenced by the distribution of responses across imperceptible, noticeable, uncomfortable, and intolerable categories (Figure 6.7).

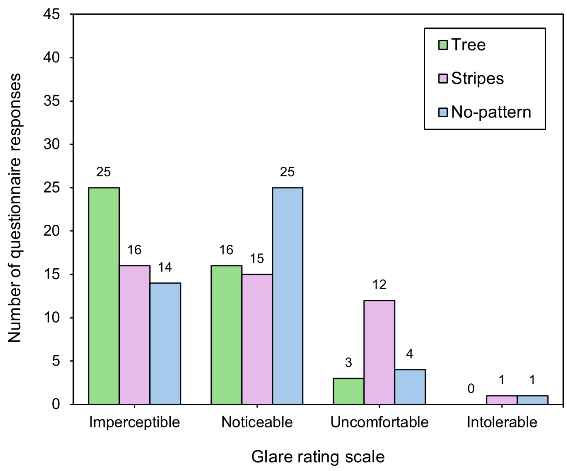


Figure 6.7: Glare perception from questionnaire responses.

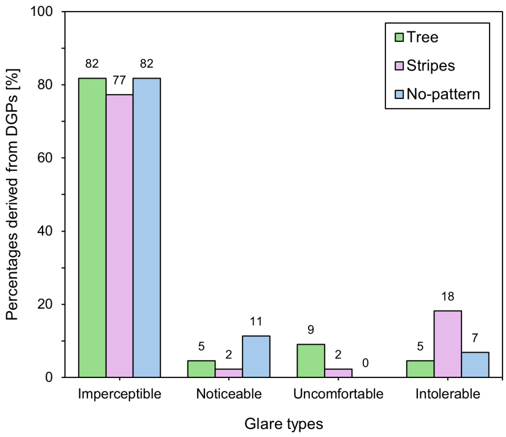
Upon reviewing the questionnaire results, it is evident that participants predominantly experienced imperceptible and noticeable glare. The Tree pattern received the highest number of ratings for imperceptible glare, with 25 out of 44 participants indicating minimal discomfort. The noticeable glare was more prevalent in the No-pattern condition, with 25 participants reporting noticeable levels of glare. The Stripes pattern gathered more ratings for uncomfortable glare compared to other patterns, with 12 participants expressing discomfort. Intolerable glare was reported by only 1 participant for both the Stripes and No-pattern conditions, indicating relatively low occurrences of extreme discomfort across all patterns.

Overall, the data suggest variations in perceived glare levels among different facade patterns, with the Stripes pattern eliciting higher levels of discomfort compared to the Tree and No-pattern conditions.

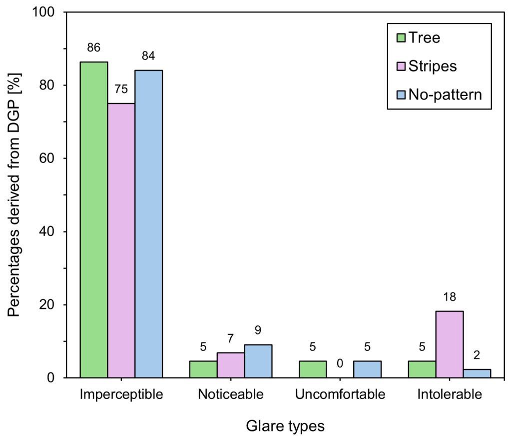
Comparison of objective and subjective data

While subjective assessments from questionnaires provide insights into participants' perceived discomfort glare levels, objective measurements of DGP or DGPs offer quantitative data on actual glare levels. Comparing the two sets of data allows for evaluation of the alignment between participants' perceptions and the measured glare levels.

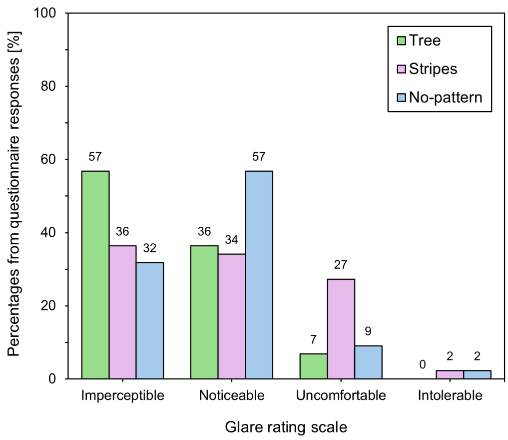
Both subjective and objective assessments reveal a prevalent occurrence of imperceptible glare across all facade patterns (Figure 6.8). Participants frequently rated glare as imperceptible in the questionnaires, which aligns well with the consistent median and mean DGP values observed in the objective measurements. This consistency suggests that participants' perceptions closely align with the measured glare levels in terms of imperceptibility. However, it appears that what was measured as imperceptible was perceived as either imperceptible or noticeable in the responses, indicating that participants could not distinguish between the two types.



(a) Simplified DGPs



(b) Edited DGP



(c) Percentages of glare types from subjective responses

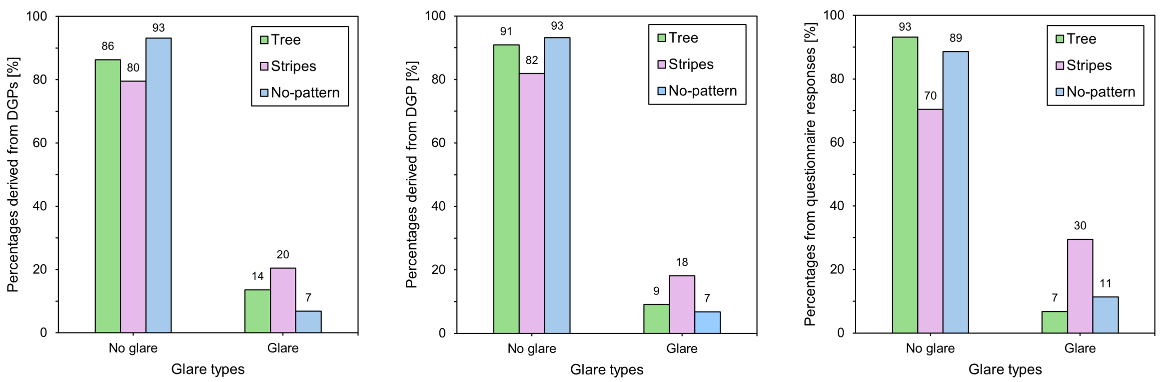
Figure 6.8: Percentages of glare types from objective and subjective measurements.

Discrepancies arise in ratings of uncomfortable and intolerable glare. For instance, the Stripes pattern received more ratings for uncomfortable glare in the questionnaires while more ratings for intolerable glare were observed in the measurements. Additionally, this observation contrasts with the objective measurements, which show heightened DGP levels for the Stripes pattern but do not necessarily reflect a big increase in discomfort glare compared to other patterns. The design of the Stripes pattern, characterized by alternating dark and transparent segments, may allow for greater light penetration, resulting in variations in perceived glare levels. Moreover, across all patterns, intolerable glare was more prevalent in the measurements, while uncomfortable glare predominated in the responses.

Participants' subjective assessments appear to be more sensitive to subtle variations in glare levels compared to the objective measurements. While the objective measurements demonstrate minimal disparities in DGP values across patterns, participants were able to discern differences in glare levels and provide varying ratings in the questionnaires. This heightened sensitivity suggests that subjective perceptions of glare may be influenced by factors beyond quantitative measurements, such as individual preferences, visual comfort thresholds, and environmental conditions.

Furthermore, the measurements were collected both before and after the pattern exposure within a short period of 15 minutes, and the glare ratings were obtained during this timeframe. Consequently, there is a possibility of slight variations in the sky condition and the performance of the facade across different parts of the pattern design during both the measurement periods and the respondents' assessments. These variations could influence participants' perceptions of glare and contribute to discrepancies between the objective measurements and subjective ratings.

From another perspective, binary data collection methods, distinguishing between glare and non-glare conditions, may yield closer alignment between measurements and questionnaire responses (Figure 6.9). This indicates that participants may find it easier to perceive the presence or absence of glare in a binary context.



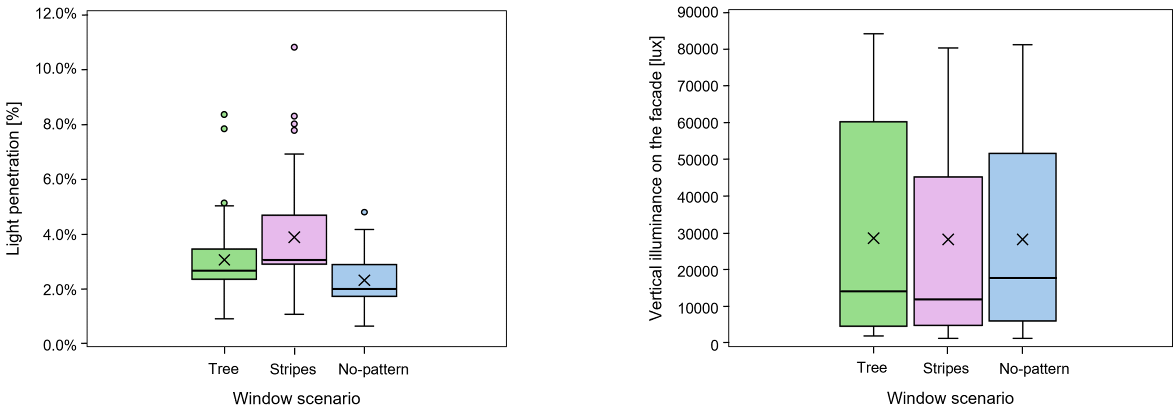
(a) Simplified DGPs (b) Edited DGP (c) Questionnaire responses

Figure 6.9: Binary percentages of glare types from objective and subjective measurements.

6.4. Light penetration and facade performance

The assessment of light penetration is fundamental for evaluating the effectiveness of different facade patterns in architectural lighting environments. In this study, light penetration was quantified as the ratio of vertical illuminance measured by a Hobo mounted on a tripod adjacent to the workstation to that measured by a Li-cor sensor positioned vertically on the facade, expressed as a percentage. This metric enables a standardized assessment of light penetration across various facade patterns, facilitating direct comparisons of their performance by capturing the variation in one stable point. By collecting data over the 15-minute exposure period of each pattern, the lighting conditions experienced by participants could be characterized and compared with outdoor lighting data. This approach allows for a comprehensive evaluation of the performance of each facade pattern, enabling meaningful comparisons between patterns.

The box plots presented in Figure 6.10 illustrate the distribution of light penetration for each facade pattern alongside the vertical illuminance on the facade during each exposure period. Stripes exhibit the widest spread of light penetration, followed by Tree and then No-pattern. Tree and No-pattern show similar central tendencies, with Tree having a slightly higher median light penetration. This can be explained by the pattern design, where the Stripes consist of alternating opaque and transparent elements, presenting higher variability in their performance. In contrast, the No-pattern consists of uniformity, showing consistent performance overall and tending to have slightly lower values of light penetration. The Tree pattern, presenting higher median light penetration compared to the No-pattern and lower than the Striped, demonstrates a balanced scenario between the other two.



(a) Light penetration (b) Vertical illuminance facade

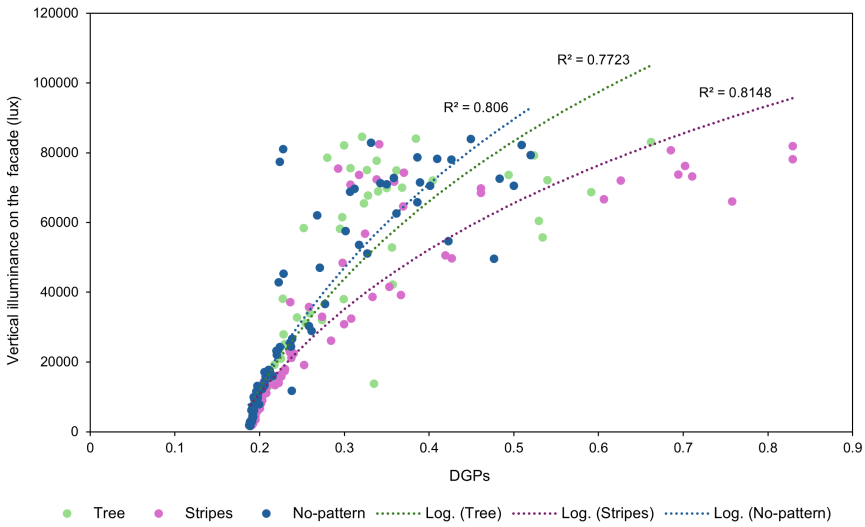
Figure 6.10: Box plots of light penetration in relation to outdoor conditions across pattern scenarios.

Overall, while Stripes may offer the highest mean light penetration, it comes with increased variability. The No-pattern, while consistent, tends to have slightly lower light penetration compared to the other patterns. The Tree pattern provides a good balance between median and mean light penetration with lower variability compared to Stripes. However, nothing can be assumed for the overall performance and efficiency of the patterns.

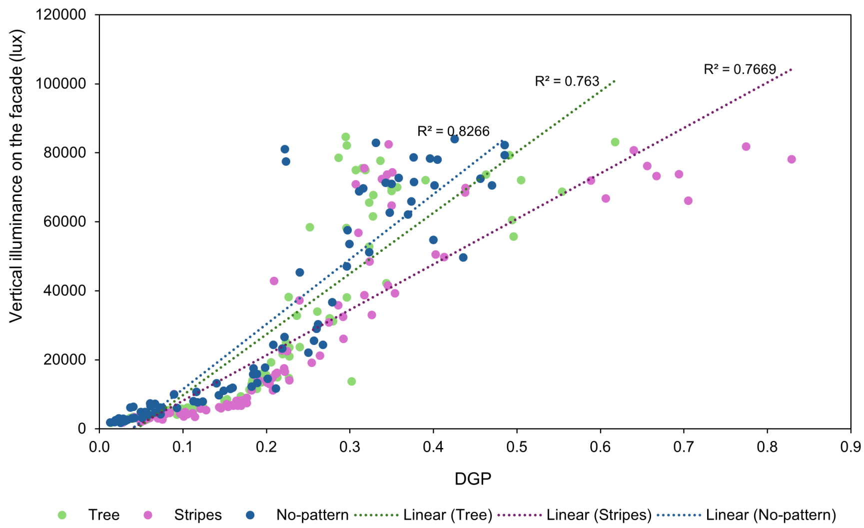
The analysis of vertical illuminance data on the facade further explains the light penetration of each pattern. The Tree exhibits the widest spread of data and greater variability in outdoor lighting levels compared to the other patterns. This suggests that the Tree pattern effectively balances this variability enabling light penetration consistently and potentially creating more even and natural changes in indoor lighting conditions. Conversely, the Striped pattern presents a narrower spread and lower mean and median values, indicating inconsistent and unbalanced light penetration performance, which may be related to the slight increase in the DGP levels. The No-pattern exhibits the highest median vertical illuminance, indicating consistently higher distribution of outdoor lighting levels compared to the other patterns. Its spread is wider than the Stripes explaining its efficiency in balancing higher lighting levels and a bit narrower than the Tree which aligns with the results from the light penetration ratio and indicates the consistent and balanced response of both patterns.

Consequently, each facade pattern exhibits distinct advantages and challenges in terms of performance. Analyzing both indoor and outdoor data provides valuable insights into photometric measurements and the lighting environment. In summary, the Striped pattern demonstrates unpredictable performance due to each design feature, while the No-pattern scenario offers consistent performance but may block more light overall compared to the other patterns. The Tree pattern presents a balanced scenario. Despite exhibiting variability in outdoor conditions, its performance remains consistent, similar to the No-pattern. This allows for a more natural change in light conditions, potentially enhancing the overall lighting environment.

Plotting outdoor light versus DGP or DGPs reveals consistent trends. There is an overall linear or logarithmic relationship between the vertical illuminance on the facade and the DGP. The DGP increases more significantly in the Stripes scenario as vertical illuminance increases, whereas the No-pattern scenario shows higher resistance to glare. The Tree pattern scenario falls between these two conditions. This suggests that the No-pattern scenario performs better in mitigating glare while allowing less light penetration through the facade. Conversely, the Stripes scenario is less effective in controlling glare and can result in uncontrolled light penetration. The Tree pattern scenario effectively manages glare, similar to the No-pattern condition, while allowing a moderate range of light penetration, potentially enhancing the light environment in a more natural manner.



(a) Simplified DGPs



(b) Edited DGP

Figure 6.11: DGP in relation to outdoor conditions.

6.5. Statistical Results

The statistical analysis in this study employed descriptive statistics to summarize key characteristics of the data. Linear mixed models were used to explore the influence of pattern scenarios on each variable. A model was generated for each of the dependent variables. Correlation analysis assessed associations and trends and a regression analysis was also conducted to check the influence of participant characteristics on the ratings. The IBM SPSS Statistics 29 software was used to generate these models (IBM Corporation 2024).

6.5.1. Descriptive statistics for main questions and measurements

Throughout the study, participants experienced a range of light conditions exemplified by variations in DGP. DGP levels tended to be higher on sunny days. However, they were mainly within the imperceptible category (≤ 0.35) for 82% of cases with only 8% within the intolerable category (≥ 0.45). Overall, DGP ranged from 0.02 to 0.80 (M = 0.22, SD = 0.14), while Ev from 52 to 10370 lux (M = 1342 lux, SD = 1912 lux) and Eh from 21 to 6651 lux (M = 1098 lux, SD = 1378 lux). Box plots of Eh and Ev across the pattern scenarios can be seen in Appendix A.19.

The office laboratory, enclosed within the Nonohouse building and separated from the rest of the space by a black curtain, was small in size and lacked operable windows and equipment for regulating temperature and relative humidity. The temperature fluctuated between 18.7 °C and 35.6 °C with a mean of 25.7 °C. Relative humidity ranged from 18.7% to 55.3% with a mean of 40% (see Appendix A.20). The absence of operable windows and limited environmental control in the confined space could have contributed to thermal discomfort, particularly considering the temperature variations. Although thermal discomfort may have arisen in some instances (4% answered hot, 13% warm and 30% slightly warm) no responses were excluded as it is not confirmed whether thermal discomfort influenced the variables under investigation.

Regarding questionnaire responses, there were slight variations and more noticeable ones (Figure 6.12). No significant differences among the scenarios were observed for the perceived satisfaction with daylight amount, color of daylight, and visual comfort. However, there were significant differences in the glare perception, satisfaction with the view, acceptance of its obstruction, pattern, and sunlight pattern aesthetics.

Glare perception and room temperature sensation are outlined separately due to their distinct rating scales (Figure 6.13), (Figure 6.14). As previously mentioned, glare received lower ratings for the Tree pattern than the other two patterns, with variability in ratings noted particularly in the Striped pattern. Regarding temperature, responses across all conditions predominantly fell within the neutral and slightly warm range, with variations skewed towards warmer options. Notably, the mean value for the stripes condition slightly exceeded other conditions.

Table 6.1 shows the mean and standard deviation of questionnaire responses and main physical measurements.

Table 6.1: Descriptive statistics of questionnaire responses and physical measurements.

Variable	**Tree (A)**		**Stripes (B)**		**No-pattern (C)**	
	Mean	SD	Mean	SD	Mean	SD
(Q1) Glare perception	1.5	0.6	1.9	0.9	1.8	0.7
(Q2) Daylight satisfaction	3.6	1.2	3.6	1.2	3.7	1.1
(Q3) Colour of daylight	3.7	1.1	3.5	1.0	3.5	1.0
(Q4) Visual comfort	3.7	1.0	3.3	1.2	3.6	1.1
(Q5) Satisfaction view out	3.4	1.2	3.0	1.1	3.8	1.0
(Q6) Acceptance of obstruction	3.3	1.2	2.7	1.3	3.9	1.2
(Q7) Pattern aesthetics	3.9	1.2	2.6	1.2	3.7	1.1
(Q8) Sunlight pattern aesthetics	3.6	1.0	2.9	1.0	3.2	1.2
(Q9) Room temperature feeling	4.7	0.9	4.8	0.9	4.6	0.8
Vertical illuminance	1251	1687	1626	2422	1150	1490
Horizontal illuminance	1172	1496	1302	1589	820	947
DGP	.21	.13	.25	.17	.20	.13
R.H.	40	8.5	40	8.4	40	8.1
Temperature	25.8	3.8	25.7	3.9	25.7	3.7

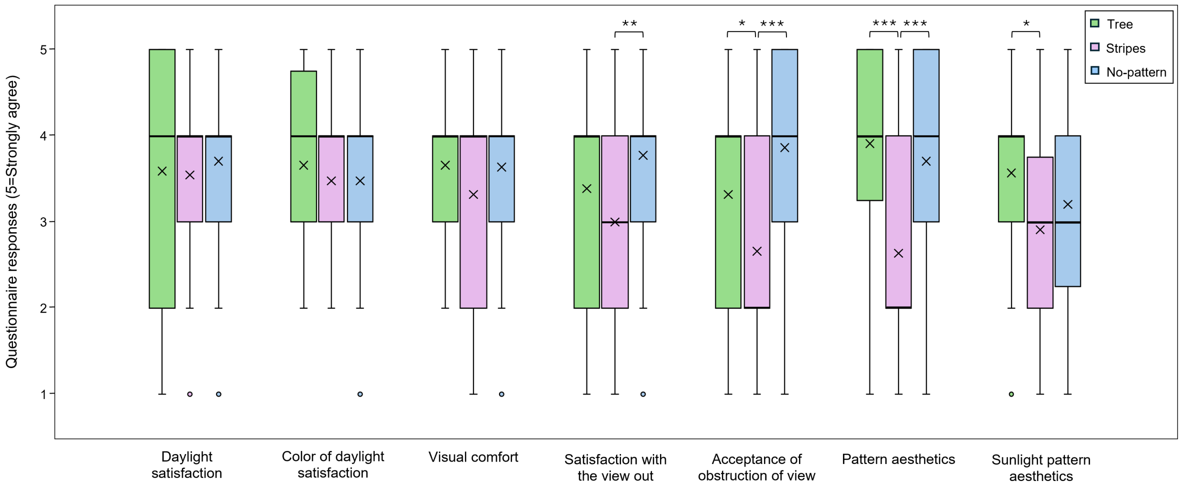
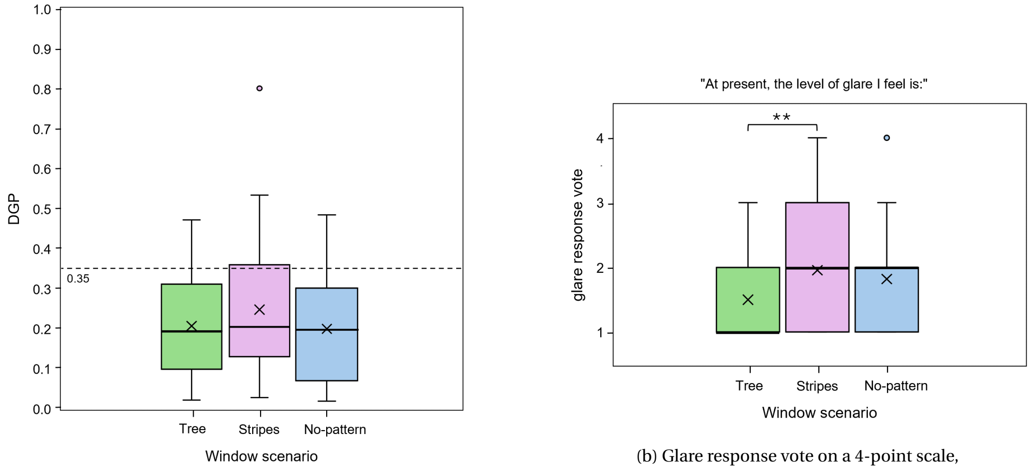


Figure 6.12: Box plot of questionnaire responses on a 5-point scale (5=Strongly agree). The 'x' within each box plot represents the means. The level of significance is as shown: "*" p-value < 0.05; "**" p-value < 0.01; p-value < 0.001.



(a) Glare measurements

(b) Glare response vote on a 4-point scale, 1=imperceptible,2=perceptible, 3=uncomfortable, 4=intolerable

Figure 6.13: Objective and subjective measurements of glare

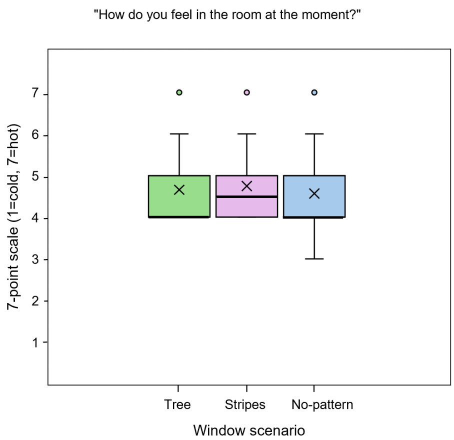


Figure 6.14: Box plot of room temperature perception, 1=cold, 2=cool, 3=slightly cool, 4=neutral, 5=slightly warm, 6=warm, 7=hot.

6.5.2. Influence of different patterns on main questions

Linear Mixed Models (LMM) were utilized to assess occupant perceptions across various factors, including glare perception, daylight satisfaction, color of daylight satisfaction, visual comfort, view out satisfaction, acacceptance of obstruction of view out, pattern and sunlight pattern aesthetics, and room temperature feeling. The fixed variables encompassed window pattern scenarios. The DGP metric and the interaction term window pattern scenario*DGP metric were added for the model with the dependent variable glare perception. The Eh and the interaction term window pattern scenario*Eh were added for the model with dependent variables the daylight satisfaction, color of daylight satisfaction, and visual comfort. The presentation order, although randomized, was checked for significance and excluded from the final model since it did not affect the results. Participant identifier numbers were included as independent random variables to account for individual differences. Post hoc analyses were adjusted using the Bonferroni correction to control for multiple comparisons. Estimated marginal means and standard errors (SE) are reported to convey the direction of results, facilitating comparisons across different conditions while considering data variability.

Glare perception

Significant differences were observed in glare perception among the window pattern conditions [F (2,34.667) = 7.636, p = .002]. Participants reported significantly lower glare votes for the Tree pattern (estimated marginal mean EMM = 1.53, SE = 0.11) compared to the Striped pattern (EMM = 2.06, SE = 0.10) [p = .003]. The Tree pattern also resulted in lower, but marginally not significant, glare votes compared to the No-pattern condition (EMM = 1.88, SE = 0.10) [p = .061]. No significant difference was found between the Striped and the No-pattern condition [p = .637]. Furthermore, a significant effect was found for the DGP metric on glare perception [F (46,42.352) = 2.032, p = .011], indicating that DGP metric is a significant predictor of glare perception. However, the effect of DGP on glare perception is consistent regardless of the window scenario, as the interaction between DGP and window scenario does not significantly differ [F (36,41.846) = .852, p = .686].

Daylight satisfaction

There were no significant differences in daylight satisfaction among the three window scenarios [F (2, 4.000) = 1.214, p = .387]. Similarly, no significant effect of horizontal illuminance on daylight satisfaction was found [F (124, 4.000) = 0.753, p = .737], and the interaction between window scenario and horizontal illuminance also did not significantly affect daylight satisfaction [F (1, 4.000) = 1.286, p = .320]. So, the horizontal illuminance did not predict the daylight satisfaction and there was no difference between the window scenarios.

Color of daylight satisfaction

No significant differences in satisfaction with the color of daylight were detected among the different window scenarios [F (2, 4) = 0.300, p = .756]. Likewise, horizontal illuminance, measured at the workstation, did not significantly influence satisfaction with the color of daylight [F (124, 4) = 0.856, p = .672]. Furthermore, the interaction between window scenario and horizontal illuminance was not significant [F (1, 4) = 0.193, p = .683]. Hence, neither horizontal illuminance nor window scenario significantly predicted satisfaction with the color of daylight.

Visual comfort

No significant differences in visual comfort were observed among the three window scenarios [F (2, 4) = 0.600, p = .592]. Additionally, horizontal illuminance did not have a significant effect on visual comfort [F (124, 4) = 2.024, p = .260]. The interaction between window scenario and horizontal illuminance was also not significant [F (1, 4) = 0.400, p = .561]. Therefore, neither horizontal illuminance nor window scenario significantly predicted visual comfort.

Satisfaction with the view out

The analysis revealed a significant effect of window scenario on satisfaction with the view out ratings [F (2, 86) = 6.928, p = .002]. Pairwise comparisons indicated that participants reported significantly higher satisfaction in the No-pattern (EMM = 3.77, SE = .17) compared to the Striped pattern (EMM = 3.00, SE = .17) [p = .001]. No significant differences were found either between the No-pattern condition and the Tree (EMM = 3.39, SE = .17) [p = .198], or between the Tree and the Stripes [p = .198], with the Tree rated lower than the No-pattern and higher than the Stripes but not with a significant effect.

Acceptance of obstruction of the view out
A significant effect was found in the window scenario regarding the acceptance of obstruction of view ratings [F (2, 86) = 11.224, p < .001]. Pairwise comparisons indicated significant differences between several window scenarios. Participants reported significantly lower ratings in the Striped pattern (EMM = 2.66, SE = .18) compared to both the No-pattern (EMM = 3.86, SE = .18) [p < .001] and the Tree pattern (EMM = 3.32, SE = .18) [p = .034]. However, there was no significant difference in the ratings between the No-pattern and Tree pattern [p = .105], with the former receiving higher but not significantly different ratings from the latter.

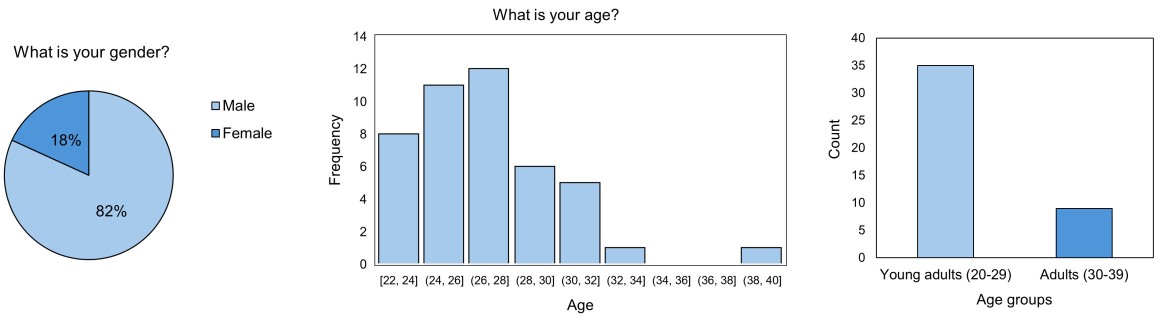
Pattern aesthetics
The analysis revealed a significant effect of window scenario on ratings of pattern aesthetics [F (2, 129) = 14.650, p < .001]. Both the Tree pattern (EMM = 3.91, SE = .18) [p <0.001] and the No-pattern (EMM = 3.71, SE = .18) [p < 0.001] were reported aesthetically more pleasing than the Striped pattern (EMM = 2.64, SE = .18). The Tree pattern was rated more aesthetically pleasing than the No-pattern but without a significant difference [p = 1.000].

Sunlight pattern aesthetics
There was a significant effect of window scenario on ratings of sunlight pattern aesthetics [F (2, 86) = 4.307, p = .016]. Participants rated the Tree scenario (EMM = 3.57, SE = .16) significantly higher in aesthetic appeal compared to the Striped pattern (EMM = 2.91, SE = .16) [p = .013]. However, there were no statistically significant differences between the Tree pattern and No-pattern (EMM = 3.21, SE = .16) [p = .329], nor between the Striped and No-pattern [p = .578].

Room temperature feeling
The analysis showed a marginal effect of window scenario on room temperature ratings, approaching significance [F (2, 86.005) = 2.774, p = .068]. This suggests that there may be some influence of window scenarios on perceived room temperature, although it did not reach conventional levels of statistical significance [p < .05].

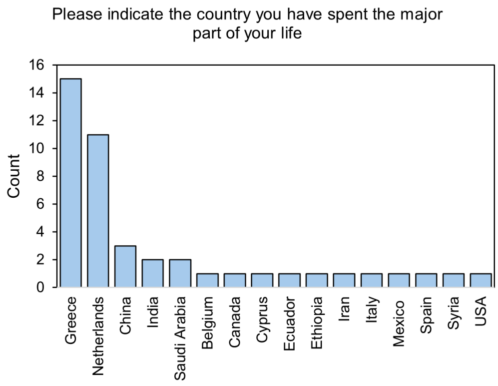
6.5.3. Participants characteristics and influence on glare

General characteristics: Out of the 44 participants who took part in the experiment, the majority were male (n = 36), with a smaller number being female (n = 8). The participants' ages ranged from 22 to 39 years, with a mean age of 27.3 years (SD = 3.2). To facilitate analysis, participants were categorized into two age groups: young adults (20-29 years) and adults (30-39 years). Regarding cultural background, the participants represented a wide range of countries and cities, highlighting the diversity of the sample. The bigger groups were participants came from Greece (n = 15) and the Netherlands (n = 11). Based on the cities associated with their major life experiences, participants were also categorized according to the climate they were familiar with, using the Köppen climate classification (University of Vienna 2024). The distribution of climate familiarity was as follows: tropical (n = 5), dry (n = 6), temperate (n = 33), and continental (n = 1).

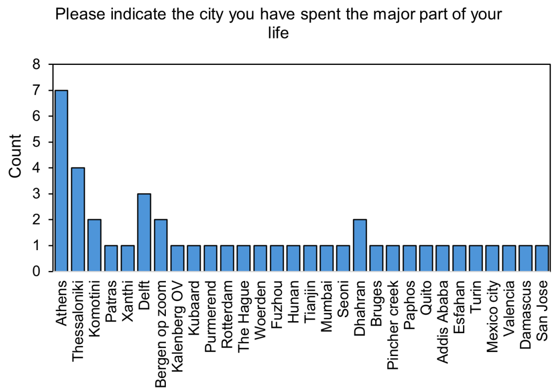


(a) Pie chart of gender (b) Histogram of age frequency (c) Bar graph of age group categorization

Figure 6.15: Gender and age characteristics of participants' sample.



(a) Country



(b) City

Figure 6.16: Bar graphs for cultural background of participnts according to country and city.

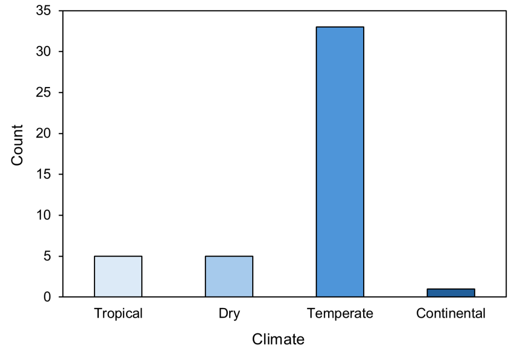
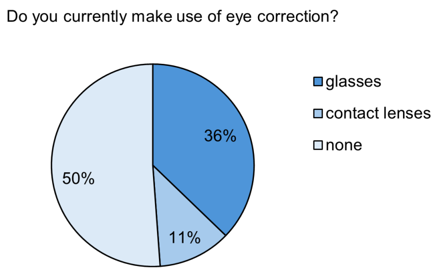
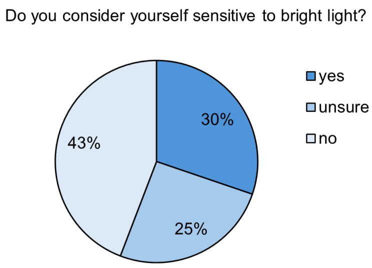


Figure 6.17: Bar graphs for categorizing the cultural background (Köppen climate classification).

Vision characteristics: None of the participants was associated with color blindness. For optical correction, 16 participants were wearing glasses, 5 were using contact lenses, and the remaining 23 did not use any optical correction. Participants were also asked to rate their sensitivity to bright light: 13 considered themselves sensitive, 11 were unsure, and 20 did not consider themselves sensitive.



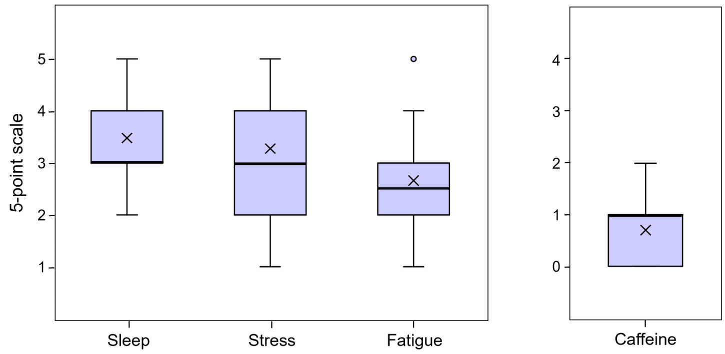
(a) Optical corection



(b) Contrast sensitivity

Figure 6.18: Vision characteristics.

Present state: The present state of the participants was assessed using several measures, including sleep, stress, fatigue, and caffeine consumption. The participants reported their average quality of sleep as 3.48 on a 5-point scale (SD = 0.79). The average stress level was 3.27 (SD = 1.17) on the same scale, indicating a moderate level of stress among participants. Fatigue levels had a mean of 2.66 (SD = 1.06), also measured on a scale from 1 to 5. The average caffeine consumption was relatively low, with a mean of 0.70 cups per day (SD = 0.59).

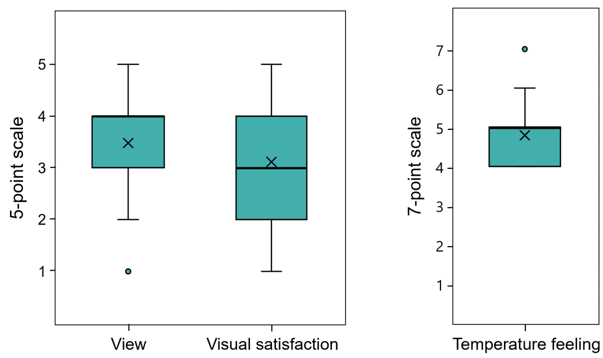


(a) Sleep quality, stress level, and fatigue level in a 1 to 5 point scale.

(b) Caffeine intake in a 0 to 4 point scale.

Figure 6.19: Box plot of questions regarding the present state of the observer.

Experience of the space: Participants were asked to evaluate their experience of the space in terms of temperature feeling, visual satisfaction, and view. The temperature feeling was rated on a scale from 1 to 7, with a mean score of 4.80 (SD = 0.77), indicating that participants generally felt warm with the temperature. Visual satisfaction, rated on a scale from 1 to 5, had a mean score of 3.11 (SD = 0.97), suggesting moderate satisfaction with the visual aspects of the space. The view was also rated on a 1 to 5 scale, with a mean score of 3.48 (SD = 1.07), indicating that participants had a generally positive perception of the view from the space.



(a) View and visual satisfaction in a 5-point scale.

(b) Temperature feeling in a 7-point scale.

Figure 6.20: Box plot of questions regarding the experience of the space.

Influence of observer characteristics on glare perception

According to the literature review on visual comfort and glare, several characteristics related to the observer have been identified to influence glare perception (Figure 3.6). A multiple regression analysis was conducted for each pattern scenario to examine the potential influence of various factors on glare perception: gender, age, cultural background (general characteristics), optical correction, contrast sensitivity (vision characteristics), quality of sleep, stress level, fatigue level, and caffeine intake (present state). Additionally, the DGP was also included to account for the factors related to lighting.

For the Tree scenario, collectively, the factors explained 36.8% of the variance in glare perception R^2 = 0.368, though the adjusted R was lower at 0.123, indicating a modest fit. The model's F-test was not statistically significant [$F(12,31) = 1.503$, p = 0.176], suggesting that, as a group, the predictors did not significantly account for variations in glare perception. Among the individual predictors, DGP was the only significant factor [$\beta = 3.424$, $p = 0.026$], indicating that higher DGP levels are strongly associated with increased glare perception. Other variables did not show significant associations with glare perception [$p > 0.05$].

In Stripes, collectively, the factors explained 47.6% of the variance in glare perception $R = 0.476$, with an adjusted R of 0.273, indicating a moderate fit. The model's F-test was statistically significant [$F(12,31) = 2.348$, $p = 0.028$], suggesting that, as a group, the predictors significantly account for variations in glare perception. Among the individual predictors, DGP was the only significant factor [$\beta = 3.017$, $p = 0.014$], indicat-

Table 6.2: Regression analysis results on the influence of potential predictors of glare perception for Tree pattern scenario.

Variable	B	Std. Error	Beta	t	Sig.
(Constant)	2.529	1.246		2.030	.051
Gender	-0.091	0.258	-0.057	-0.355	.725
Age	-0.405	0.247	-0.263	-1.638	.112
Cultural background climate	0.134	0.143	0.151	0.933	.358
Optical correction	0.015	0.118	0.022	0.124	.902
Contrast sensitivity	0.065	0.117	0.088	0.553	.584
Sleep quality	-0.040	0.148	-0.051	-0.273	.787
Stress level	-0.075	0.090	-0.139	-0.835	.410
Fatigue level	0.002	0.101	0.003	0.017	.986
Caffeine intake	0.161	0.193	0.152	0.836	.410
Satisfaction with the view out	0.047	0.080	0.090	0.585	.563
DGP	3.424	1.466	0.714	2.336	.026*
Temperature	-0.060	0.052	-0.364	-1.156	.257

ing that higher DGP levels are strongly associated with increased glare perception. Other variables did not show significant associations with glare perception [$p > 0.05$].

Table 6.3: Regression analysis results on the influence of potential predictors of glare perception for Striped pattern scenario.

Variable	B	Std. Error	Beta	t	Sig.
(Constant)	4.555	1.547		2.944	.006
Gender	0.121	0.319	0.055	0.379	.708
Age	0.015	0.304	0.007	0.049	.961
Cultural background climate	-0.271	0.180	-0.223	-1.503	.143
Optical correction	-0.214	0.136	-0.233	-1.570	.126
Contrast sensitivity	-0.184	0.144	-0.183	-1.272	.213
Sleep quality	-0.315	0.182	-0.289	-1.729	.094
Stress level	-0.012	0.109	-0.016	-0.109	.914
Fatigue level	-0.130	0.124	-0.160	-1.052	.301
Caffeine intake	0.389	0.243	0.268	1.599	.120
Satisfaction with the view out	-0.133	0.103	-0.176	-1.296	.205
DGP	3.017	1.160	0.584	2.601	.014*
Temperature	-0.017	0.052	-0.078	-0.333	.741

For No-pattern, collectively, the factors explained 44.2% of the variance in glare perception $R = 0.442$, with an adjusted R of 0.226, indicating a moderate fit. The model's F-test was marginally non-significant [$F(12,31) = 2.047$, $p = 0.054$], suggesting that, as a group, the predictors approached but did not achieve statistical significance in accounting for variations in glare perception. Among the individual predictors, DGP [$\beta = 3.606$, $p = 0.029$] and stress [$\beta = -0.249$, $p = 0.010$] were significant factors. Higher DGP levels were strongly associated with increased glare perception, while higher stress levels were associated with decreased glare perception. Other variables did not show significant associations with glare perception [$p > 0.05$].

Overall, the investigation into various potential factors influencing glare perception in this study revealed non-significant effects for the majority of predictors, except for DGP in all the pattern scenarios and stress levels in No-pattern. These findings highlight the nuanced impact of lighting and psychological factors on glare perception. Some results are consistent with prior research, particularly for factors like gender and optical correction, which showed negligible influence, or DGP showed significance in all cases. However, other factors categorized as potentially influential or inconclusive did not demonstrate significant effects in this study.

Overall, a significant result on DGP in all cases was expected according to the literature review on glare factors. The fact that higher results on DGP led to increased glare perception suggests that participants were capable of perceiving the glare scale of the experiment in all cases. Regarding the findings on the negative association of stress level for the No-pattern case, the experimental design does not allow to indicate whether

Table 6.4: Regression analysis results on the influence of potential predictors of glare perception for No-pattern scenario.

Variable	B	Std. Error	Beta	t	Sig.
(Constant)	3.700	1.214		3.048	.005
Gender	-0.334	0.269	-0.189	-1.241	.224
Age	-0.241	0.253	-0.142	-0.955	.347
Cultural background climate	0.028	0.154	0.029	0.181	.857
Optical correction	0.026	0.122	0.036	0.217	.830
Contrast sensitivity	0.013	0.121	0.016	0.107	.916
Sleep quality	0.153	0.153	0.175	0.997	.326
Stress level	-0.249	0.090	-0.420	-2.755	.010*
Fatigue level	0.051	0.104	0.077	0.487	.630
Caffeine intake	0.058	0.203	0.049	0.284	.779
Satisfaction view out	-0.019	0.099	-0.028	-0.195	.846
DGP	3.606	1.574	0.679	2.290	.029*
Temperature	-0.073	0.059	-0.396	-1.244	.223

higher stress levels can be associated with a decrease in glare perception.

6.5.4. Relationship between visual comfort and aesthetic considerations

From the literature review, it was found that there is a potential relationship between visual comfort and aesthetics. A correlation analysis was conducted testing the following hypothesis:

- There is a significant relationship between visual comfort and aesthetic consideration, particularly concerning pattern aesthetics and sunlight pattern aesthetics.

The correlation analysis revealed intriguing findings regarding the relationship between visual comfort and aesthetic considerations. A moderate positive correlation was observed between visual comfort and pattern aesthetics [Pearson's r = 0.439, $p < 0.01$]. This indicates that as visual comfort increases, so does the perceived aesthetic appeal of patterns in the environment. Similarly, a weak to moderate positive correlation was found between visual comfort and sunlight pattern aesthetics [Pearson's r = 0.383, $p < 0.01$], indicating that better visual comfort is linked to an increased appreciation of sunlight-specific patterns.

Table 6.5: Pearson correlation between main questionnaire.

Variables	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
Q1 Glare assessment	1	0.067	0.002	-0.371	-0.084	-0.117	-0.215	-0.156	0.298
Sig. (2-tailed)		0.443	0.981	< 0.001*	0.336	0.182	0.013*	< 0.001*	
Q2 Daylight satisfaction	0.067	1	0.432	0.294	0.274	0.307	0.236	0.132	0.098
Sig. (2-tailed)			< 0.001*	< 0.001*	0.001*	< 0.001*	0.007*	0.132	0.264
Q3 Colour of daylight	0.002	0.432	1	0.329	0.335	0.187	0.325	0.283	0.105
Sig. (2-tailed)		< 0.001*		< 0.001*	< 0.001*	0.032*	< 0.001*	< 0.001*	0.230
Q4 Visual comfort	-0.371	0.294	0.329	1	0.424	0.258	0.439	0.383	0.034
Sig. (2-tailed)	< 0.001*	< 0.001*	< 0.001*		< 0.001*	0.003*	< 0.001*	< 0.001*	0.701
Q5 Satisfaction view out	-0.084	0.274	0.335	0.424	1	0.474	0.470	0.391	0.034
Sig. (2-tailed)	0.336	< 0.001*	< 0.001*	< 0.001*		< 0.001*	< 0.001*	< 0.001*	0.700
Q6 Obstruction view out	-0.117	0.307	0.187	0.258	0.474	1	0.466	0.175	-0.057
Sig. (2-tailed)	0.182	< 0.001*	0.032*	0.003*	< 0.001*		< 0.001*	0.044*	0.513
Q7 Pattern aesthetics	-0.215	0.236	0.325	0.439	0.470	0.466	1	0.439	-0.050
Sig. (2-tailed)	0.013*	0.007*	< 0.001*	< 0.001*	< 0.001*	< 0.001*		< 0.001*	0.571
Q8 Sunlight pattern aesthetics	-0.156	0.132	0.283	0.383	0.391	0.175	0.439	1	0.109
Sig. (2-tailed)	0.074	0.132	< 0.001*	< 0.001*	< 0.001*	0.044*	< 0.001*		0.215
Q9 Room temperature	0.298	0.098	0.105	0.034	0.034	-0.057	-0.050	0.109	1
Sig. (2-tailed)	< 0.001*	0.264	0.230	0.701	0.700	0.513	0.571	0.215	

When examining the specific pattern conditions in additional models, the correlation analysis showed the following: For the Tree pattern condition, there was a significant moderate positive correlation between visual comfort and pattern aesthetics [Pearson's r = 0.397, $p < 0.01$]. For the Striped pattern condition, a significant strong positive correlation was found [Pearson's r = 0.574, $p < 0.01$]. In the No-pattern condition, a positive but not significant correlation was also observed [Pearson's r = 0.369, $p < 0.05$]. Sunlight pattern aesthetics exhibited similar trends with significant positive associations for the Tree [Pearson's r = 0.373, $p = 0.013$] and the Stripes [Pearson's r = 0.471, $p = 0.001$], and a positive but non-significant result for the No-pattern [Pearson's r = 0.283, $p = 0.063$]. These results suggest that there is a consistent relationship between visual comfort and the aesthetic appreciation of patterns across different pattern conditions. Moreover, if these findings are compared with the mean values of the questions regarding the ratings of visual comfort and pattern aesthetics (Table 6.1) the high mean ratings for Tree pattern and No-pattern, combined with their positive correlations, imply that these patterns likely enhance visual comfort, which in turn increases their aesthetic appeal. Conversely, in Stripes, improving visual comfort could enhance the perceived aesthetic value of the pattern.

The correlation analysis was conducted on all the main questions (Table 6.5). Additional insight provides the relationship of these aspects with glare. Higher levels of glare negatively impact visual comfort and both pattern aesthetics [Pearson's r = -0.215, $p = 0.013$] and sunlight pattern aesthetics [Pearson's r = -0.156, $p < 0.001$], indicating the importance of overall aesthetic satisfaction for mitigating glare even though the correlation is relatively weak. By inspecting again each pattern separately, a significant effect appears only in Stripes, where as glare perception increases, the perceived aesthetics of the Striped pattern decrease [Pearson's r = -0.414, $p = 0.005$].

These findings support the initial hypothesis and highlight the interconnections of visual comfort and aesthetic perceptions. The moderate negative correlations observed between glare and both pattern aesthetics and sunlight pattern aesthetics, along with the positive correlations between visual comfort and aesthetic measures, emphasize the role of the overall aesthetic experience in shaping comfort perceptions within an environment. However, it is important to interpret these results as indicative rather than causal. Further experimental research is needed to explore the underlying mechanisms and causal relationships.

6.5.5. Pattern obstruction

The coverage and transparency levels of each pattern varied, impacting the degree of view obstruction (see Figure 6.21). During pattern generation, coverage was calculated relative to the total window area, resulting in 75% coverage for the Tree pattern, 50% for Stripes, and 100% for No-pattern, considering the threshold of 53% of the average total transparency. However, the presence of monitors obstructs portions of the window and, consequently, the outside view. To address this, pattern presence percentages on the facade were calculated, excluding areas covered by monitors. These percentages were derived from a fisheye image representing the observer's field of view, resulting in slight distortion in the images. While actual perception may vary slightly, this method facilitates comparisons between patterns. It's important to note that the VideowindoW product's layers introduce a slight tint and reduce window clarity, adding complexity to the issue of obstruction.

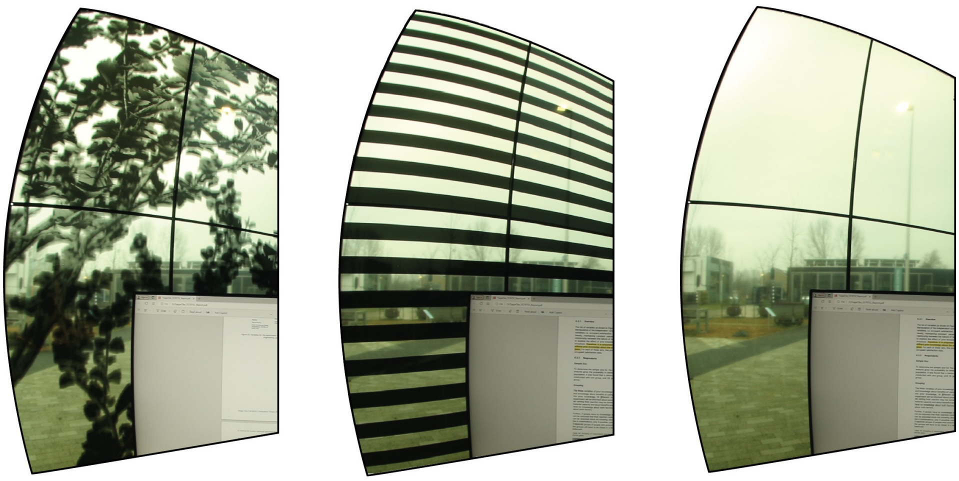


Figure 6.21: Pattern as obstruction of view out from fish-eye lens pictures for the tree (left), stripes (middle), no-pattern (right).

The percentages representing pattern coverage of the outside view for each pattern are presented in Table 6.6 and visually depicted in Figure 6.22. The view, as indicated by the No-pattern coverage, is primarily of the sky, with some building elements, pavement features, and sparse vegetation present in the scene. Comparing the coverage of the Tree and Stripes patterns, it's evident that the Tree pattern, as anticipated, has a higher overall coverage, primarily obstructing the sky.

Table 6.6: Coverage analysis of different patterns (excluding the area covered by the monitor)

Category	Tree	Stripes	No-pattern (whole view)
Sky	40%	30%	63%
Building elements	6%	6%	11%
Pavement	9%	8%	19%
Trees	4%	3%	7%
Total pattern coverage	58%	47%	100%

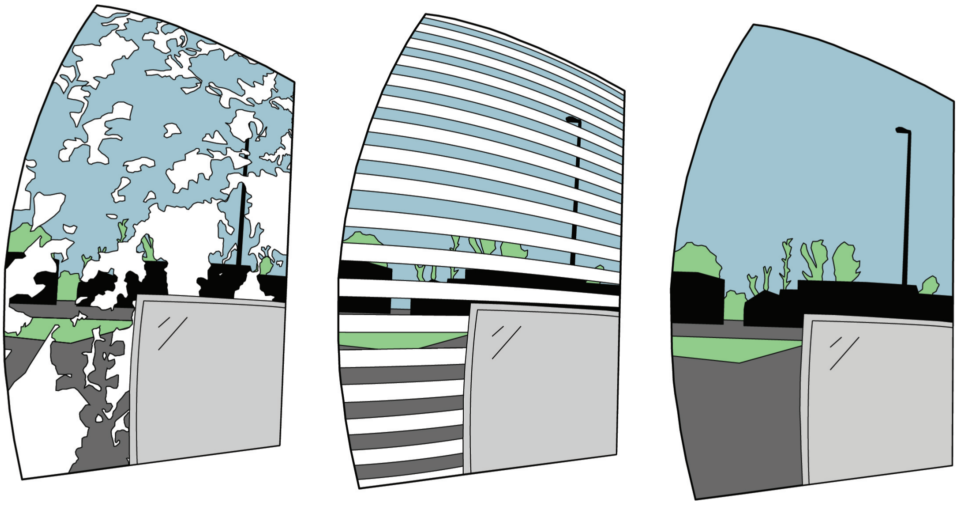


Figure 6.22: Obstruction parts of view out.

Despite the No-pattern having a 100% coverage theoretically, its high transparency results in lower perceived obstruction. Furthermore, even if the Stripes have an overall lower obstruction of view out from the Tree pattern, the acceptance of obstruction of the view out was significantly higher for the Tree as aforementioned in the statistical analysis. This suggests that transparency plays a crucial role in how occupants perceive view obstruction and even complete coverage can be acceptable if the transparency is high enough.

Influence of pattern scenario on satisfaction with the view out
Descriptive statistics and paired-sample t-tests identified significant differences between the clear view ratings and the satisfaction with the view. The aim was to inspect how the different scenarios influenced the satisfaction with the initial clear view.

One model was developed to assess statistically the influence of the differences regarding satisfaction with the view out for each pattern. The descriptive statistics for the satisfaction with the view and the initial clear view rating can be seen below in Table 6.7. The paired-sample t-tests identify the significance by comparing each pattern with the clear view and can be seen in Table 6.8.

Table 6.7: Descriptive statistics for satisfaction ratings across different conditions.

Condition	Mean Satisfaction	Std. Deviation
Clear View	3.48	1.07
Tree Pattern	3.39	1.21
Striped Pattern	3.00	1.14
No-Pattern	3.77	1.01

Table 6.8: Paired-samples t-tests for satisfaction with the view ratings.

Comparison	Mean Difference	t-value	p-value
Clear View vs. Tree	0.091	0.550	0.585
Clear View vs. Stripes	0.477	2.226	0.031*
Clear View vs. No-pattern	-0.295	-1.671	0.102

Regarding the view satisfaction with and without the pattern presence, participants reported significantly lower satisfaction when viewing through a window with a Striped pattern compared to a clear view [$t = 2.226$, $p = 0.031$]. Other patterns included the Tree [$t = 0.550$, $p = 0.585$] and the No-pattern [$t = -1.671$, $p = 0.102$] did not significantly alter satisfaction ratings. The Cohen's d effect size of 0.336 indicates a small to moderate effect for the decrease in satisfaction when viewing through the Striped pattern compared to a clear window.

Overall, participants' satisfaction with the view when a tree pattern or no-pattern condition was present did not differ significantly from their satisfaction with a clear view. In contrast, the striped pattern significantly reduced participants' satisfaction compared to a clear view, suggesting a negative effect on view satisfaction. Therefore, the implementation of biophilic patterns, such as the tree pattern, is unlikely to detract from the perceived quality of the view compared to clear windows. These findings support the application of biophilic design elements in architectural settings, as they can enhance the aesthetic and psychological benefits of indoor environments without compromising visual satisfaction. The use of natural patterns in window designs holds potential for improving occupant well-being while maintaining high levels of satisfaction with the external view.

In addition to assessing the impact of the pattern presence on satisfaction with the view outside and acceptance of obstructions, the role of various environmental parameters in shaping occupants' perceptions is explored. In the previous section, a correlation analysis for the main questions was conducted (Table 6.5). This investigated also the relationship between these parameters and participants' responses regarding satisfaction with the view outside (Q5) and acceptance of obstructions in the view outside (Q6). The findings reveal various correlations for the two questions:

- **Satisfaction with the view out:** Daylight satisfaction [$r = 0.274$, $p < 0.001$], colour of daylight [$r = 0.335$, $p < 0.001$], visual comfort [$r = 0.424$, $p < 0.001$], and pattern aesthetics [$r = 0.474$, $p < 0.001$] showed significant positive correlations. This suggests that higher levels of satisfaction with daylight, preferences for daylight colour, visual comfort, and aesthetic preferences for patterns are associated with greater satisfaction with the view outside.

- **Acceptance of obstruction of view out:** Daylight satisfaction [$r = 0.307$, $p < 0.001$], colour of daylight [$r = 0.187$, $p = 0.032$], visual comfort [$r = 0.258$, $p = 0.003$], satisfaction view out [$r = 0.474$, $p < 0.0014$], and pattern aesthetics [$r = 0.466$, $p < 0.001$] exhibited significant correlations with obstruction view out. These results indicate that higher levels of satisfaction with daylight, preferences for daylight colour, visual comfort, satisfaction with the view outside, and aesthetic preferences for patterns are associated with greater acceptance of obstructions in the view outside.

These correlation findings provide valuable additional evidence, highlighting the multifaceted nature of occupants' perceptions of the view outside and the role of various environmental parameters in shaping their satisfaction and acceptance. However, it is important to remember that correlation does not imply causation. Therefore, these results should be interpreted as indicative of potential relationships rather than definitive proof of causal links..

6.6. Psychological effects and preferences regarding biophilia

The study aimed to assess preferences associated with three facade pattern scenarios: Tree, Stripes, and No-pattern. Participants initially indicated their favorite pattern. The study explored whether a biophilic design, specifically the Tree pattern, is preferred over non-biophilic designs. Subsequently, additional questions were introduced to delve into the psychological effects and perceived connection to nature provided by each pattern. The focus was on understanding how these patterns influence psychological states related to biophilia and related theories, such as a sense of calm, relaxation, stress reduction, mental fatigue recovery, improved productivity, fascination, and overall preference.

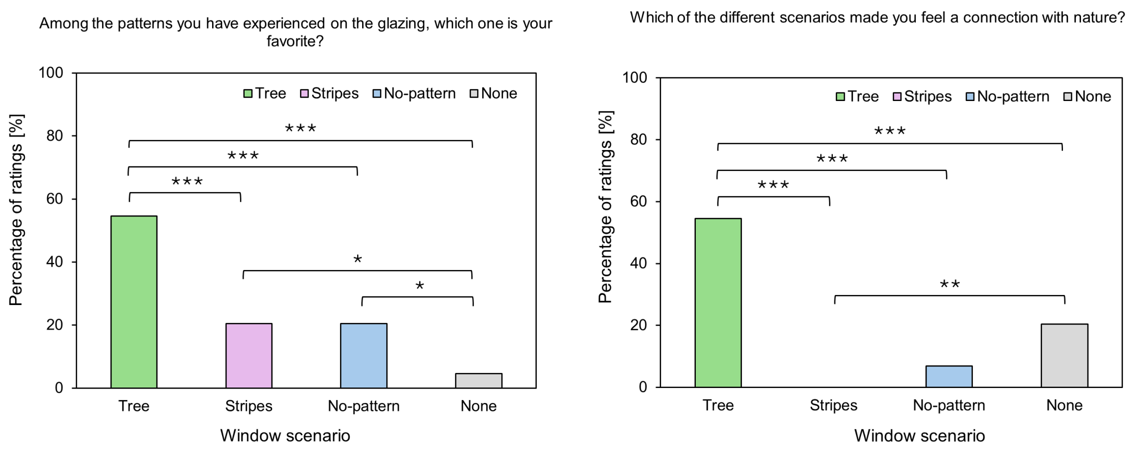
The initial question about favorite facade patterns revealed that the Tree pattern was the most preferred, with 55% of participants selecting it as their favorite (Figure 6.23a). This preference for the Tree pattern underscores a natural affinity towards biophilic designs. The rest of the patterns were represented by 20% each for the Stripes and the No-pattern conditions. A small percentage of 5% selected None, a scenario that was not included as stimuli, but included in the procedure for the introduction and the closure part, when this question was answered.

A Chi-Square Goodness-of-Fit test was conducted to determine if the observed pattern preferences were significantly different from what would be expected by chance. The results were significant, $\chi^2(3, N = 44) = 23.455, p < 0.001$, indicating a strong preference for the Tree pattern compared to the other options. Additional two proportion z-test calculations revealed pairwise comparisons (StatsKingdom 2024). The Tree was significantly preferred when compared with all the other options [$p < 0.001$], and the Stripes and No-pattern were significantly preferred over the None option [$p < 0.023$].

Regarding the sense of connection to nature (answered by 36 participants, 82% of total sample), 67% of participants identified the Tree pattern as the scenario that best enabled this connection (Figure 6.23b). This strong association between the Tree pattern and a sense of nature further supports the preference for biophilic designs.

A Chi-Square Goodness-of-Fit test confirmed the significant preference for the Tree pattern in this context as well, $\chi^2(2, N = 36) = 19.500, p < 0.001$. Additional two proportion z-test calculations revealed pairwise comparisons (StatsKingdom 2024). The Tree again was significantly chosen among all the options [$p < 0.001$] and the None option was significantly rated higher compared with the Stripes, which gathered no votes [$p < 0.001$].

It is worth mentioning that the Stripes were not associated with a connection with nature at all and that the option of None of the patterns collected 25% of the total responses. This could be also associated with the connection with the view outside and the access to the real environment on the surroundings through the window, which also represents a biophilic design implementation. The No-pattern was selected by 8% of the answers, which can be attributed to the fact that in comparison with the rest of the patterns, its design was uniform and its obstruction overall not present, as the changes were mainly at the clarity of the view. Also, in all cases, it was selected by subjects who rated the Striped pattern as their favorite. Their answer on No-pattern instead of None may be driven by their preference of selecting one of the stimuli and not indicating a lack of preference or they may not have found the None option relevant.



(a) Pattern reference

(b) Pattern that enables connection with nature

Figure 6.23: Bar graphs of percentages of occupants responses for pattern preference and pattern that enabled connection with nature.

Figure 6.24 illustrates the responses that were collected for each pattern related to the psychological and emotional state of the participants. The question was asked while the participants were still exposed to each pattern. The Tree pattern enhanced participants' psychological well-being, evidenced by the highest number of responses for the sense of calm and relaxation, reduction of stress, and fascination. No pattern scenario also showed considerable positive effects, particularly in the sense of calm and relaxation however it did not exceed the number of ratings for the other two patterns. The Striped pattern gathered the majority of the answers regarding improved productivity and a few votes for other options. It is worth mentioning that the answer to the current question could be in some cases biased since all the options were mainly positive characteristics and the other option was not generally preferred. Despite the potential bias in the response options towards positive characteristics, the Tree pattern gathered the majority of votes overall.

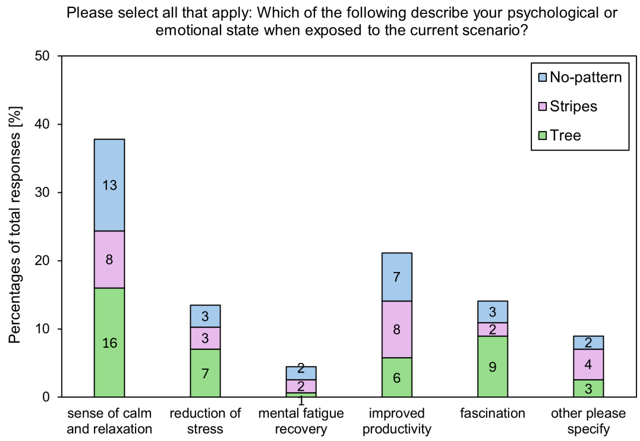


Figure 6.24: Stacked bar graph of percentages regarding the psychological state associated with the pattern scenarios.

In addition to the predefined options related to biophilic design, participants were provided with an "other" option, allowing them to specify their responses. Analysis of these responses revealed additional insights into participants' experiences with each pattern. For the Tree pattern, a few participants reported experiencing slight discomfort (n = 1) or distraction (n = 1). Feedback concerning the Striped pattern included some participants likening it to a prison-like environment (n = 2). Additionally, individual responses indicated feelings of sleepiness (n = 1) and fatigue-discomfort (n = 1). Discomfort (n = 1) was also associated with the No-pattern condition, along with reports of visual discomfort (n = 1). One participant expressed feeling prevented from looking outside due to the design's characteristics. Interestingly, one participant associated a "normal" feeling with all options, and another participant reported feeling "normal" specifically in response to the Tree pattern.

In conclusion, this study sheds light on the intricate relationship between facade patterns, psychological states, and preferences, particularly in the context of biophilic design. The findings underscore the strong preference for the Tree pattern, not only for its aesthetic appeal but also for its ability to evoke a sense of connection to nature. Moreover, the observed psychological effects highlight the importance of considering biophilic elements in architectural design to promote well-being and positive emotional experiences among occupants.

Additional feedback from comments

In the closure questionnaire, the participants were asked to rate their favorite scenario. The last part was open for comments, where they justified their option and provided both positive and negative opinions from their experience (Appendix A.21, A.22). Below, is a summarized part of the main aspects reported.

Tree pattern

- Positive feedback
  The tree pattern was correlated with several positive aspects regarding its natural and aesthetic appeal, its effective light diffusion, and its connection with nature. Many participants appreciated the tree pattern for its natural, interesting and attractive look, creating a calming and relaxing environment. Moreover, subjects reported that the tree pattern effectively reduced glare while providing a balanced amount of natural light, creating shadows or gradient light with variations across the room and the furniture and thus creating a cozy and visually comfortable workspace. At the same time, they stated that it made the space feel warmer without being uncomfortable. The pattern geometry combined with irregular and organic features were praised for enhancing a connection with nature, mimicking the outdoor space, and creating a spacious feeling as stated by some participants. The effect of privacy was also stated as a positive effect from one participant.

- Mixed or negative feedback
The comments for the tree pattern varied in some cases regarding the obstruction of view or the resolution of the outcome on the window. Regarding the obstruction of the view out, many responses stated that it does not affect the outdoor view and the situation is balanced, while some others felt that the tree pattern obstructed the outside view more than they liked. At the same time, there were comments related to the pixelization and blurry effects reducing the clarity of the window. This effect was also linked with the artificial design of the tree. A level of distraction was also stated.

Striped pattern

- Positive feedback
The Striped pattern was justified as a preferred scenario due to the balanced lighting environment suitable to the office activity and for each aesthetic and practical appeal. It was appreciated for providing a good balance of light inside the room without causing excessive glare. Many subjects felt that it allowed them to maintain a good view of the outside while minimizing distractions and providing a sense of order, making it easier to focus on tasks. Furthermore, the stripes were linked to the conventional window blinds, which felt more familiar and normal to some participants, reducing the amount of sunlight in a manageable way.

- Mixed or negative feedback
The striped pattern was criticized for being visually uncomfortable and obstructive, lacking a natural feel, and darkening the room. The pattern was described as "strict" and obstructive, creating a sense of being in a confined or jail-like environment. In addition, it was perceived as too geometric and artificial, failing to provide the calming effect some users sought. Even if the impact on room brightness was positively stated, participants mentioned that it created a feeling of coldness and reduced the amount of daylight, making the room feel less inviting, which was also associated at some cases with the cloudy weather.

No-pattern

- Positive feedback
The No-pattern was associated with a balanced lighting environment, with more simplicity and less distraction, and with an unobstructed view outside. This option was noted for allowing more sunlight to enter the room, making it brighter more inviting, comfortable for working. Participants also appreciated the ability to see outside clearly without any artificial obstructions, maintaining a connection with the outdoor space. What is more, it was considered less distracting and more conducive to concentration, especially in professional settings.

- Mixed or negative feedback
The No-pattern condition was associated with mixed feedback regarding, glare and light intensity and the perceived atmosphere of the space. More specifically, some participants commented that glare situations were more present with this option. Moreover, mainly on cloudy days, it was perceived as a 'cold' and less inviting environment.

None

- Overall feedback
The None option was included to avoid biased answers for the three scenarios tested. The participants were exposed to this additional scenario at the beginning and at the end of the sessio, when they filled this part of the survey. In general, it was associated with increased daylight and higher availability of view outside.

6.7. Conclusions

In conclusion, the comprehensive analysis of objective and subjective data related to occupant perception among the facade patterns yields valuable insights into implications and design.

Objective measurements of Daylight Glare Probability (DGP) revealed consistently low levels of discomfort glare across all facade patterns, predominantly falling within the imperceptible category. Such findings, albeit influenced by prevailing weather conditions, suggest further exploration under more glare occurrences. Subsequently, subjective evaluations from participant questionnaires revealed variations in perceived glare levels across different patterns, with the Stripes pattern eliciting higher levels of discomfort compared to the Tree and No-pattern conditions. While participants demonstrated heightened sensitivity to subtle glare differences, their perceptions generally aligned with objective measurements in terms of imperceptibility or binary categorization, thus indicating a heightened sensitivity in identifying two distinct scenarios: glare and its absence.

Participants' characteristics were evaluated for their influence on glare along with the DGP measurements. DGP was a predictor of glare perception as expected for all pattern cases. A negative association was found with stress in the No-pattern scenario, however, nothing can be indicated regarding high stress being associated with less glare perceived.

Furthermore, the assessment of light penetration elucidated distinct advantages and challenges for each facade pattern. The Striped pattern demonstrated unpredictable performance due to its design features, enabling more light penetration even if outdoor data were presented with lower lighting conditions. Moreover, the No-pattern offered consistent performance, blocking more light penetration. The Tree pattern provided a balanced scenario, managing glare while allowing moderate light penetration consistently.

Statistical analyses underscored the consequential impact of facade patterns on various aspects of user experience, encompassing glare perception, satisfaction with outdoor views and associated obstructions, and pattern and sunlight pattern aesthetics and overall preferences. Noteworthy differences emerged between the pattern scenarios, particularly in glare perception, wherein the Tree pattern garnered significantly lower glare perception. Similarly, satisfaction with outdoor views was noticeably inferior in the No-pattern compared to the Stripes. The acceptance of obstruction was higher in the Tree and No-pattern compared to the Stripes. Aesthetically, both the Tree and the No-pattern were rated as more pleasing than the Stripes on a significant level and the Tree was also rated significantly higher regarding sunlight pattern aesthetics.

Psychological effects and preferences regarding biophilic patterns revealed nuanced responses among participants. The Tree pattern was associated with the majority of psychological effects as a total compared with the other patterns, especially regarding the sense of calm and relaxation. Additionally, it received positive feedback for its natural appeal with organic features and glare-reducing properties, creating a balanced lighting environment with natural light and shadow variations. However, it received criticism for the resolution and the obstruction of view. Similarly, the Stripes was commended for its suitability related to office activity, minimizing distraction and improving productivity but faced criticism for its geometric design and artificial feel and again for the view obstruction. Conversely, the No-pattern condition was favored for its unobstructed view and brightness but received feedback regarding increased glare situations.

Overall, more than half of the participants rated the Tree pattern as their favorite scenario and almost two-thirds associated it with a connection with nature, underscoring the biophilic impact on preferences and its potential to improve the perception of the architectural space..

7

Pattern design and Application

Incorporating biophilic patterns into building facades has been shown to significantly enhance occupants' glare tolerance and overall visual satisfaction. By exploiting these findings, the design of office spaces can be optimized to improve both visual comfort and aesthetic appeal. This chapter outlines the application of biophilic patterns in office environments and the generation of custom patterns to meet varying user preferences.

7.1. Pattern generation

To implement biophilic patterns effectively, it is essential to consider the diverse needs and preferences of office occupants. The following scenarios have been developed to address different conditions of glare and view preferences (Figure 7.1, Figure 7.2):

1. **Enhanced biophilic pattern for glare protection:** This scenario accounts for providing the necessary glare protection using a biophilic pattern when the outside view is not preferred over the pattern presence. Since the tree was praised for its control and natural variation of lighting conditions, tree branches and leaves with varying transparency levels are used to create light variations that mimic natural lighting. This pattern covers a significant portion of the window, providing a strong biophilic element and enhancing the visual appeal of the facade while effectively reducing glare.

2. **Minimal biophilic pattern with inverted shading:** In this case it is important to maintain a connection to the outside view while providing glare protection when the view is preferred over a pattern presence. A minimal presence of tree branches is combined as an inversion of a pattern (shaded and darker background), reducing opacity but allowing some natural light, ensuring that the view out is still visible, while still benefiting from glare reduction, thus preserving visual comfort with a biophilic pattern presence without completely obstructing the view.

3. **Biophilic pattern for non-glare conditions:** This option includes maintaining a biophilic presence without obstructing the view when there is no glare present. Sparse branches and leaves are strategically placed to enhance the aesthetic without significant shading. The pattern maintains high transparency overall, ensuring a clear view outside. The subtle biophilic effect enhances the visual appeal of the space without significantly affecting the view, promoting a connection to nature even without glare.

In all three scenarios, the same pattern base can be adjusted for each occasion. A key aspect of the pattern application is its user-centric design, where the occupant plays a central role in selecting the most suitable pattern scenario according to their preferences. This approach ensures that the design is tailored to meet individual needs, enhancing both satisfaction and comfort.

The dynamic nature of the product itself offers quick adjustments and exposure to multiple patterns with a significant degree of freedom. The pattern generation proposed combines the results of the patterns tested in this study, maintaining the tree presence, which was the favorite scenario, and providing alternatives in terms of the pattern's transparency and density to deal with glare and the desired view. The No-pattern and

Tree scenarios are combined to produce the inverted example. More clear geometries and shapes are selected to address the drawbacks of the tree pattern performance, aiming for less distraction and better concentration, unlike the strict pattern like the striped one tested.

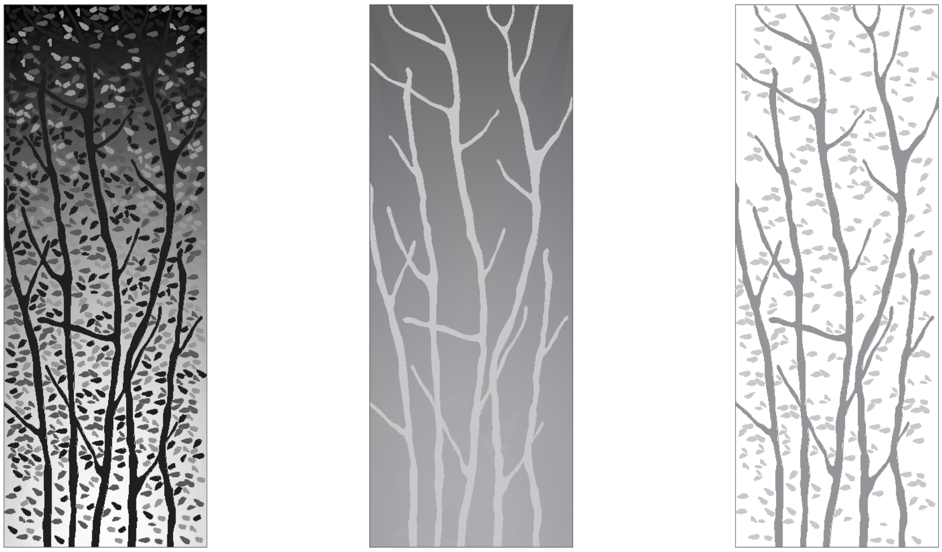


Figure 7.1: Pattern scenarios, the different shading values represent the level of transparency: enhanced biophilic pattern for glare protection (left), minimal biophilic pattern with inverted shading to maintain the outdoor view (middle), biophilic pattern for non-glare conditions (right).

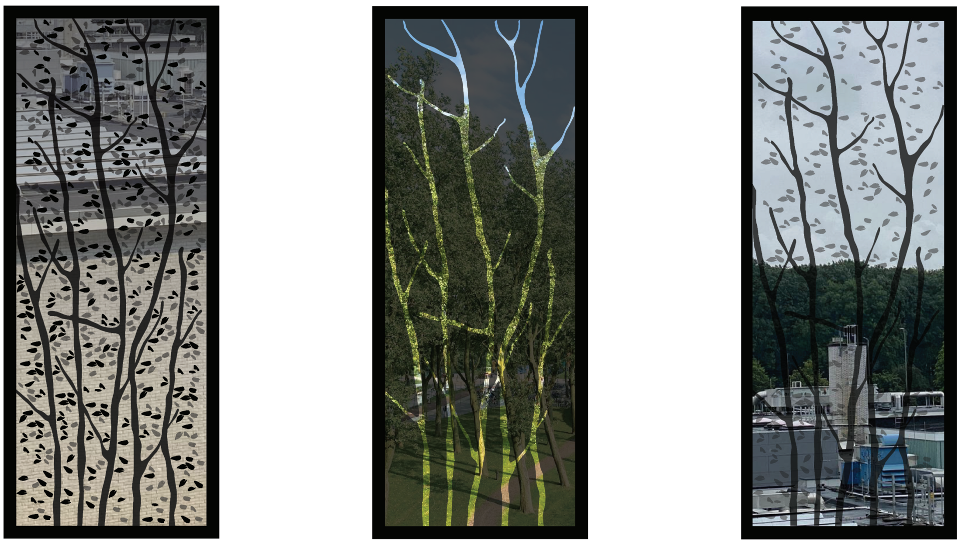


Figure 7.2: Pattern scenarios in different types of view, pattern as intentional obstruction of the outdoor view without interest (left), pattern as glare protection while maintaining the outdoor view (middle), distinctive preference for maintaining the view when glare is not priority (right)

7.2. Challenges in Glare Prevention

Implementing biophilic patterns to mitigate glare presents several challenges, especially in office environments where occupants are positioned differently. Glare perception can vary significantly based on factors such as desk orientation, proximity to windows, and individual sensitivity to light (Figure 7.4). These varia-

Figure 7.3: The different pattern scenarios in the office environments.

tions make it difficult to ensure uniform glare prevention for everyone within the workspace.

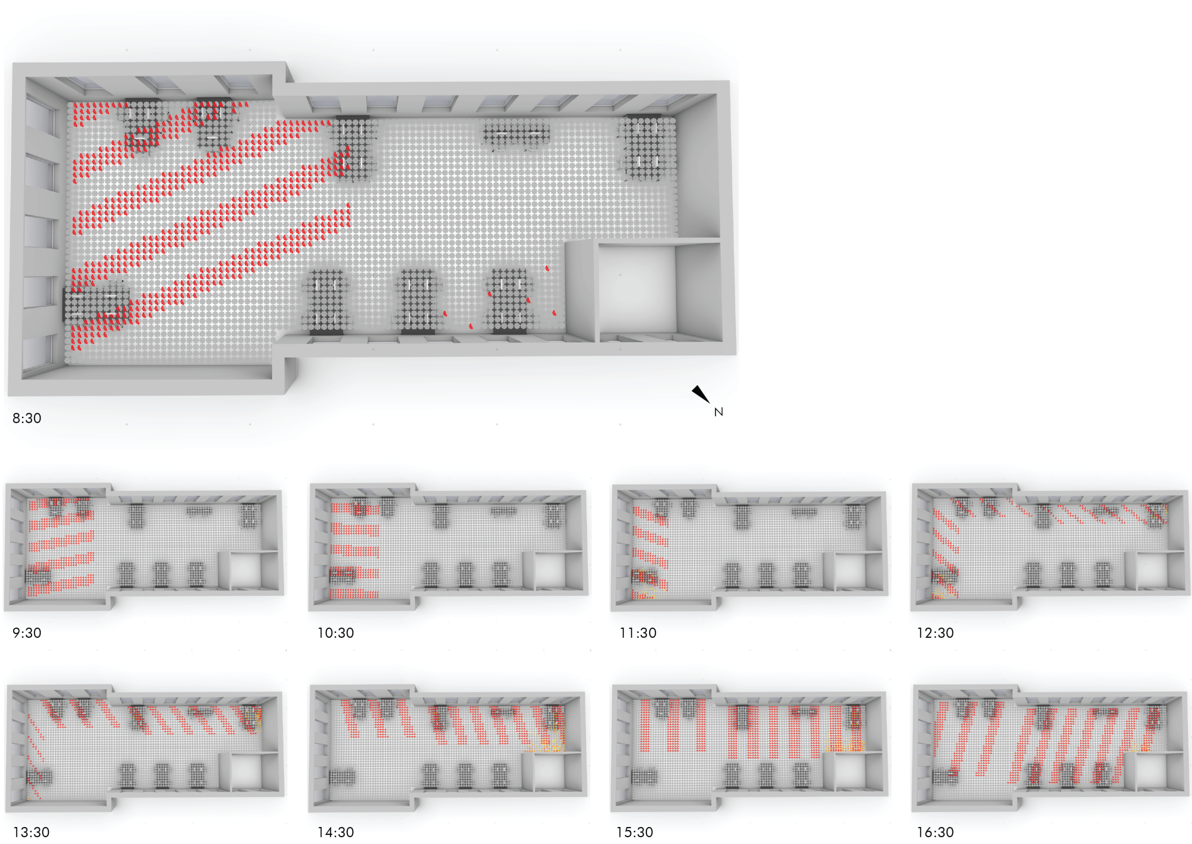


Figure 7.4: Hourly glare variations in an open office on March 15th were simulated to represent glare presence throughout the day.

To mitigate this challenge, a combination of dynamic patterns and smart glass technology can be used:

- **Dynamic patterns:** The use of liquid crystal technology in smart glass, such as VideowindoW, allows for real-time adjustments of biophilic patterns. Sensors can detect light intensity and glare levels at different positions within the office. Fractal and nature-inspired patterns with variable densities can change dynamically based on the time of day and weather conditions. Higher-density patterns can be applied during peak sunlight hours to reduce glare, while lower-density patterns can be used during overcast conditions and when the office space is not in use.
- **Smart glass technology:** Real-time adjustments and localized control can be achieved by integrating light sensors and occupancy sensors that monitor light levels and the position of occupants. Advanced systems that detect occupants' presence like point clouds can be applied to control the system to adjust the smart glass according to the window configuration and the identification of the direct sun on the glazing. The Figure 7.5 illustrated possible positions of equipment needed. Additional algorithms and coordination are needed to clarify the parts of the window that present critical points that cause discomfort. The implementation of zonal control within the smart glass panels allows specific areas of the window to adjust independently. This ensures that occupants in different positions receive optimal glare control tailored to their specific location.
- **User customization:** An intuitive user interface allows occupants to input their preferences for glare control and view obstruction (Figure 7.6). This interface can be accessible via desktop applications or mobile devices. Machine learning algorithms can analyze user inputs and usage patterns, thereby creating personalized glare control settings that can adapt to the user's preferences.

By combining these approaches, it is possible to create a workspace that accommodates the diverse needs of its occupants, ensuring consistent visual comfort and satisfaction. The integration of biophilic patterns with smart technology not only enhances the aesthetic appeal of office spaces but also promotes a healthier, more productive work environment.

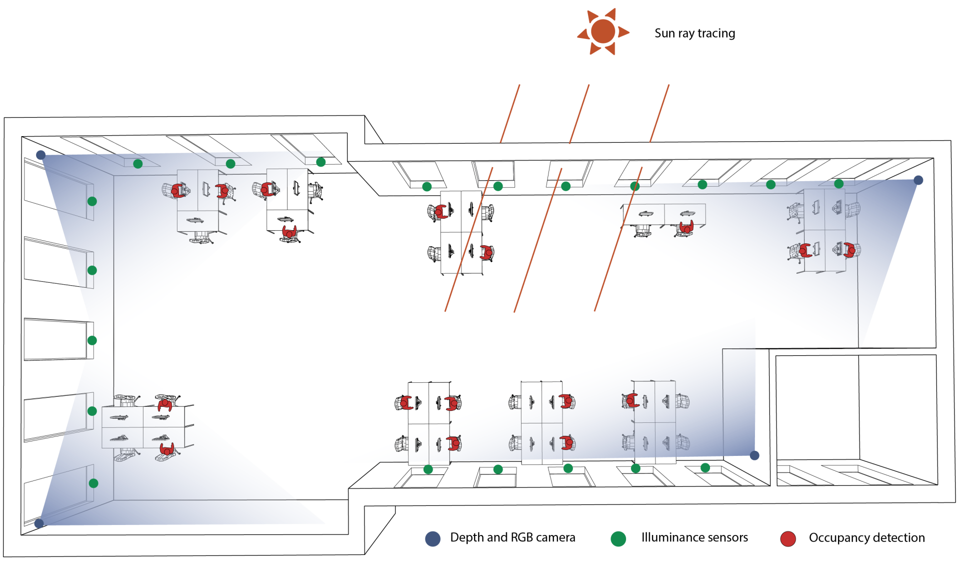


Figure 7.5: Diagram of equipment needed for the point cloud system.

Figure 7.6: Example of interface that could enable personal control of the pattern presence by the user, selection of window of interest for adjustments (left), select pattern for window exposure (middle), adjust transparency through zonal control of the window (right).

7.3. Conclusions

Incorporating biophilic patterns into building facades represents a significant advancement in architectural design, offering multifaceted benefits that enhance both occupant well-being and environmental sustainability. By strategically integrating these patterns into smart glazing systems, designers can effectively manage glare, optimize daylight penetration, and create visually appealing environments across various building types.

While biophilic patterns offer numerous advantages, their application requires thoughtful integration with existing architectural elements and adherence to regulatory frameworks. This chapter underscores the importance of balancing innovation with sensitivity to context, thereby ensuring that biophilic design enhances both the functionality and aesthetic appeal of buildings while contributing positively to occupant comfort and overall environmental quality.

The flexibility of biophilic patterns allows for tailored solutions that cater to diverse user preferences and environmental conditions. Whether enhancing productivity in office environments, fostering healing in healthcare settings, or promoting relaxation in residential spaces, these patterns play a pivotal role in shaping modern architectural landscapes. Moreover, in public spaces and historic buildings, careful consideration of architectural integrity and cultural significance ensures that biophilic patterns enrich rather than detract from the built environment.

In conclusion, biophilic patterns on smart glazing exemplify a harmonious convergence of nature-inspired design and technological innovation. Embracing these patterns not only enhances visual and psychological comfort but also underscores a commitment to sustainable and human-centered architecture in the 21st century.

8

Conclusions and Reflection

8.1. Revisiting the research question

In the current thesis, research was carried out to investigate occupant perception among different patterns on an innovative smart facade technology that deals with glare and visual comfort and is related to psychological aspects. The following main research question was formulated:

- **Does integrating biophilic patterns on building facades influence occupant perception compared to non-natural patterns or clear conditions?**

To find an answer to the main research question, the thesis was divided into several sub-questions which were answered by literature review and practical research. The sub-questions are answered below:

Literature review (background questions)

- **(SQ1) What is the evidence of the impact of biophilic design and patterns on occupants?**

  The investigation into the impact of biophilic design and patterns on occupants draws from empirical studies conducted both in artificial and natural environments. These studies collectively contribute to a comprehensive understanding of how biophilic elements influence individual experiences.

  In artificial settings, investigations into elements such as natural light, fractal patterns, and nature-inspired geometries have consistently demonstrated their positive influence on individual experiences. For instance, studies have shown a clear preference for natural light over artificial sources due to its perceived benefits for health, concentration, and aesthetics (Haans 2014). Similarly, experiments with projected fractal patterns have revealed a distinct preference for fractals over regular geometries, suggesting their potential to enhance occupants' overall experience of a space (Abboushi, Elzeyadi, Taylor, et al. 2019). Moreover, research on facade geometry in virtual environments has indicated that irregular patterns are perceived as more pleasant and interesting, further emphasizing the significance of biophilic design elements (Chamilothori, Chinazzo, et al. 2019). So, natural is identified, is preferred, and is perceived as more pleasant and beneficial.

  However, limited research has been conducted in natural environments, which represents a gap in the current understanding. Studies such as those evaluating office environments with different window patterns have highlighted the complexities of incorporating biophilic elements in real-world settings. While natural views have been associated with reduced discomfort glare over urban ones (Tuaycharoen et al. 2007), no differences appear between fractal, striped, and clear conditions on the window glazing on visual comfort, visual interest and view aspects (Abboushi, Elzeyadi, Wymelenberg, et al. 2021). This raises questions regarding the presence of certain patterns and their influence, their potential distraction, and their impact on the perceived interest and obstruction of views, factors that differ in a clear condition but do not show differences in the current study.

  Further research in real-world environments is necessary to fully elucidate the impact of biophilic patterns, particularly on facades, as highlighted by the limited findings in this area. Addressing this gap will not only contribute to a more comprehensive understanding of biophilic design's influence on occupants but also inform future design practices aimed at creating healthier and more sustainable built environments.

- **(SQ2) What are the factors that affect discomfort glare?**
  Several potential factors of glare have been tested for their influence either in field or laboratory experiments (Clotilde Pierson et al. 2018). They are further categorized into groups according to their relevance and their influence factor:

  1. Related to lighting:
     - Lighting environment: luminance of the glare source, adaptation level (vertical illuminance at eye, background illuminance), contrast effect, saturation effect
     - Interaction between the observer and the glare source: size and position of the glare source as seen by the observer
  2. Related to context:
     - Environmental characteristics: spectrum and color temperature, view direction and position, attractiveness of the view through the window, room temperature
     - Glare experiment characteristics: time of the day, season, task difficulty, glare rating scales, and experimental design
  3. Related to the observer:
     - General characteristics: gender, age, culture, chronotype, self-assessed glare sensitivity
     - Vision characteristics: optical correction, iris pigmentation, macular pigment optical density, cortical hyperexcitability, contrast sensitivity
     - Present state: previous luminous environment, physical state, emotional state, caffeine ingestion, food ingestion, fatigue

  The influence of these factors can be seen in Figure Figure 3.6. In general, the tools used in experimental design that are related to lighting and have a certain influence factor were monitored by objective measurements with appropriate equipment. Factors related to the present state of the observer were checked for their influence during the analysis of results. For the rest of the factors, several steps were taken to control or keep fixed or balanced the factors between the scenarios during the experimental design.

- **(SQ3) What are the challenges of automation systems according to occupant perception?**

  Determining the optimal balance between automated control and user interaction in facade automation systems remains a significant challenge. While automated systems that respond to environmental data can greatly enhance energy efficiency and indoor environmental quality, including visual comfort and glare reduction (Day et al. 2019), they often face limitations due to occupant perception and acceptance. Conventional systems with different levels of automation have been tested to explore and reach this gap and present several challenges.

  One major challenge is the variability in individual user preferences regarding daylight and views. Studies indicate that automated systems frequently face overrides from users seeking to increase their exposure to natural light and outdoor views, which suggests a gap in understanding and meeting these personal preferences (Voss 2003), (Sadeghi et al. 2016). This lack of customization can lead to reduced satisfaction with automated systems, despite their potential benefits.

  Moreover, the impact of control strategies on users is not fully understood. Users generally desire a certain degree of control over their environment and may be quick to adjust shading systems manually, even if these adjustments do not significantly enhance their overall comfort (Meerbeek et al. 2014). This indicates a need for more intuitive and user-friendly interfaces that allow for personal adjustments without compromising the benefits of automation.

  Another challenge is the potential disruption caused by the operation of automated systems (Baker et al. 2014). Frequent adjustments and noise generated by these systems can be distracting, leading to dissatisfaction among occupants. Ensuring that automated adjustments are smooth, quiet, and infrequent enough to minimize disruptions is crucial for occupant acceptance.

An experiment within this project evaluates the upcoming VideowindoW, a dynamic liquid crystal glazing that aims to address these challenges. The study offers valuable insights into the product's performance, its alignment with user preferences, and overall acceptance. For this project, adjustments to the tested facade patterns are manually selected and fixed, instead of automated. This approach utilizes the adaptability of smart technology to test various versions of patterns.

Practical research sub-questions

In this experiment, a dynamic switchable technology utilizing liquid crystals applied on the facade by VideowindoW was employed to produce different patterns. The patterns tested included a Tree pattern, a Striped pattern, and a No-pattern condition, representing biophilic, non-biophilic, and clear conditions, respectively. These patterns were designed to have the same average light transparency and were exposed to participants through an experimental procedure. Both quantitative and qualitative data were collected to comprehensively assess the impact of these patterns on various aspects of occupant experience. The analysis of the results addresses the main questions of interest which are listed below:

- **(SQ4) Does the pattern affect occupants' glare sensation?**
  The experiment revealed that facade patterns significantly affect occupants' glare sensation. Glare was perceived significantly less in the Tree pattern scenario compared to the Striped one, and less but marginally non-significant compared with the No-pattern condition. Therefore, the experiment demonstrated that glare is perceived less in biophilic patterns at a significant level in comparison with regular or Euclidean patterns, and is comparable to uniform window conditions in terms of transparency with the absence of a pattern.

  Objective measurements of Daylight Glare Probability (DGP) consistently showed low levels of discomfort glare across all patterns, with most measurements falling within the imperceptible category aligning with the sky condition. However, notable variations in glare levels were observed, particularly with the Striped pattern, which exhibited slightly higher glare due to its design allowing more light penetration. Overall, the measurements were at similar levels without striking effects and presented consistency between the scenarios.

  Subjective evaluations indicated that participants reported variations in their glare level ratings that align to an extent with the objective measurements. Particularly, they perceived better glare categorized as either present or absent, where they rated higher discomfort glare levels for the Striped compared to the Tree and No-pattern condition. The Tree was the most effective in mitigating glare perception.

- **(SQ5) Does the pattern affect visual comfort and daylight satisfaction?**
  No significant differences were observed regarding visual comfort and daylight satisfaction among the different patterns. Participants' ratings were generally positive, with scores above the median rating (3=Neither agree nor disagree), indicating overall satisfaction with the lighting conditions. The lack of distinct preferences suggests that all patterns provided a satisfactory visual environment. Objective measurements, such as Horizontal Illuminance and Light Penetration, confirmed these findings by showing similar lighting conditions across the different patterns. This uniformity in objective measurements further supports the conclusion that the patterns did not significantly impact visual comfort or daylight satisfaction.

- **(SQ6) Does the pattern affect satisfaction with the outdoor view?**
  The experiment provided clear evidence that satisfaction with the outdoor view and acceptance of obstruction by the pattern varied significantly across different pattern conditions. The view included mainly the sky, low buildings, paving, and scarce vegetation. Theoretically, No-pattern obstructed the entire view but practically only reduced the clarity through the window, which can explain the high acceptance of obstruction. The Tree and Striped patterns covered similar proportions of view elements differently, with the former being more abstract and natural, and the latter more geometric and strict.

  Participants rated satisfaction with the view significantly higher in the No-pattern condition compared to the Striped condition, indicating a preference for unobstructed views. While the Tree pattern fell between the other two patterns in satisfaction ratings, it was closer to the No-pattern condition, suggesting a mitigated impact on satisfaction comparable to a uniform clear condition.

Significant differences were also observed in participants' acceptance of obstruction of the outdoor view among the different patterns. Similarly, the Tree condition and the No-pattern pattern received higher ratings compared to Striped patterns, indicating that biophilic patterns are more acceptable compared to regular patterns and equivalent to uniform clear states.

Under clear conditions, participants rated the view with a mean score above the middle ratings, indicating a generally positive perception of the outside view from the interior space. Comparing the ratings of clear view and the ones for each pattern evaluation, significant differences occur only for the Striped version. This suggests that the presence of a Striped pattern can reduce the satisfaction with the view out. On the contrary, biophilic patterns and uniform clear conditions can maintain high ratings, which further validate the high acceptance of the obstruction by these patterns.

- **(SQ7) Does the pattern itself affect visual satisfaction in terms of aesthetics?**

  The experiment revealed that facade patterns significantly affect visual satisfaction associated with aesthetic criteria. Participants found both the Tree pattern and the No-pattern condition to be more aesthetically pleasing than the Striped pattern, with the Tree pattern rated slightly higher than the No-pattern condition, though this difference was not statistically significant.

  Significant differences were observed in sunlight pattern aesthetics only between the Tree pattern and Stripes. Sunlight patterns were found aesthetically more pleasing in the case of natural patterns than regular ones, indicating that with the presence of patterns, a natural pattern creates more pleasant sunlight characteristics.

  These findings underscore the importance of pattern aesthetics in influencing visual satisfaction, with biophilic and unobstructed views contributing more positively than geometric patterns. The findings highlight the necessity of incorporating visually comfortable and aesthetically pleasing elements in facade design.

- **(SQ8) Which pattern is most preferred by participants based on their overall experience and perceived connection with nature?**

  Overall, participants significantly preferred the Tree pattern. The majority of their ratings regarding their favorite scenario were collected for the biophilic pattern, underscoring the natural affinity towards biophilic designs. The same pattern was chosen as well for the scenario that enabled more connection with nature, supporting further this idea.

Conclusions

Integrating biophilic patterns on building facades influences occupants' perception compared to non-natural patterns or creates comparable scenarios with clear conditions. The experiment's findings demonstrate that biophilic design elements positively impact occupant experiences by reducing glare perception, promoting aesthetic appeal, and maintaining satisfactory levels concerning the acceptance of obstruction of the view outside.

The Tree pattern, a biophilic design, was particularly effective in reducing perceived glare significantly compared to the Striped pattern and marginally non-significantly compared to the No-pattern condition.

Furthermore, satisfaction with the outdoor view and acceptance of its obstruction was highest in the No-pattern condition, yet the Tree pattern did not significantly detract from this satisfaction. Significant results were found between the No-pattern and Stripes both is satisfaction with the view out and in acceptance of obstruction and between the Tree and the Striped pattern in the acceptance of obstruction. This suggests that the presence of biophilic patterns does not adversely affect the view and is generally accepted despite some level of obstruction.

Both the Tree pattern and the No-pattern condition were rated significantly higher in aesthetic appeal compared to the Striped pattern. The natural aesthetics of the Tree pattern created more pleasant sunlight characteristics compared to the Striped pattern.

At the same time, participants rated the Tree pattern as their favorite scenario and associated it with a connection with nature, indicating a strong preference for biophilic design.

Overall, the evidence supports that biophilic patterns can positively influence overall occupant perception compared to non-natural patterns or clear conditions and overall are preferred.

8.2. Discussion

In this study, the hypothesis that occupants will show a higher preference for natural patterns, associating them with increased comfort, aesthetic appeal, and acceptance of obstruction of view was supported. First, participants undoubtedly preferred the Tree pattern over the other scenarios, even with a 'None' option available. The Tree pattern was also selected for its ability to enable a connection with nature, underscoring its biophilic impact. Additionally, the findings show that the Tree pattern scenario received significantly higher ratings for glare sensation, pattern aesthetics, sunlight pattern aesthetics, and acceptance of obstruction of view compared to the Striped pattern, with similar trends observed when compared to a clear condition.

Previous studies in real office environments did not show significant differences between three similar stimuli (fractal pattern, striped pattern, clear) in terms of visual comfort, sunlight pattern aesthetics, and satisfaction with the view out (Abboushi, Elzeyadi, Wymelenberg, et al. 2021). The current study aligns with these non-significant results only for visual comfort. In contrast, significant results were observed for aesthetic and view considerations between the Tree or No-pattern conditions and the Stripes. The difference in sunlight pattern aesthetics was notable only between the Tree and Stripes, likely due to the lack of light variations in the No-pattern condition.

Similar to previous studies, where irregular patterns were perceived as more interesting in a simulated space (Chamilothori, Chinazzo, et al. 2019), the pattern aesthetics and sunlight pattern aesthetics of the non-regular Tree pattern were significantly higher than the regular Stripes. The Tree pattern was preferred over the other stimuli, highlighting the impact of biophilic characteristics on preference, psychology, and aesthetics.

The experimental space relied solely on daylighting, and no significant results were found among the pattern scenarios regarding daylight satisfaction and visual comfort. Ratings were generally towards higher satisfaction levels, even though the space experienced a mixture of insufficient, sufficient, and excessive daylighting for office activities. This emphasizes the appreciation of natural light, as demonstrated in previous research (Haans 2014).

Regarding view aspects, there was a preference for unobstructed views only when comparing the No-pattern with the Striped scenario. The Tree pattern received votes close to the No-pattern and significantly higher results than the Stripes. Thus, irregular clear and semi-transparent obstructions with natural elements are more accepted than the strict repetitive obstructions of Striped patterns and can be almost as acceptable as a clear condition.

It is worth mentioning that the biophilic characteristics of the Tree pattern rely mainly on its natural geometrical properties (indirect experience of nature), which differentiate the pattern from the other scenarios, and the light penetration (direct experience of nature). While light penetration is present in all scenarios, it creates more natural and interesting sunlight patterns in the Tree case. Additionally, the pattern enabled a connection with the outdoor view, albeit with some level of obstruction. The view itself, at ground level, consisted of a few building elements and sparse vegetation and was rated high in terms of satisfaction when unobstructed. The high acceptance of the obstructed view with the Tree pattern highlights the overall acceptance of an artificial product over a natural view, suggesting a higher acceptance of the technology.

Overall, the study provides evidence that window patterns can substantially influence occupants' perceptions and preferences. Specifically, the presence of natural patterns has a positive impact on view satisfaction and acceptance of its obstruction, likely facilitating greater acceptance of automated shading controls for energy efficiency. The aesthetic appeal of both the pattern and the sunlight patterns in combination with the preference and the connection with the nature of the tree pattern, emphasizes its potential to add architectural value to indoor spaces. Therefore, there is a great opportunity for this pattern to enhance occupant satisfaction and increase acceptance of conditions with obstructed views or reduced daylight levels. However, future research is necessary to validate these findings.

8.3. Limitations

Several limitations should be considered when interpreting the results of this study:

- **Laboratory setting:** The controlled environment of the laboratory experiment may not fully replicate real-world conditions. The participants' responses might differ in actual office settings where other environmental factors and personal preferences come into play. Unique features of the laboratory setting, such as the enclosure of the space with curtains, predominant black surfaces, the position of the desk at 45 degrees, the participation of one person at a time, and the interruptions for measurements and questionnaires, may have influenced the results. In addition, while the controlled environment allowed for focused data collection, it may not fully represent the dynamics of a typical office setting where multiple occupants with diverse preferences are present simultaneously. This limitation underscores the need for further research to explore how facade patterns impact visual comfort in multi-user environments.

- **Weather conditions and lack of glare conditions:** The experiment was conducted under mostly cloudy weather conditions, which led mostly to non-glary occurrences that may have influenced participants' perceptions of glare and outdoor views. Cloud cover can affect the intensity and distribution of natural light, potentially altering the way participants interact with different facade patterns. Therefore, the generalizability of the findings to environments with varying weather conditions may be limited.

- **Short-term exposure:** The experiment measured participants' immediate reactions to the patterns, with each participant exposed to each pattern for only 15 minutes. Long-term studies are needed to understand how prolonged exposure to biophilic patterns affects glare tolerance and overall well-being.

- **Limited patterns tested:** Only three patterns (Tree, Striped, and No-pattern) were tested. The Striped and No-pattern conditions were more familiar to participants, being related to conventional shading systems (blinds) or the performance of smart technologies (electrochromic glazing). Including a broader range of biophilic and geometric patterns could provide a more comprehensive understanding of their effects on glare tolerance and visual comfort.

- **Sample size and diversity:** The sample size and demographic diversity of participants may limit the generalizability of the findings. The population was not chosen according to specific criteria. Although the minimum number of participants was reached to report a moderate effect on the outcome, future studies should include a larger and more diverse participant sample to validate the results.

- **Task activity:** The reading tasks conducted during the experiment, while simulating office-like activities and selected according to the participants' interests, may not fully replicate the diverse range of tasks and activities typically performed in real office environments. This limitation could impact participants' responses to glare and their overall satisfaction with the outdoor view, as office activities vary in complexity and visual demands.

- **Limited consideration of surrounding space use:** The experiment was conducted in a space typically used for small events and presentations. Although measures were taken to minimize acoustical and visual distortions through the glazing, the presence of people in the vicinity may have influenced the experiment's proceedings.

8.4. Recommendations

To enhance future research and practical applications, the following recommendations are proposed:

Future research

- **Field Studies:** Conduct field studies in actual office environments to validate the laboratory findings. This would provide insights into how biophilic patterns perform in real-world settings over extended periods.

- **Exploration of the level of acceptance of the automated practice:** Further exploration into the acceptance of automated performance for energy efficiency. Understanding how users perceive and interact with such technologies could provide valuable insights into enhancing indoor environmental quality and occupant satisfaction.

- **Customization and Adaptability:** Test dynamic facade systems to assess their capability to adapt to individual preferences and environmental conditions, thereby enhancing occupant satisfaction and comfort.

- **Optimizing Transparency Levels for Glare Mitigation:** Investigate optimal transparency levels and their performance on the liquid crystal glazing to determine the fundamental transparency levels that effectively mitigate glare in response to varying light intensities.

- **Broader Pattern Range:** Explore a wider variety of biophilic and geometric patterns to identify which specific elements most effectively enhance visual comfort and glare tolerance.

- **Longitudinal Research:** Implement longitudinal studies to assess the long-term effects of biophilic patterns on occupant comfort, productivity, and well-being. This would help in understanding the sustained impact of these designs.

For VideowindoW and other companies:

- **Optimizing Glare Mitigation with Advanced Systems:** Utilize advanced technologies such as point cloud data to monitor occupant presence and accurately identify areas where direct sunlight is visible in the window from their perspective. Adjust the algorithm controlling the liquid crystal glazing to strategically produce dynamically and alter the patterns and their transparency to these window areas.
- **Pattern Diversity:** Offer a wider range of biophilic and geometric patterns to suit various aesthetic preferences and functional needs. Conduct additional research to identify natural patterns that maximize visual comfort and glare reduction.
- **Field Testing:** Conduct thorough field testing of the smart facade technology in diverse real-world settings, such as offices, schools, and hospitals. Gather long-term user feedback and data to validate laboratory findings and assess practical effectiveness.
- **Customization:** Enable users to personalize patterns based on their preferences and requirements. Develop intuitive interfaces for easy customization without compromising system benefits.
- **Feedback Mechanisms:** Establish robust feedback mechanisms to continuously monitor user satisfaction and identify areas for improvement. Utilize feedback to refine product offerings and enhance user experience.
- **Integration with Glazing Systems:** Collaborate with glazing manufacturers to seamlessly integrate smart facade technology with existing or new glazing systems. Aim for compatibility and synergy to optimize building envelope performance.
- **Circularity and Sustainability:** Prioritize the use of recycled materials and eco-friendly manufacturing processes in facade component production. Design systems for modularity and easy disassembly to support maintenance, repair, and end-of-life recycling or repurposing efforts.

8.5. Reflection

Graduation Process

The graduation project has proven to be highly relevant within the studio, seamlessly integrating the core sectors of climate and facade design. By focusing on occupants' preferences for biophilic patterns and their impact on occupant perception and acceptance of dynamic glazing shading systems, the project addresses a significant gap in the field of facade design and human-centric architecture. Utilizing a laboratory experiment with human participants, subjective perceptions were captured alongside environmental sensor data, providing a comprehensive analysis of the impact of different facade patterns.

The research approach, while innovative and interdisciplinary, encountered both strengths and weaknesses. The primary strength was the project's integration of multiple disciplines, which allowed for a holistic examination of the problem. The controlled laboratory setting and use of advanced equipment ensured rigorous data collection. However, the novelty of integrating psychology through biophilia in facade design presented challenges due to limited prior evidence and established methodologies. Additionally, the extensive time required for research and experiment execution constrained the ability to conduct follow-up studies.

Despite these challenges, the approach led to meaningful results, confirming the hypothesis that biophilic patterns enhance occupant perception and comfort. The results underscore the importance of incorporating biophilic elements in facade design. This interdisciplinary project not only contributes valuable insights to the academic field but also offers practical recommendations for industry professionals.

Societal Impact

The project's practical applicability is significant, offering valuable guidance for architects, designers, and building professionals in the realm of biophilic design and smart technology. By identifying patterns that are preferred by occupants and reduce glare, the study informs the design of future facade products aimed at enhancing occupant comfort and well-being. These findings align with sustainable building practices, promoting healthier indoor environments and potentially leading to increased productivity and quality of life.

The projected innovation has been notably achieved, addressing gaps in biophilic facade design. The preference for biophilic patterns and their effectiveness in reducing glare contribute to both academic knowledge and practical applications, suggesting that such designs can enhance occupant comfort and satisfaction while mitigating glare. This research supports sustainable development by promoting energy-efficient and human-centric building solutions.

The project's impact on sustainability is multifaceted, enhancing occupant comfort (people), promoting energy efficiency (planet), and providing valuable insights for facade developers (profit/prosperity). Additionally, it addresses socio-cultural and ethical considerations by promoting well-being through biophilic design and adhering to strict ethical standards in research.

In the wider social context, the project contributes to the goal of creating healthier and more sustainable urban environments. By integrating biophilic patterns that enhance psychological well-being and energy efficiency, the research aligns with societal goals of health, sustainability, and improved quality of life. The innovative facade designs developed through this project have the potential to significantly impact architecture and the built environment, providing architects and developers with guidelines for creating more efficient, aesthetically pleasing, and human-centric buildings that can be dynamically adjusted to various climate requirements.

A

Appendices

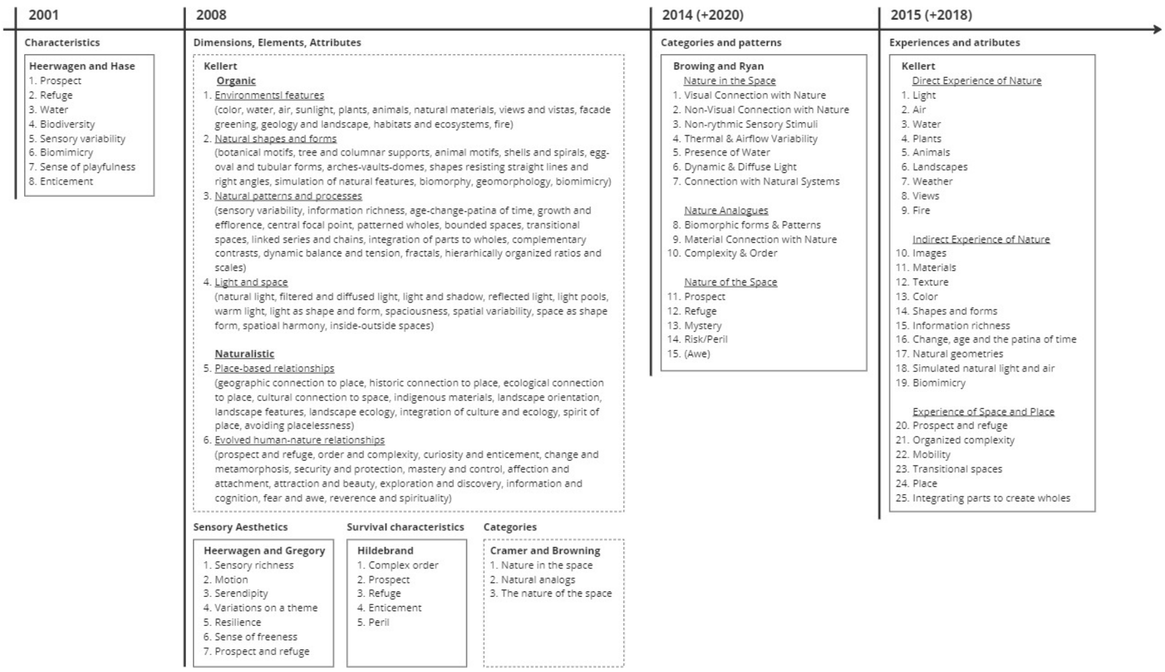
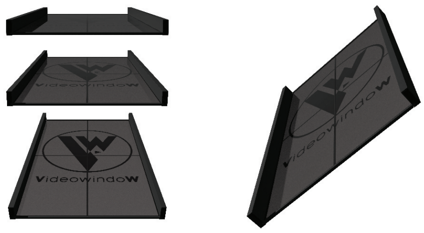
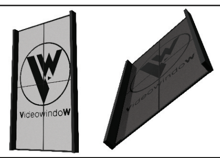


Figure A.1: Biophilic principles review



VideowindoW 4UP Product Information

	
Number of screens	**4** consists of four 65" Full HD module
Near a window	**tbc** VideowindoW HangAlone can be placed in full sun and can endure UV and Infrared heat
Size	**1755mm x 2890mm x 200mm**
Screen Size Active area	**1430mm x 805 mm x 4pc = 4,6 m2**
Pixel Size	**0,74mm x 0,74 mm**
Pixels	**1922 × 1083**

Hardware components	**Electronics bar**
	- anodized aluminum for structural strength, protection and passive cooling
	- PCBs TCON + SCON
	- 51pin + 68 pin flex cables
	- light sensor
	    - A/D converter
	- Single Board Computer (SBC)
	- mini-HDMI cable
	Glass
	- glass 2900mm x 835mm x 44.2 or 66.2
	- UV-curable bonding
	TFT Module
	- transparent monochrome 65" TFT module
	    - 3mm glass (2 x 1,5mm)
	    - Liquid Crystals
	    - ITO
	    - XPCB
	    - Flex cables

Ratio	**Native 16:9**
Layout	**Layouts need to be predefined** **several streams can be shown simultaneously** Dynamic changes between layouts seamlessly integrate all kinds of content. e.g., Information Branding films Wayfinding
	Artistic content Gaming (via QR) **Procedural generative video is at full HD**
Object Orientation	**Portrait or Landscape**

Specificaties

Format Still	**Any**
Format Video	**Any**
Format Audio	**Standard No audio** Added services audio via QR
Videotype	**Any**
Maximum Size Video	**Any**
Maximum Size Still	**Any**
Filename	**Company_**
Delivery Time Before Start Of Campaign	**5 working days** for adaptation, preview and client approval Because of the innovative use of video content as the active layer controlling the transparency of our tintable glass - creating dynamic glare control - we need to adjust all content prior to uploading it to our custom CMS player.
Upload Artwork	**artwork@videowindow.io**

Bill of Material for VideowindoW 4Up

LCD components approximatedd
- 90% tempered glass
- <1% liquid crystals > non toxic
- 2% flex cables > copper wrapped
- 5% PCB boards

	LCD modules			
	Standards for safety	UL 62368-1, 2nd Ed., Issue Date: 2014-12-01		
	CCN	AZOT2, AZOT8 (Audio/video, Information and Communication Technology Equipment)		
	Class	Class III		
	Fulfills requirements	EN 62368-1:2014 + A11:2017		
	EMC	LCD is a pure "input" component		
	power consumption	8Watt psm / sqyds		
	power	12V with passive cooling		
	MTBF	24/7 5 years 50.000 hours (already 15 months 24/7 at RTHA without issues)		

Supporting components (subject to change)

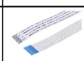
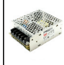
	description	quantity	picture	
	Tempered layered glass 44.2 or 66.2 Front plate 1450mm x 2000mm x ~9mm or 1450mm x 2000mm x~13mm	2 x		
	Glass framing profiles for tempered glass, depending on local situation. Top and bottom	2x		
	LCD modules 1444mm x 821mm x 3mm	4 x	see above	
	Aluminium support u-profiles 6x6x1mm glued to tempered glass with PU Glue for LCD module mounting	12 x		
	Flex Cable 68 pin will be copper shielded	8 x		
	TCON	4 x		
	Flex Cable 51 pin VbyOne will be copper shielded	4 x		
	SCON	4 x		
	Single Board Computer SBC DFI WiFi/4G	1 x		
	Video Distribution With 12-5v power converter????	1 x	???????	?????
	Lightsensor Novastar NS60 Certification: CE, RoHS.	1 x		????? Changed!
	Powersupply Meanwell 12V	1 x		?????
	HDMI cable kramer will be copper shielded	5 x		
	Aluminum construction materials L beam 150x50x5mm	2x		
	Aluminium sheetmetal covers 2mm thick	4x		

Figure A.2: Product information

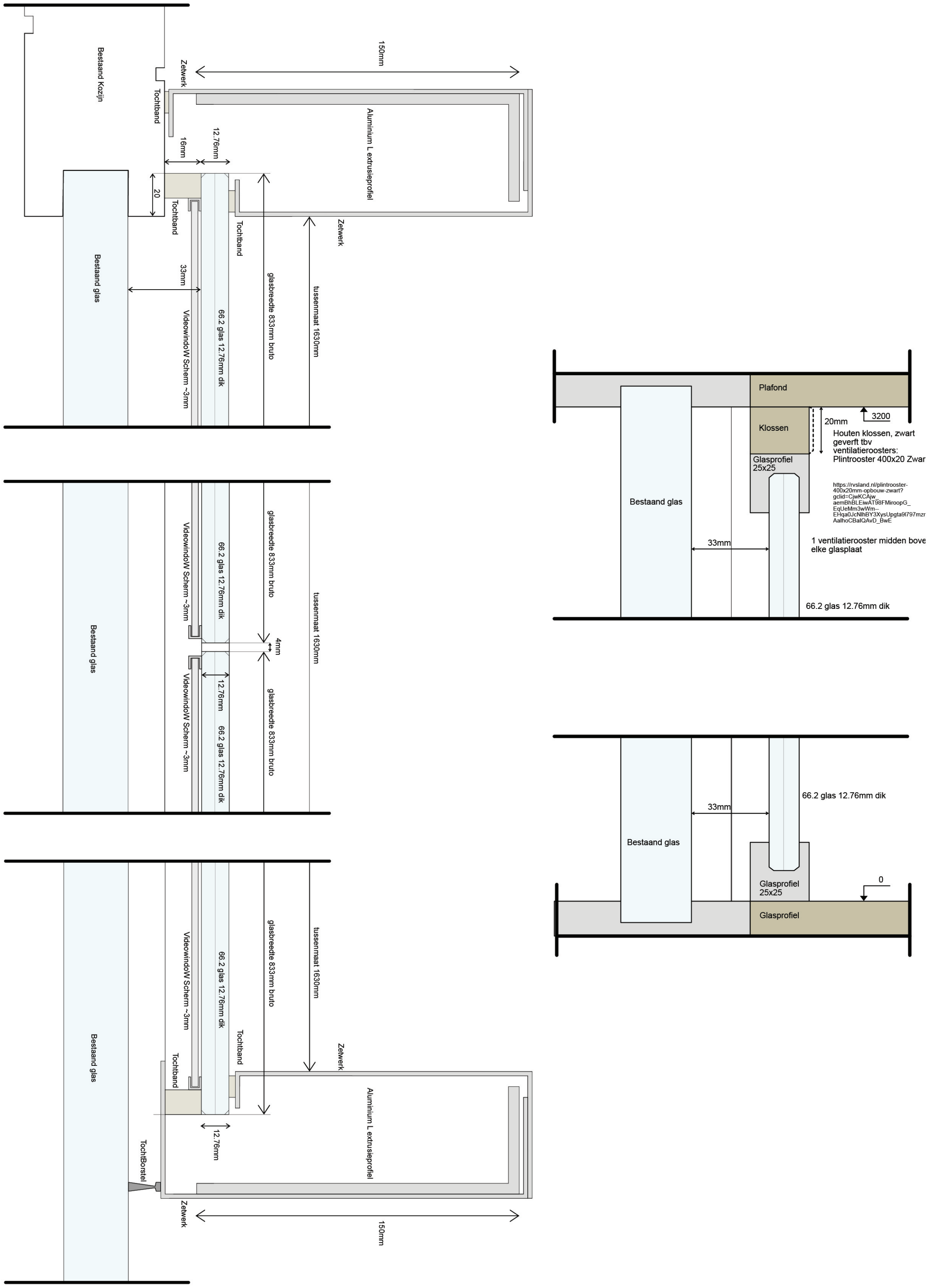


Figure A.3: Product details in plan and section

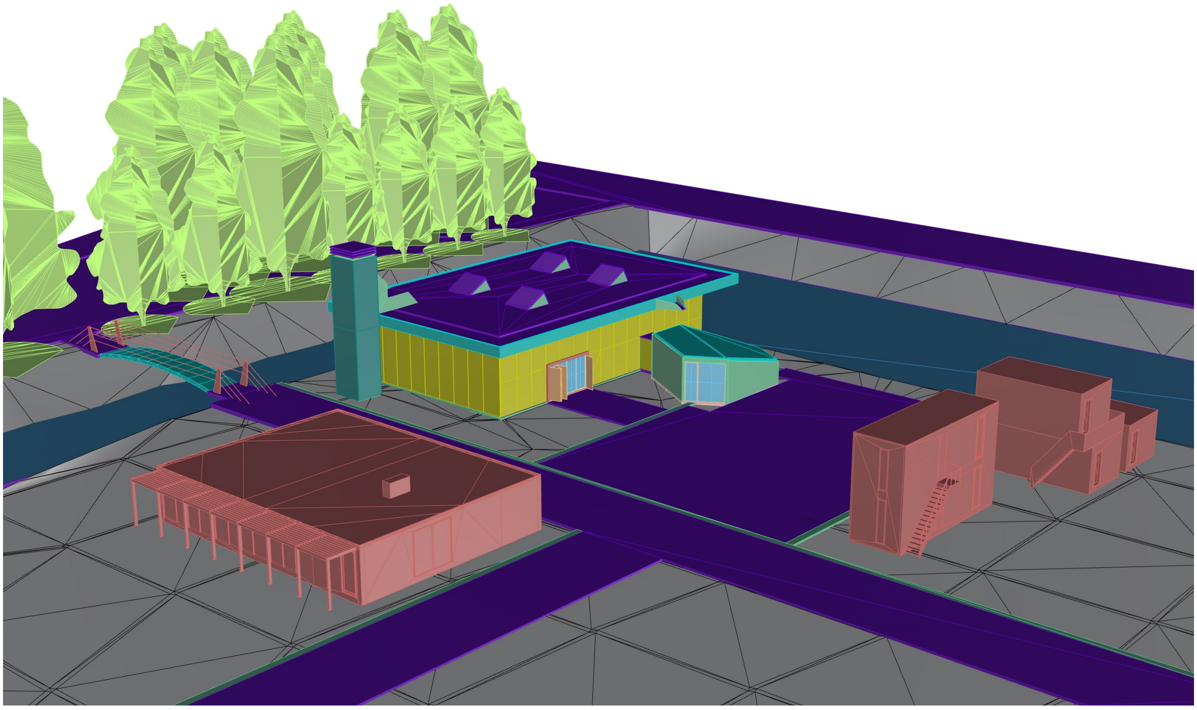


Figure A.4: Rhino 3D model

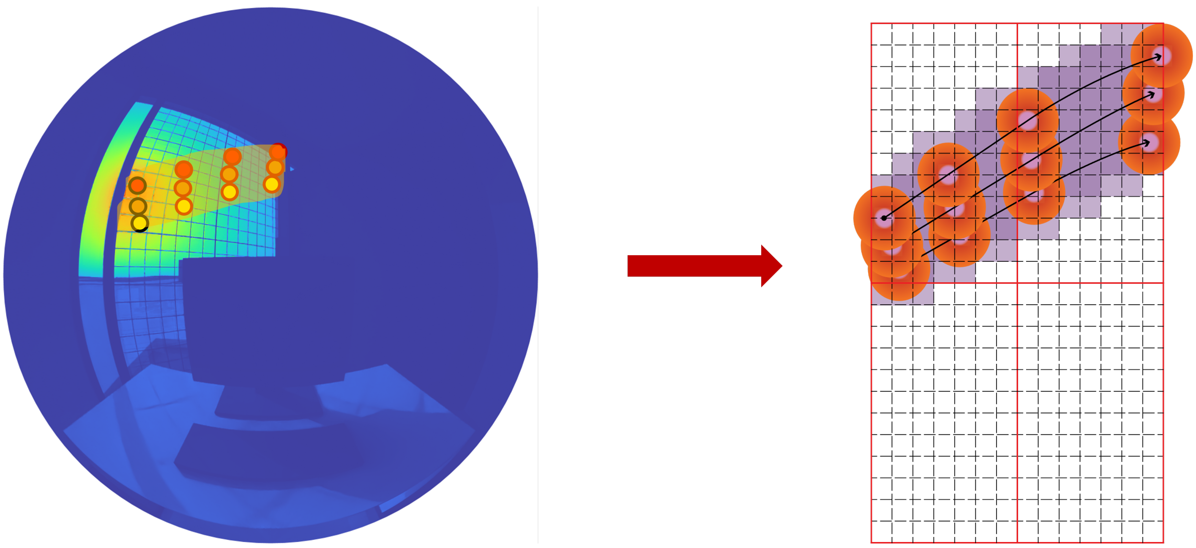


Figure A.5: Sun position in the facade grid

```
(Tree pattern)

from PIL import Image

def calculate_average_shading_percentage(image_path):
    # Open the image
    img = Image.open(image_path)

    # Convert image to grayscale
    img_gray = img.convert('L')

    # Get pixel data
    pixel_data = img_gray.load()

    # Initialize sum and count
    total_shading = 0
    total_pixels = img_gray.width * img_gray.height

    # Iterate through each pixel
    for y in range(img_gray.height):
        for x in range(img_gray.width):
            # Get grayscale value of the pixel
            shading = pixel_data[x, y]

            # Normalize shading value (0 for black, 255 for white)
            normalized_shading = shading / 255.0

            # Add normalized shading value to the sum
            total_shading += normalized_shading

    # Calculate average shading as a percentage
    average_shading_percentage = (total_shading / total_pixels) * 100

    return average_shading_percentage

def calculate_average_shading(image_path):
    # Open the image
    img = Image.open(image_path)

    # Convert image to grayscale
    img_gray = img.convert('L')

    # Get pixel data
    pixel_data = img_gray.load()

    # Initialize sum
    total_shading = 0
    total_pixels = img_gray.width * img_gray.height

    # Iterate through each pixel
    for y in range(img_gray.height):
        for x in range(img_gray.width):
            # Get grayscale value of the pixel
            shading = pixel_data[x, y]

            # Add shading value to the sum
            total_shading += shading

    # Calculate average shading
    average_shading = total_shading / total_pixels

    return average_shading

# Example usage for calculating average shading percentage
image_path = 'C:\\Users\\Eleni\\Desktop\\python script\\P_09.PNG'
avg_shading_percentage = calculate_average_shading_percentage(image_path)
print("Average shading percentage:", avg_shading_percentage)

# Example usage for calculating average shading
image_path = 'C:\\Users\\Eleni\\Desktop\\python script\\P_09.PNG'
avg_shading = calculate_average_shading(image_path)
print("Average shading:", avg_shading)

------------------------------------------------------------------------------------


#%% (Striped pattern)


def calculate_average_shading(image_path):
    # Open the image
    img = Image.open(image_path)

    # Convert image to grayscale
    img_gray = img.convert('L')

    # Get pixel data
    pixel_data = img_gray.load()

    # Initialize sum
    total_shading = 0
    total_pixels = img_gray.width * img_gray.height

    # Iterate through each pixel
    for y in range(img_gray.height):
        for x in range(img_gray.width):
            # Get grayscale value of the pixel
            shading = pixel_data[x, y]

            # Add shading value to the sum
            total_shading += shading

    # Calculate average shading
    average_shading = total_shading / total_pixels

    return average_shading

def create_striped_image(image_path, num_stripes):
    # Ensure num_stripes is even
    if num_stripes % 2 != 0:
        num_stripes += 1

    # Get the average shading of the input image
    avg_shading = calculate_average_shading(image_path)

        # Open the image
        img = Image.open(image_path)
        width, height = img.size

        # Calculate the height of each stripe
        stripe_height = height // num_stripes

        # Ensure the image height is divisible by the number of stripes
        new_height = stripe_height * num_stripes
        if new_height != height:
            height = new_height
            img = img.crop((0, 0, width, height))  # Crop the image to match the new height

        # Create a new blank image
        new_img = Image.new('L', (width, height))

        # Calculate the shading value for the shaded stripe
        shaded_stripe_shading = max(0, int(2 * avg_shading) - 255)  # Calculate shaded stripe shading

        # Iterate through each stripe
        for i in range(num_stripes):
            # Define the bounding box for the current stripe

        top = i * stripe_height
        bottom = (i + 1) * stripe_height
        box = (0, top, width, bottom)

        # Fill the stripe with the appropriate color
        if i % 2 == 0:
            new_img.paste(255, box)  # White stripe
        else:
            new_img.paste(shaded_stripe_shading, box)  # Shaded stripe

    return new_img


# Example usage for calculating average shading
image_path = 'C:\\Users\\Eleni\\Desktop\\python script\\P_09.PNG'
avg_shading = calculate_average_shading(image_path)
print("Average shading:", avg_shading)

# Example usage
image_path = 'C:\\Users\\Eleni\\Desktop\\python script\\P_09.PNG'
num_stripes = 40  # Ensure this is an even number
striped_img = create_striped_image(image_path, num_stripes)
striped_img.show()  # Display the resulting image

# Save the resulting image
striped_img.save('C:\\Users\\Eleni\\Desktop\\python script\\striped_image.png')

------------------------------------------------------------------------------------


#%%(No-pattern pattern)


def calculate_average_shading(image_path):
    # Open the image
    img = Image.open(image_path)

    # Convert image to grayscale
    img_gray = img.convert('L')

    # Get pixel data
    pixel_data = img_gray.load()

    # Initialize sum
    total_shading = 0
    total_pixels = img_gray.width * img_gray.height

    # Iterate through each pixel
    for y in range(img_gray.height):
        for x in range(img_gray.width):
            # Get grayscale value of the pixel
            shading = pixel_data[x, y]

            # Add shading value to the sum
            total_shading += shading

    # Calculate average shading
    average_shading = total_shading / total_pixels

    return average_shading

def create_uniform_shaded_image(image_path, target_image_path):
    # Get the average shading value of the reference image
    average_shading = calculate_average_shading(image_path)

    # Open the reference image
    img = Image.open(image_path)
    width, height = img.size

    # Create a new blank image with the same size
    new_img = Image.new('L', (width, height))

    # Set each pixel in the new image to the average shading value
    for y in range(height):
        for x in range(width):
            new_img.putpixel((x, y), int(average_shading))

    # Save the new image
    new_img.save(target_image_path)

    print(f"Average shading of {image_path}: {average_shading}")
    print(f"Uniform shaded image saved at {target_image_path}")

# Example usage
image_path = 'C:\\Users\\Eleni\\Desktop\\python script\\P_09.PNG'
target_image_path = 'C:\\Users\\Eleni\\Desktop\\python script\\uniform_shaded_image.png'
create_uniform_shaded_image(image_path, target_image_path)
```

Figure A.6: Python script for the generation of comparable stimuli

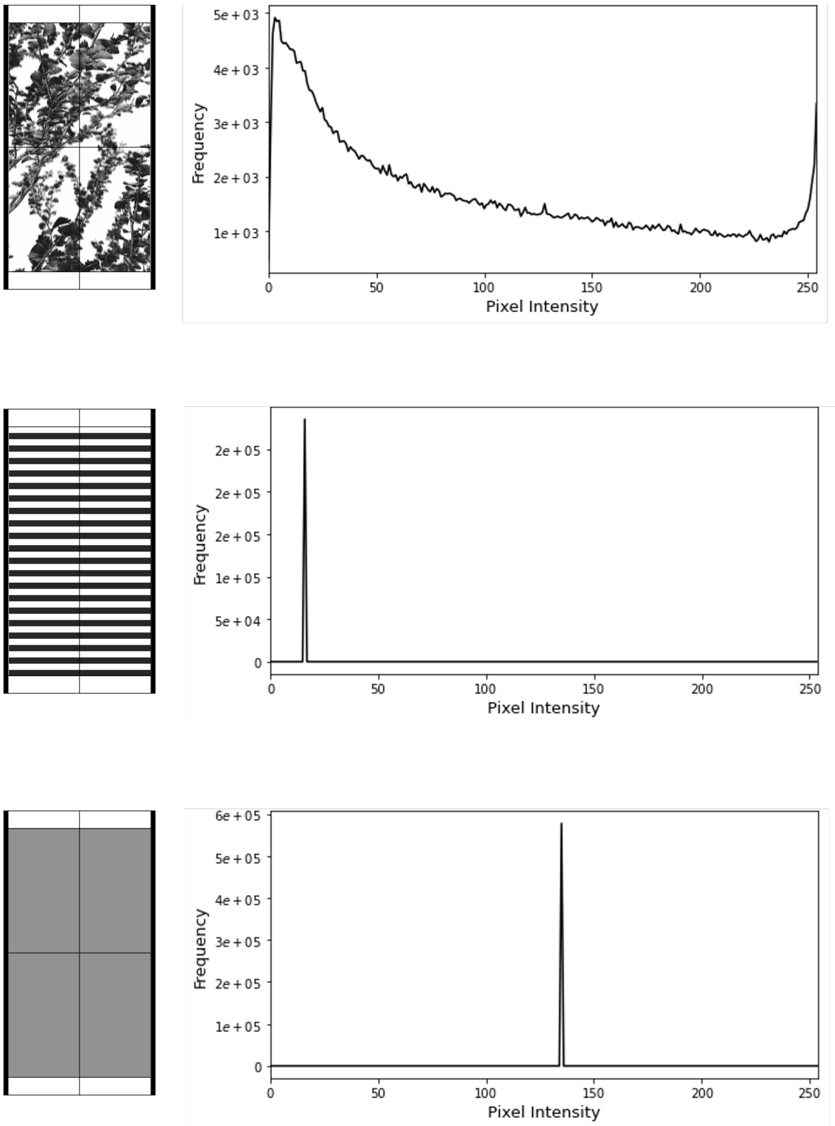
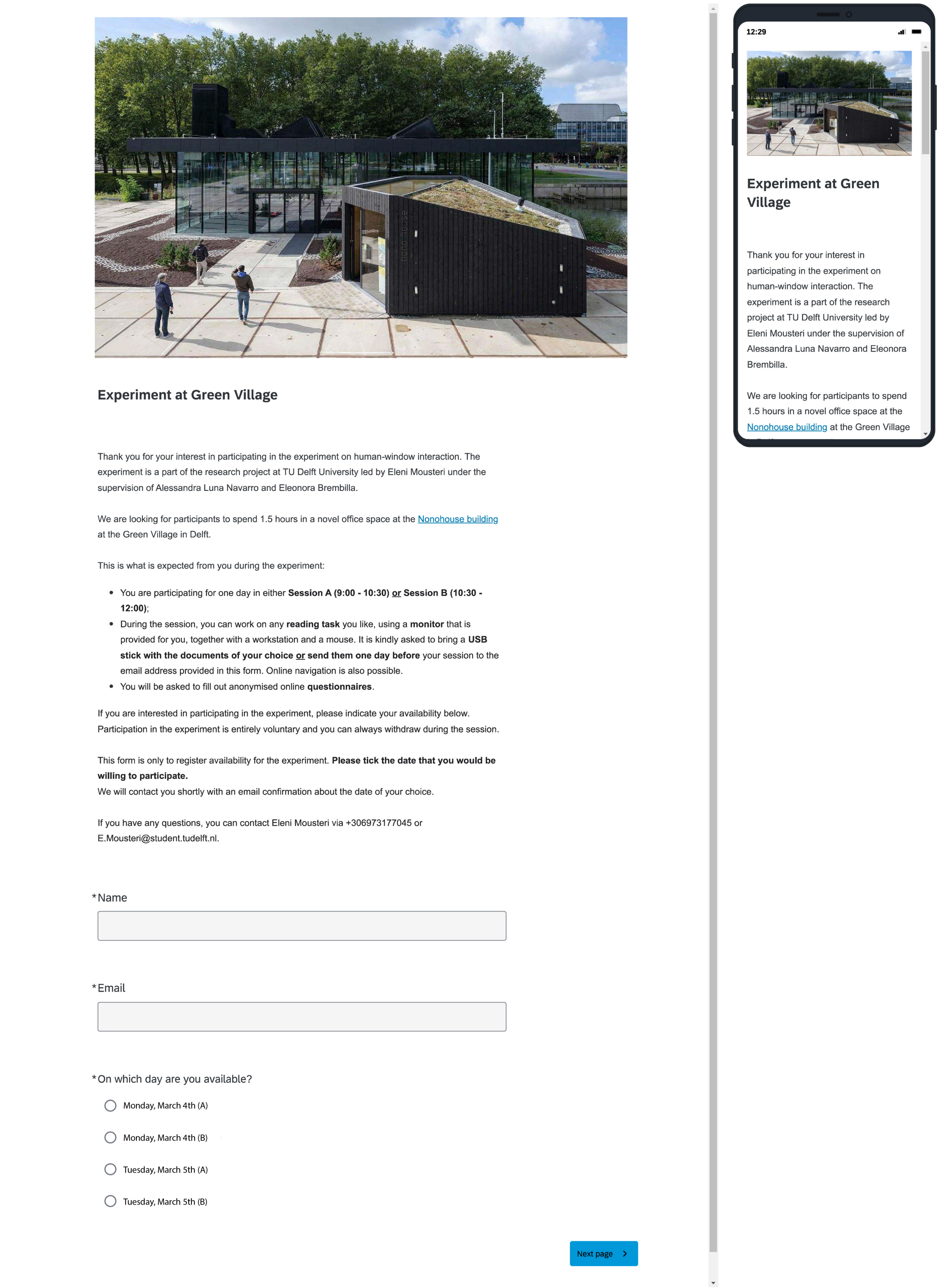


Figure A.7: Transparency of patterns represented by grey shades



Experiment at Green Village

Thank you for your interest in participating in the experiment on human-window interaction. The experiment is a part of the research project at TU Delft University led by Eleni Mousteri under the supervision of Alessandra Luna Navarro and Eleonora Brembilla.

We are looking for participants to spend 1.5 hours in a novel office space at the Nonohouse building at the Green Village in Delft.

This is what is expected from you during the experiment:

- You are participating for one day in either **Session A (9:00 - 10:30)** or **Session B (10:30 - 12:00)**;
- During the session, you can work on any **reading task** you like, using a **monitor** that is provided for you, together with a workstation and a mouse. It is kindly asked to bring a **USB stick with the documents of your choice or send them one day before** your session to the email address provided in this form. Online navigation is also possible.
- You will be asked to fill out anonymised online **questionnaires**.

If you are interested in participating in the experiment, please indicate your availability below. Participation in the experiment is entirely voluntary and you can always withdraw during the session.

This form is only to register availability for the experiment. **Please tick the date that you would be willing to participate.**
We will contact you shortly with an email confirmation about the date of your choice.

If you have any questions, you can contact Eleni Mousteri via +306973177045 or E.Mousteri@student.tudelft.nl.

*Name

*Email

*On which day are you available?

- Monday, March 4th (A)
- Monday, March 4th (B)
- Tuesday, March 5th (A)
- Tuesday, March 5th (B)

Next page

Figure A.8: Invitation for participation: preview of survey

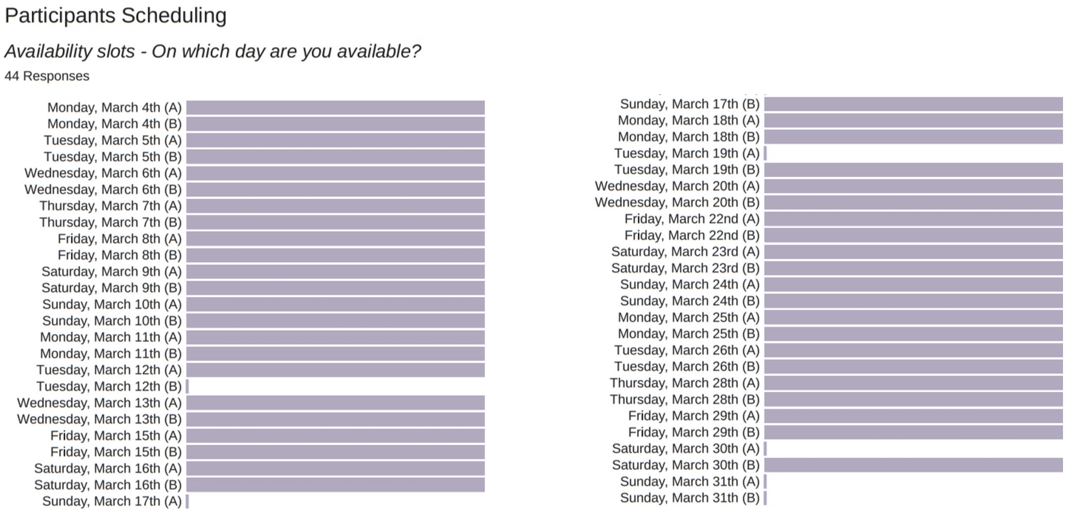


Figure A.9: Participants scheduling

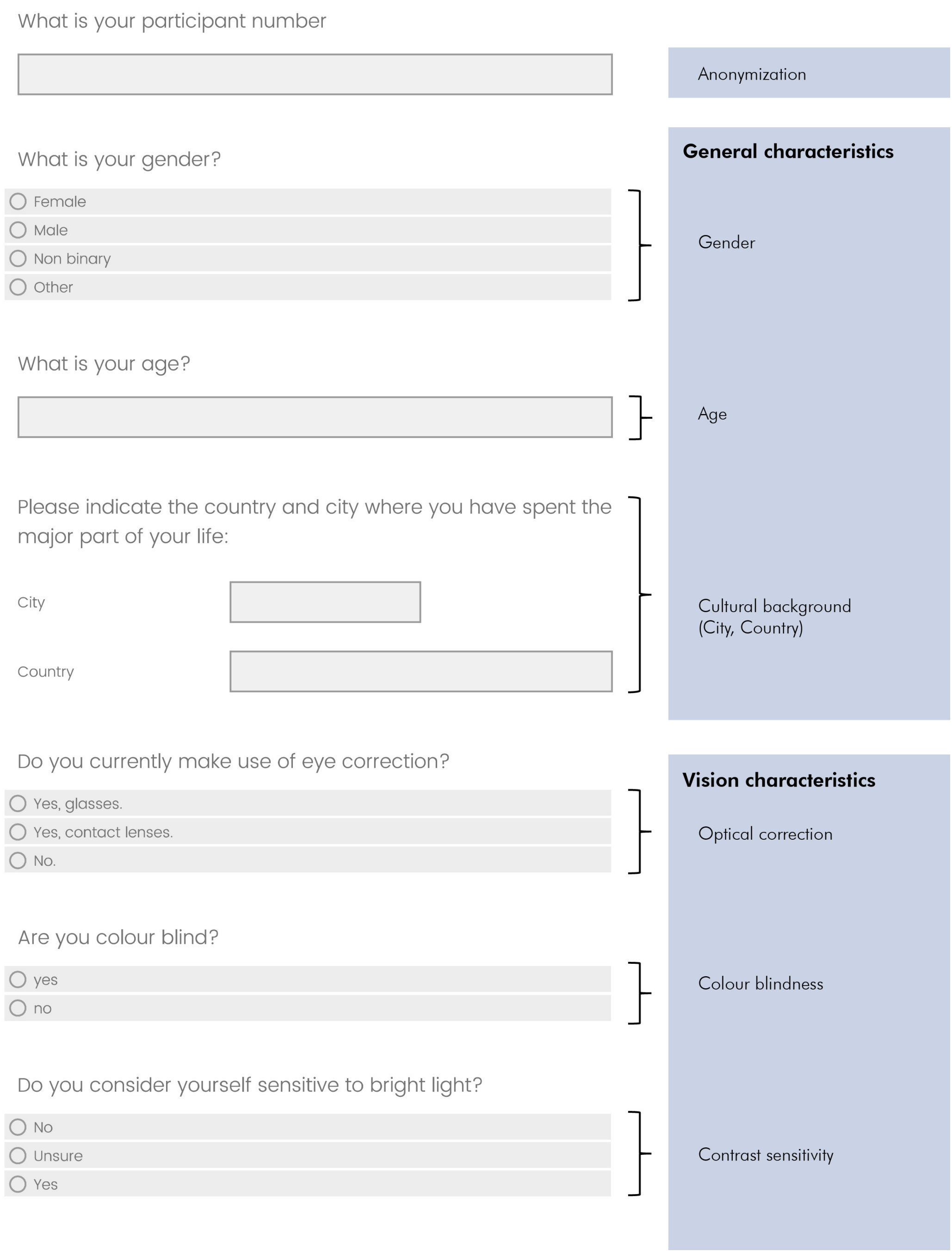
```
#!/bin/bash

pic_fn=$1
printf $pic_fn
pic_s=${pic_fn%.*}

pcompos -x 1525 -y 1525 $pic_fn -597 -143 | pfilt -1 -x 1000 -p 1 > $pic_s.hdr
pcomb -h -f fisheye_corr.cal -o $pic_s.hdr | getinfo -a "VIEW= -vta -vh 184 -vv 184" > $pic_s-vta.hdr
evalglare -i 3250 -d -c $pic_s-coloured.hdr $pic_s-vta.hdr > $pic_s-metrics.txt
normtiff $pic_s-coloured.hdr $pic_s-coloured.jpg

rm $pic_s.hdr $pic_s-coloured.hdr
```

Figure A.10: Evalglare script used in Ubuntu


What is your participant number

Anonymization

General characteristics

What is your gender?

- Female
- Male
- Non binary
- Other

Gender

What is your age?

Age

Please indicate the country and city where you have spent the major part of your life:

City

Country

Cultural background (City, Country)

Vision characteristics

Do you currently make use of eye correction?

- Yes, glasses.
- Yes, contact lenses.
- No.

Optical correction

Are you colour blind?

- yes
- no

Colour blindness

Do you consider yourself sensitive to bright light?

- No
- Unsure
- Yes

Contrast sensitivity

Figure A.11: Questionnaire: Introduction - Demographics

Present state

Sleep

Considering last night, how was the quality of your sleep on a scale of 1 (=worst) to 5 (=best)?

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

Stress

Considering the last 24 hours how was your stress level on a scale of 1 (=uncommon) to 5 (=regular)?

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

Fatigue

Considering the current moment, how would you rate your fatigue level on a scale of 1 (=zero) to 5 (=extremely high)?

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

Caffeine ingestion

How many cups of coffee have you consumed today?

0 ○ 1 ○ 2 ○ 3 ○ 4 or more ○

Experience of the space

Room temperature feeling

How do you feel in the room at the moment?

hot ○ warm ○ slightly warm ○ neutral ○ slightly cool ○ cool ○ cold ○

Visual satisfaction

Considering the current moment, how would you rate your visual satisfaction on a scale of 1 (=minimal) to 5 (=maximal)?

1 ○ 2 ○ 3 ○ 4 ○ 5 ○

View

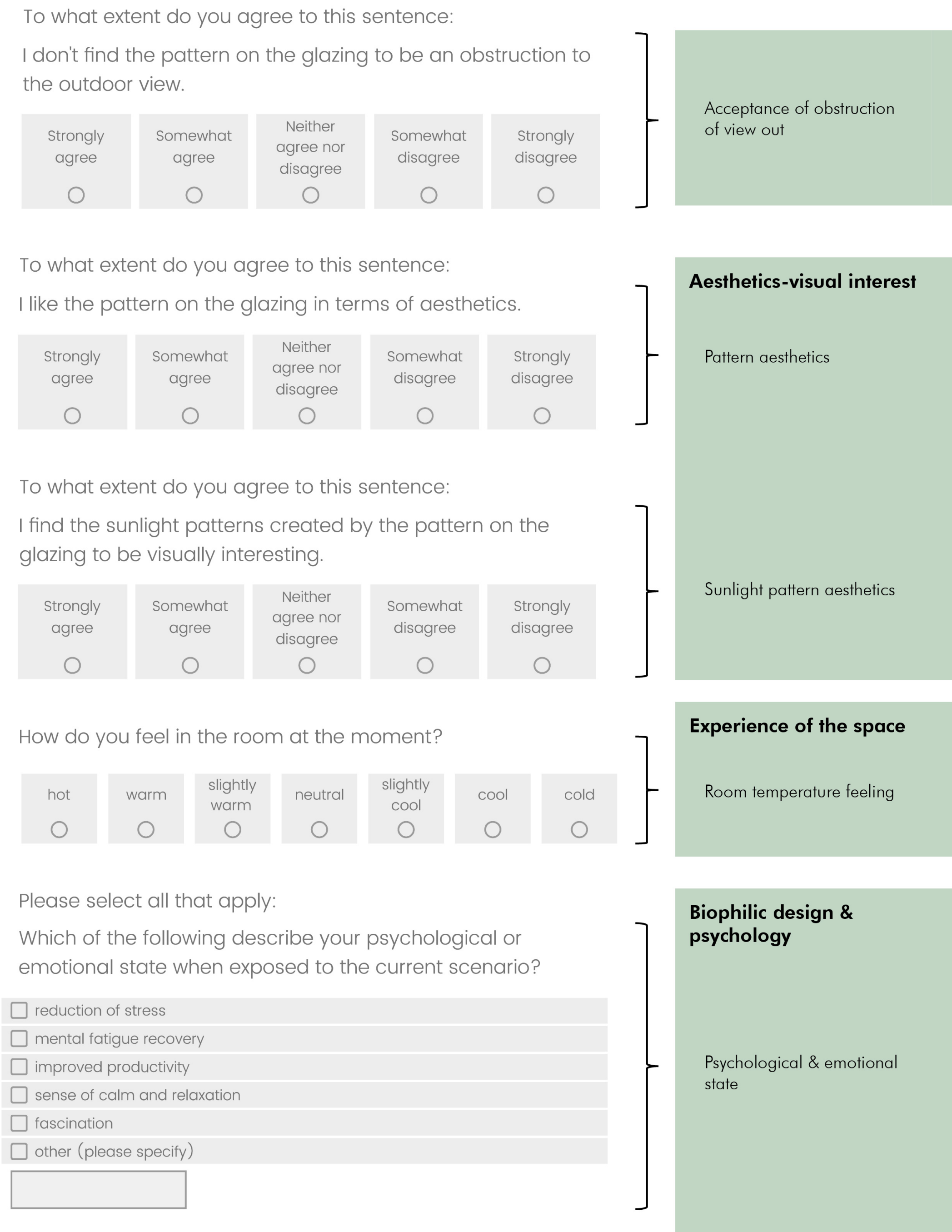
To what extent do you agree to this sentence:

I like the view from the glazing in terms of aesthetics.

Strongly agree ○ Somewhat agree ○ Neither agree nor disagree ○ Somewhat disagree ○ Strongly disagree ○

Figure A.12: Questionnaire: Introduction - Demographics

Figure A.13: Questionnaire: Evaluation


To what extent do you agree to this sentence:

I don't find the pattern on the glazing to be an obstruction to the outdoor view.

Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree

Acceptance of obstruction of view out

To what extent do you agree to this sentence:

I like the pattern on the glazing in terms of aesthetics.

Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree

Aesthetics-visual interest

Pattern aesthetics

To what extent do you agree to this sentence:

I find the sunlight patterns created by the pattern on the glazing to be visually interesting.

Strongly agree | Somewhat agree | Neither agree nor disagree | Somewhat disagree | Strongly disagree

Sunlight pattern aesthetics

How do you feel in the room at the moment?

hot | warm | slightly warm | neutral | slightly cool | cool | cold

Experience of the space

Room temperature feeling

Please select all that apply:

Which of the following describe your psychological or emotional state when exposed to the current scenario?

- reduction of stress
- mental fatigue recovery
- improved productivity
- sense of calm and relaxation
- fascination
- other (please specify)

Biophilic design & psychology

Psychological & emotional state

Figure A.14: Questionnaire: Evaluation

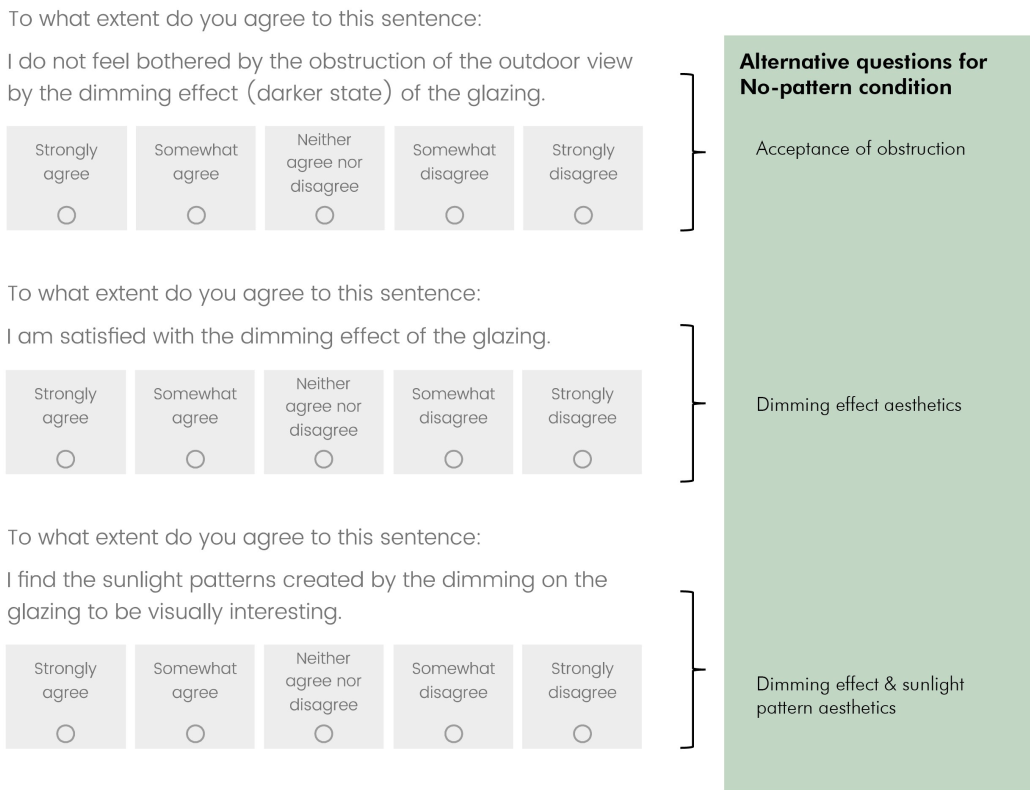


Figure A.15: Questionnaire: Alternative questions for evaluation of No-pattern condition

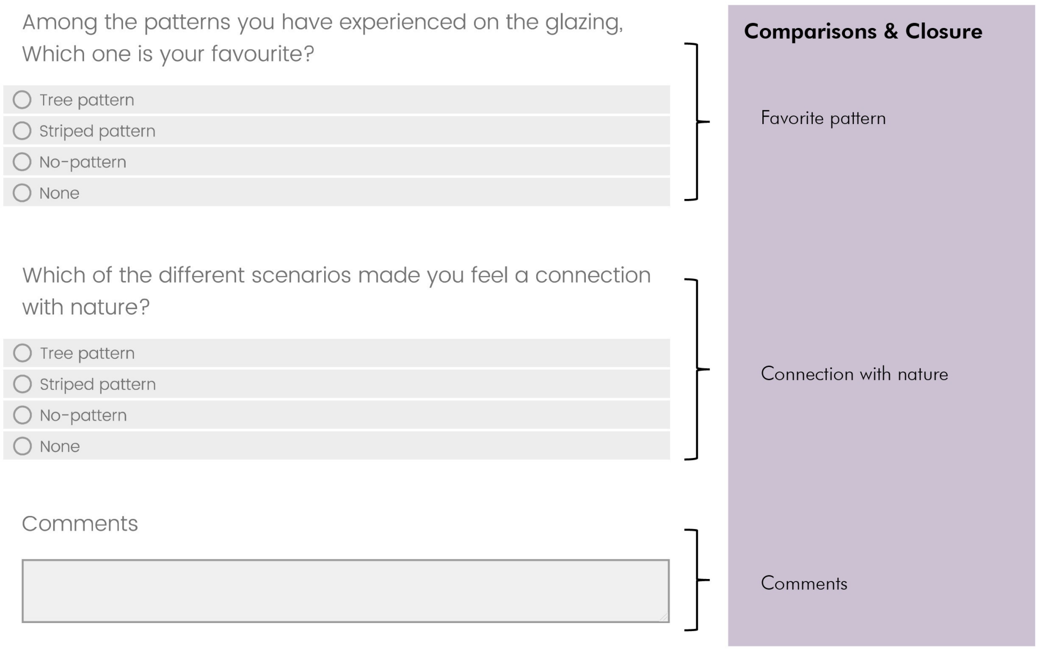


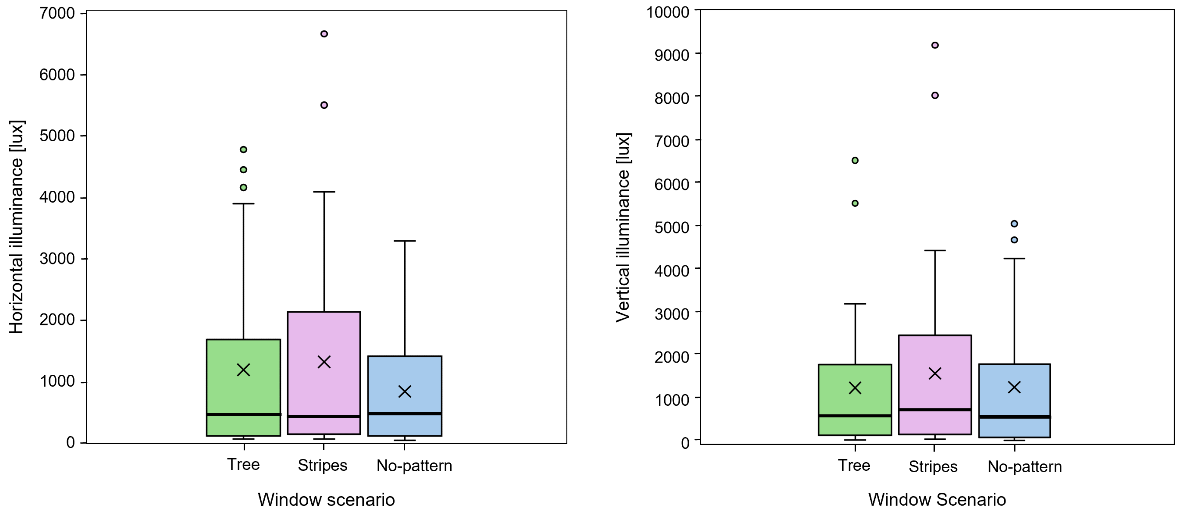
Figure A.16: Questionnaire: Closure

CAMS radiation service - SoDa			Sky condition		
Day	Time	Average DHI/GHI	Clear	Partly Cloudy	Cloudy/Overcast
3/4/2024	9:30-9:45	0.40		Partly Cloudy (to Clear)	
3/4/2024	9:50-10:05	0.76		Partly Cloudy	
3/4/2024	10:10-10:25	0.81			Cloudy/Overcast
3/4/2024	11:00-11:15	0.54		Partly Cloudy	
3/4/2024	11:20-11:35	0.18	Clear		
3/4/2024	11:40-11:55	0.15	Clear		
3/5/2024	9:30-9:45	1.00			Cloudy/Overcast
3/5/2024	9:50-10:05	1.00			Cloudy/Overcast
3/5/2024	10:10-10:25	1.00			Cloudy/Overcast
3/5/2024	11:00-11:15	1.00			Cloudy/Overcast
3/5/2024	11:20-11:35	1.00			Cloudy/Overcast
3/5/2024	11:40-11:55	0.98			Cloudy/Overcast
3/6/2024	9:30-9:45	0.29	Clear		
3/6/2024	9:50-10:05	0.28	Clear		
3/6/2024	10:10-10:25	0.26	Clear		
3/6/2024	11:00-11:15	0.23	Clear		
3/6/2024	11:20-11:35	0.22	Clear		
3/6/2024	11:40-11:55	0.21	Clear		
3/7/2024	9:30-9:45	0.27	Clear		
3/7/2024	9:50-10:05	0.26	Clear		
3/7/2024	10:10-10:25	0.26	Clear		
3/7/2024	11:00-11:15	0.25	Clear		
3/7/2024	11:20-11:35	0.25	Clear		
3/7/2024	11:40-11:55	0.25	Clear		
3/8/2024	9:30-9:45	0.25	Clear		
3/8/2024	9:50-10:05	0.24	Clear		
3/8/2024	10:10-10:25	0.23	Clear		
3/8/2024	11:00-11:15	0.22	Clear		
3/8/2024	11:20-11:35	0.21	Clear		
3/8/2024	11:40-11:55	0.21	Clear		
3/9/2024	9:30-9:45	0.21	Clear		
3/9/2024	9:50-10:05	0.20	Clear		
3/9/2024	10:10-10:25	0.35		Partly Cloudy (to Clear)	
3/9/2024	11:00-11:15	0.79		Partly Cloudy (to Cloudy)	
3/9/2024	11:20-11:35	0.21	Clear (to Partially Cloudy)		
3/9/2024	11:40-11:55	0.17	Clear		
3/10/2024	9:30-9:45	1.00			Cloudy/Overcast
3/10/2024	9:50-10:05	1.00			Cloudy/Overcast
3/10/2024	10:10-10:25	1.00			Cloudy/Overcast
3/10/2024	11:00-11:15	1.00			Cloudy/Overcast
3/10/2024	11:20-11:35	1.00			Cloudy/Overcast
3/10/2024	11:40-11:55	1.00			Cloudy/Overcast
3/11/2024	9:30-9:45	1.00			Cloudy/Overcast
3/11/2024	9:50-10:05	1.00			Cloudy/Overcast
3/11/2024	10:10-10:25	1.00			Cloudy/Overcast
3/11/2024	11:00-11:15	1.00			Cloudy/Overcast
3/11/2024	11:20-11:35	1.00			Cloudy/Overcast
3/11/2024	11:40-11:55	0.99			Cloudy/Overcast
3/12/2024	9:30-9:45	0.99			Cloudy/Overcast
3/12/2024	9:50-10:05	0.98			Cloudy/Overcast
3/12/2024	10:10-10:25	0.96			Cloudy/Overcast
3/13/2024	9:30-9:45	1.00			Cloudy/Overcast
3/13/2024	9:50-10:05	1.00			Cloudy/Overcast
3/13/2024	10:10-10:25	1.00			Cloudy/Overcast
3/13/2024	11:00-11:15	1.00			Cloudy/Overcast
3/13/2024	11:20-11:35	1.00			Cloudy/Overcast
3/13/2024	11:40-11:55	1.00			Cloudy/Overcast
3/15/2024	9:30-9:45	1.00			Cloudy/Overcast
3/15/2024	9:50-10:05	1.00			Cloudy/Overcast
3/15/2024	10:10-10:25	1.00			Cloudy/Overcast
3/15/2024	11:00-11:15	0.95			Cloudy/Overcast
3/15/2024	11:20-11:35	0.98			Cloudy/Overcast
3/15/2024	11:40-11:55	0.97			Cloudy/Overcast
3/16/2024	9:30-9:45	1.00			Cloudy/Overcast
3/16/2024	9:50-10:05	1.00			Cloudy/Overcast
3/16/2024	10:10-10:25	0.99			Cloudy/Overcast
3/16/2024	11:00-11:15	0.95			Cloudy/Overcast
3/16/2024	11:20-11:35	0.97			Cloudy/Overcast

Figure A.17: Sky classification according to ratio

3/16/2024	11:40-11:55	0.97			Cloudy/Overcast
3/17/2024	11:00-11:15	1.00			Cloudy/Overcast
3/17/2024	11:20-11:35	1.00			Cloudy/Overcast
3/17/2024	11:40-11:55	0.99			Cloudy/Overcast
3/18/2024	9:30-9:45	0.52		Partly Cloudy	
3/18/2024	9:50-10:05	0.27	Clear (to Partially Cloudy)		
3/18/2024	10:10-10:25	0.23	Clear		
3/18/2024	11:00-11:15	0.20	Clear		
3/18/2024	11:20-11:35	0.19	Clear		
3/18/2024	11:40-11:55	0.24	Clear		
3/19/2024	11:00-11:15	0.32		Partly Cloudy	
3/19/2024	11:20-11:35	0.32		Partly Cloudy (to Clear)	
3/19/2024	11:40-11:55	0.64		Partly Cloudy (to Clear)	
3/20/2024	9:30-9:45	0.83			Cloudy/Overcast
3/20/2024	9:50-10:05	0.86			Cloudy/Overcast
3/20/2024	10:10-10:25	0.87			Cloudy/Overcast
3/20/2024	11:00-11:15	0.81			Cloudy/Overcast (to Partially Cloudy)
3/20/2024	11:20-11:35	0.78		Partly Cloudy	
3/20/2024	11:40-11:55	0.72		Partly Cloudy	
3/22/2024	9:30-9:45	1.00			Cloudy/Overcast
3/22/2024	9:50-10:05	1.00			Cloudy/Overcast
3/22/2024	10:10-10:25	1.00			Cloudy/Overcast
3/22/2024	11:00-11:15	1.00			Cloudy/Overcast
3/22/2024	11:20-11:35	1.00			Cloudy/Overcast
3/22/2024	11:40-11:55	1.00			Cloudy/Overcast
3/23/2024	9:30-9:45	0.94			Cloudy/Overcast
3/23/2024	9:50-10:05	0.96			Cloudy/Overcast
3/23/2024	10:10-10:25	0.74		Partly Cloudy (to Cloudy)	
3/23/2024	11:00-11:15	0.60		Partly Cloudy	
3/23/2024	11:20-11:35	0.87			Cloudy/Overcast (to Partially Cloudy)
3/23/2024	11:40-11:55	0.92			Cloudy/Overcast
3/24/2024	9:30-9:45	1.00			Cloudy/Overcast
3/24/2024	9:50-10:05	1.00			Cloudy/Overcast
3/24/2024	10:10-10:25	0.99			Cloudy/Overcast
3/24/2024	11:00-11:15	0.99			Cloudy/Overcast
3/24/2024	11:20-11:35	0.99			Cloudy/Overcast
3/24/2024	11:40-11:55	0.98			Cloudy/Overcast
3/25/2024	9:30-9:45	0.39		Partly Cloudy	
3/25/2024	9:50-10:05	0.30	Clear (to Partially Cloudy)		
3/25/2024	10:10-10:25	0.25	Clear		
3/25/2024	11:00-11:15	0.20	Clear		
3/25/2024	11:20-11:35	0.20	Clear		
3/25/2024	11:40-11:55	0.21	Clear		
3/26/2024	9:30-9:45	0.98			Cloudy/Overcast
3/26/2024	9:50-10:05	0.97			Cloudy/Overcast
3/26/2024	10:10-10:25	0.99			Cloudy/Overcast
3/26/2024	11:00-11:15	0.99			Cloudy/Overcast
3/26/2024	11:20-11:35	0.99			Cloudy/Overcast
3/26/2024	11:40-11:55	0.97			Cloudy/Overcast
3/28/2024	9:30-9:45	1.00			Cloudy/Overcast
3/28/2024	9:50-10:05	0.97			Cloudy/Overcast
3/28/2024	10:10-10:25	0.91			Cloudy/Overcast
3/28/2024	11:00-11:15	0.68		Partly Cloudy	
3/28/2024	11:20-11:35	0.73		Partly Cloudy	
3/28/2024	11:40-11:55	0.68		Partly Cloudy	
3/29/2024	9:30-9:45	0.93			Cloudy/Overcast
3/29/2024	9:50-10:05	0.89			Cloudy/Overcast
3/29/2024	10:10-10:25	0.70		Partly Cloudy	
3/29/2024	11:00-11:15	0.48		Partly Cloudy	
3/29/2024	11:20-11:35	0.74		Partly Cloudy	
3/29/2024	11:40-11:55	0.62		Partly Cloudy	
3/30/2024	11:00-11:15	1.00			Cloudy/Overcast
3/30/2024	11:20-11:35	1.00			Cloudy/Overcast
3/30/2024	11:40-11:55	1.00			Cloudy/Overcast

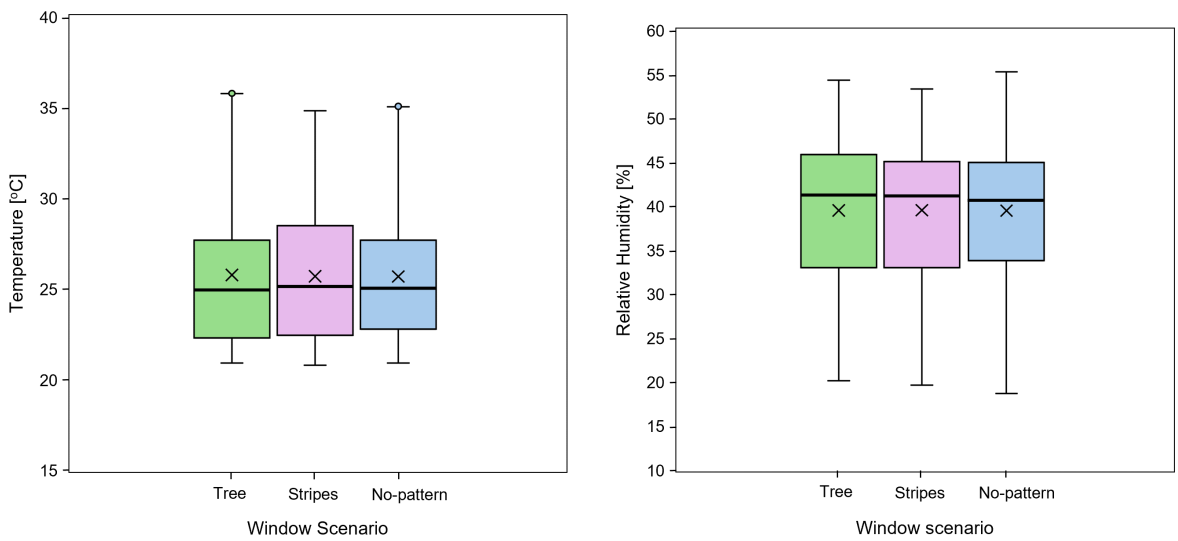
Figure A.18: Sky classification according to ratio (continuity)



(a) Horizontal illuminance

(b) Vertical illuminance

Figure A.19: Horizontal illuminance at the work plane and vertical illuminance from occupants perspective..



(a) Room temperature

(b) Relative humidity

Figure A.20: Room conditions measured at the Hobo mounted on the tripod at the height of the participant's head.

Favourite pattern	Comments
Tree pattern	I liked the tree pattern but would prefer it if it had better resolution. I was neutral to the daylight but was probably also affected by the black surrounding surfaces.
Tree pattern	The sunlight entering the room was varying due to the clouds movement during small time duration.
No-pattern	The glare i was experiencing was from my screen and not the window
Striped pattern	I don't like the blur effect, which is present in all settings no-matter the pattern. It could be used in ground-floor homes for privacy. Great experience! I want to know how this technology works
Tree pattern	No comments
Striped pattern	The tree obstructed a bit more the outside view and was more chaotic.
No-pattern	Although the tree one is aesthetically ideal both for the visual environment and the connection with the outdoor environment, it's still annoying the daylight coming directly into your eyes. That's why no pattern one covers every aspect of discomfort that one would experience.
Striped pattern	I liked the striped pattern the most as I felt at the same time I have good view of outside but not too transparent to distract me. Also, the amount of light inside with this pattern was more satisfactory as it was not too much glare inside. The tree patterns distracted me a bit.
Tree pattern	No comments
Tree pattern	I prefer the tree pattern out of all options because there where more shadows in the room and gradients of light, making the space a better and more comfortable environment to work in. Also, with the tree pattern the room was warm but did not feel uncomfortable at all. With the other two patterns the glare was much more noticeable, especially with the stripped pattern, where the room also got noticeably warmer and it was much more difficult and uncomfortable to work.
Tree pattern	No comments
Tree pattern	After the tree pattern the sunlight was reduced. The discomfort from sunlight was reduced for the stripes pattern because of that.
Tree pattern	Not sure if it is caused by the shading or the window but there is a slight blurring of the image. The tree pattern was my favourite because it did not obstruct the view and the blurring of the window was mitigated. It also made me imagine a tree outside. There was no perceptible change of lighting on the inside space.
Striped pattern	I like the first one the most because it gives me a feeling of order and working in a professional place, and gives me the motivation to work. The second one is a little bit dark when it is cloudy outside. You mention that it is darker than the initial one, and that could be the reason that I keep noticed of it. The third one is a bit too attractive at first. When I get used to it, I can concentrate on my work. I personally think the pattern like this shouldn't appear in a formal business occasion.
No-pattern	Because the glass is a little bit blurry and dark in combination that it is the start of the day, I would like to receive more daylight.
Tree pattern	For a sunny day the tree is aesthetic and really cool. However today is grey and I would prefer no screen at all, not even turned off.
Striped pattern	Bravo Eleni! Very professional approach. I liked the procedure. I chose the striped pattern because i felt that I could focus on the screen very easilty without getting distracted. The other patterns made me look outside more often.
Tree pattern	Tree pattern was by far the nicest window glaze, and offered a nice mix of varied lighting that helped with reduced stress and increased concentration. The varied lighting also helped to minimize glare from the window without overly darkenning the window. Experiment was well conducted with no further comments or concerns.
None	I found the idea of using pattern for glare is interesting , but I would prefer a smaller print(pattern), dimming the glazing can be tolerated during the summer, but since the weather mostly cloudy the day light becomes cold and boring.
No-pattern	The glass appeared dark in all the scenarios. In combination with that dark walls, it created a feeling of discomfort. The dimness/texture of the glass obscured my visual connection to the outside world. However, it allowed me to concentrate better at my work. Out of all the scenarios, the stripes were my least favorite.
Tree pattern	Option of trees has the irregular shape and more space to get the outdoor view which made me feel more fancy, while other patterns just only repeat the interval texture or get frosted with less interests for me.
Tree pattern	The tree pattern seemed most natural and casts the most pleasing shadows. The striped pattern obstructed my view a little bit and is quite distracting in my opinion.
Tree pattern	I think the darker clear glass was better because with the flowers the sun was annoying and with the stripes it was weird. However, the light clear window was also too bright. Therefore the dark clear was blocking the amount of sunlight without disturbing me.
Striped pattern	The light of the room was easier on my eyes when there was a pattern. The leaves pattern was quite obnoxious, but the striped pattern made it seem like window blinds, which felt more normal.
No-pattern	The dimming of the screen is really subtle. I hardly noticed it at first, so it's not annoying or distracting at all, and it really helps against the glare. I thought I was going to like the tree best (I had seen the moving tree before, since I work at The Green Village). I prefer the moving tree over the static tree, because the static tree pattern was really pixelated. Maybe with the moving tree that's harder to notice; at least the moving tree looks more 'realistic' to my eyes. Furthermore I think the moving tree has more relaxing effect.
No-pattern	I liked the no-pattern but I really enjoyed the tree pattern too. I just feel that in different working environments in the city, working with a window pattern like that would appear a little tacky, so I would rather have an actual plant giving me the sense of nature and a neutral window dealing with the glare.
Tree pattern	Tree pattern reduced the glare which was coming inside and it was also aesthetically pleasing. Moreover, it was not affecting much the outdoor view. Strip pattern, I found not a good pattern for glazing as it gives a sense of visual discomfort.

Figure A.21: Additional comments at the closure questionnaire as justification of the favorite scenario question

Tree pattern	I think the first one was th best because of a combination of factors such as the the height of the sun, the weather outside and the nice diffused shadow of sunlight it was created. I deifinitely preferred it over the second on (stripes) because it has a much less classical "office" vibe
Striped pattern	I liked a lot the horizontal fins and the tree pattern because they made the space feel more cozy and because the sun that I was facing in front of me was better blocked. The latter made my workflow (screen and document i was reading) more comfortable and at the same time they enabled the light necessary for me to maybe keep notes or something similar. The only disadvantage in my opinion is the lack of clear view outside, but this was almost the same in all the different scenarios.
Tree pattern	I prefer the tree pattern over the stripes because of the organic figures, also I preferred it over no pattern because it attracted my sight which made me focus less on the actual scenery (better for concentration) and still have the feeling of not being surrounded by walls on all sides (spacious feeling). The stripes were more ''present'' and noticeable. The glare with no-pattern felt a bit too dark (for a cloudy day as today), if at home I would turn down the brightness of the screen. Overall well organized experiment!
Tree pattern	Tree pattern offers the most relaxed and connected to nature feeling. It also offers some sense of relaxation. It would be ideal for days with sufficient amount of light; however, I believe it was also okay during the experiment day with the typical Dutch (cloudy) weather. I wouldn't prefer the stripped pattern at all, given it provided a claustrophobic sense and gave the impression of no escape. Also it served as an obstacle to outside view, whereas the tree pattern did not. Lastly, the no-pattern is similar to the tree pattern, but since it allowed more light to come in, it sometimes was difficult to concentrate to the screen in front of me.
Striped pattern	I found the tree pattern not to full-fill its purpose of trying to enhance a connection with nature, as the pattern itself was blurry and unclear, which I found discomforting. On the other hand the stripped pattern made the room a lot more 'cozy' with the right amount of sunlight in the room.
Tree pattern	The tree pattern felt more natural and made me feel more relaxed and productive. It almost felt like there was a moving tree outside the facade.
Tree pattern	Without any scenes I notice the visibility outside is distorted which is not nice. But once the tree scene is applied, i did not mind the visual distortion and felt like it was a great aesthetic for glazing pattern, inducing sense of calmness and intrigue.
Striped pattern	I feel the most comfortable was the stripped pattern, however the connection with nature using that pattern was somewhat limited due to the width of the strips. I would like to check if minimizing the width or making the strips horizontal instead of vertical could solve this issue.
No-pattern	Tree pattern was a bit too distracting, maybe even more subtle patterns might help. Stripes were too 'strict' not nice to look at or be in. The clear yellower window was for me the nicest, a bit vague outside objects and yellow made it nicer for the eyes with less glare.
Tree pattern	I liked the tree pattern the most, as it had a calming and relaxing effect on me. However, the dimmed glazing at the end was nice as well, as the glaring was reduced and I had a heightened concentration.
None	I felt that non was more relaxing as I can easily see the nature, and also I liked it as it enabled more sun entrance to me. But also the stripes was the second favorable one to me. Then the no-patterns was the following one. Personally, I found the no-pattern was the least favorable one as I could not enjoy the outside view and there was no enough daylight.
Tree pattern	I liked the tree pattern because it creates a joyful environment that does not block the whole outdoor view. Also, it blocks some unwanted visual outdoor elements such as a construction small equipment. Besides, it provides a sense of privacy. Furthermore, it has an inspiration from the nature.
Tree pattern	I liked the tree pattern a lot, however I would choose the plane one in days like today (overcast). The strip pattern was darkening the room a lot... Also the feeling was like being in a Jail? I would understand this patter to prevent glare, but there was no chance today.
Tree pattern	or me the none option is closed to nature because it's a view that isn't changed nor obstructed by anything and the view is clean. However, the view with the tree pattern was the most interesting as it played with what was visible and what's not with a irregular pattern and limited the intensity of the outside.
No-pattern	There were a couple reasons for choosing the no-pattern scenario as my favorite option. In the tree-vine scenario, I found the pattern to be distracting, and it covered too much of the window. Additionally, it still felt like an artificial representation of a natural scene which was distracting, and the dark color made it feel ominous. The straight-line scenario was also not preferred because it felt even more artificial and geometric while also disrupting the amount of light entering the room. The pattern reminded me a blinds that were half open but that I was unable to open all the way. I liked the no-pattern scenario best since it limited the amount of sheer sunlight that entered the room while still giving me the ability to see the outside clearly. The light pattern in this scenario was also the most interesting.
Tree pattern	I prefer the tree pattern because the shades on the floor and table due to the sun makes me feel like I am outside in the nature. I find it more interesting and attractive than the other ones.
No-pattern	It was a very interesting experience. The illuminance is the room is satisfying with the no-pattern set up and I would like to work in such environment. I am also looking forward to see how this works in different weathers.

Figure A.22: Additional comments at the closure questionnaire as justification of the favorite scenario question (continuity)

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