INTEGRATED FACADE SIMULATOR: DYNAMIC TOOL TO STUDY THE IMPACT OF SOLAR RADIATION ON HUMAN FACADE INTERACTION

by

Amir Hosseinzadeh Zarrabi

A dissertation submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in
Infrastructure and Environmental Systems

Charlotte

2023

Approved by:

Dr. Mona Azarbayjani

Dr.Dimitris Papanikolaou

Dr.Zachary Wartell

Dr.Faramarz Farahi

ABSTRACT

AMIR HOSSEINZADEH ZARRABI. Integrated facade simulator: Dynamic tool to study the impact of solar radiation on human facade interaction. (Under the direction of DR. MONA AZARBAYJANI)

Today, people are spending more than 90% of their time indoors that have a great influence on their well-being and visual and thermal satisfaction. In addition, the building sector, as a major urban infrastructure, consumes about 40% of global produced energy, which is mostly used for providing comfortable conditions, yet people are still largely dissatisfied with their environmental comfort. Recent research is trying to leverage occupants' demand in the building's control loop to consider the occupant's well-being as well as the building's energy savings. However, current approaches for studying the relationship between facade systems and occupants' facade control have remained limited since the existing tools do not take into account the simultaneous effect of facade visual and thermal performance on human comfort perception. The lack of empirical data means and methods to study Human Facade Interaction (HFI) have led to uncertainty in occupants' behavior models that influence the accuracy of human comfort and building energy consumption estimates. This dissertation proposes a novel assist-tool for a human facade interaction lab consisting of a cost-effective solar simulator in an indoor testbed to provide solar radiation at different intensities and angles in human facade interaction studies. Three studies covering the proposed tool are presented in order to: 1) Provide a review of methods and tools applied in Human facade interaction; 2) Development of a Low-Cost Large-Scale Solar Simulator with Flexible Mounting; and, 3) Thermal assessment of a testbed equipped with an indoor solar simulator to be utilized for hybrid reality in an integrated framework with building performance simulation. The first study reviews how different tools, means, and methods are employed to investigate human facade interaction studies and examines recent research applications and findings.

Throughout the study, we identify the influencing external and internal factors that impact human behavior and the findings related to the application of those factors in each method of the HFI investigation's tools and mediums; namely, Physical Prototyping and acclimatized chamber, Immersive Virtual reality, Hybrid Reality as well as a number of identified gaps within each method. This paper also provides insight into current practices, trends in future methodologies, and required tools in the field of HFI. According to this study, the impact of solar radiation energy was one of the significant factors for human facade interaction that has been overshadowed by the daylight and visual qualities in human facade interaction studies. In the second study, we developed a dynamic solar simulator designed to address the aforementioned gap in the human facade interaction and provide standard, accurate, solar radiation data for facade studies. In order to examine the accuracy of solar simulators to provide uniform solar intensity for varying times of day and season, a series of experiments were conducted with regard to the solar spectrum, while uniformity in different angles has been achieved and optimized. The third study examines the adequacy of the novel use of a solar simulator to provide solar radiation for the (multi-sensory) hybrid environment in an integrated framework with Performance Simulations (BPS). To that end, we compare three states of a dynamic facade on the temperature stratification of a seated man, from ankle to head, in a physical environment, with simulated data in building performance simulation tools. This study confirms the compatibility of the novel indoor solar simulator as a sufficient alternative to provide thermal stimuli for the hybrid multi-sensory environment that could be utilized as a complementary tool with building performance tools. This dissertation is one of the first attempts to develop a cost-effective solar simulator for an indoor, multi-sensory, hybrid reality that provides precise and accurate thermal stimuli for human facade interaction studies. The findings of this dissertation demonstrates the importance of affordable and precise tools in the human-centric facade design approach with a goal to promote

more sustainable and efficient building facade technologies.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Energy consumption in the building sector accounts for approximately 41% of total energy consumption in the United States [1]. Heating, cooling, and ventilation are the major contributors to energy consumption in commercial buildings and are largely influenced by the performance of the building envelope system [1]. Despite advances in facade systems, design processes, and the integration of new technologies such as sensors and semi/automated shading and lighting systems, current systems are not performing more efficiently than traditional buildings [2]. This is partly due to the lack of incorporating human dimensions in modeling, leading to uncertainty in occupant behavior modeling. Research has shown that human factors, such as physiology and psychology, play a significant role in human-facade interactions. Still, this aspect has often been overlooked in favor of focusing on external factors such as climate, daylight, and solar radiation. To achieve more energy-efficient facades and better integration of new technologies and sustainable design, it is crucial for architects, design consultants, building engineers, and operators to understand the relationship between occupant behavior and building energy consumption [2]. This dissertation aims to address this gap by exploring how dynamic facade features, daylight, and solar radiation can impact occupant interactions with facades, and by proposing a new framework and tools to address gaps in human-facade interactions.

0.1 Problem Statement

Building science acknowledges that people's internal factors significantly impact their experiences and behaviors within the built environment. Similarly, research in the areas of daylight and solar radiation has established a connection between physiological differences and varying perceptions and sensations of space [3]. However, most modeling tools and metrics tend to consider external factors (e.g., sun angle, outside weather, context, etc.) to calculate the facade performance. This trend has been criticized and recognized as the main cause of uncertainty in occupantsâ facade-related behavior that impacts the buildingâs energy consumption in the operation phase life cycle [4]. In parallel, the contemporary facade design process shows a shift towards user-centric approaches that consider humans in the loop and address well-being, comfort, and efficiency simultaneously. While much research has focused on the impact of daylight alone on occupant behavior in human-facade interactions, less emphasis has been placed on the combined effects of solar radiation and daylighting on the occupantsâ decision-making process. Given the cross-effect of daylight and thermal impact on how occupants perceive their environment, current methodologies in daylight research stress the significance of conducting multi-sensory experiments [5]. This includes conducting empirical studies at varying dates and times to build a comprehensive training data set for predicting and controlling facade performance [?]. To achieve this, we develop and use an experimental tool designed to address the limitations of existing methods, specifically the lack of a multi-sensory tool for studying the impact of solar radiation on human-facade interact

0.2 Objectives and Research Questions

The overarching goal of this project is to introduce an assist tool and method to study the impact of solar radiation on human Facade interactions by taking into thermal stimuli along with other factors to promote a user-centric approach for a more efficient and sustainable built facade system. This research evaluated the simulation of solar radiation in a physical environment for the multi-sensory study of human facade interactions. Specific objectives of the project can be separated into three main sections: Section 1) A review of methods and tools applied in Human facade interaction. Section 2) Development of A Low-Cost Large-Scale Solar Simulator with

Flexible Mounting. Section 3) Thermal Assessment of testbed equipped with the indoor solar simulator to be utilized for hybrid reality in an integrated framework with building performance simulation.

Section 1:A review of methods and tools applied in Human facade interaction assessment

In this section, we first reviewed all factors that could potentially impact human facade interactions and then evaluated different methods and tools that use those factors to study the impact of facades on human behavior. And finally, we illustrate the gap in the studies that need to be addressed in a future study.

Objective 1 to investigate internal and external factors that impact occupant behaviors.

Question 1-1: What are the significant factors that could potentially impact facade-related behaviors?

Question 1-2: How could each factor potentially impact human facade interaction?

Objective 2: To demonstrate the application of internal and external factors in a different method and tool. This study's goal is to find out the current gap to study the impact of those factors on human facade interaction,

Question 2-1: which major factors caused uncertainty and have not been studied sufficiently?

Question 2-2: what are the most comprehensive and effective approaches that cover most of the significant factors that impact human facade interaction?

Section 2. Development of A Low-Cost Large-Scale Solar Simulator with Flexible Mounting

In this section, we investigate how the spatial impact of the Facade under the co-presence of thermal and visual stimuli influences the user decision-making process in HFI. In that sense, the users' behavioral information (the number type, hierarchical order, occurrence probabilities, patterns, response time) are identified, and their correlations with physiological data (heart rate, skin temperature) are examined.

Since solar radiation significantly impacts human behavior and could be utilized with virtual reality for a hybrid lab environment as a multi-sensory environment, we developed a solar simulator to mimic solar radiation with different intensities and angles. Therefore, we first explain the construction of a cost-effective solar simulator, then examine and optimize it based on the Specification for Solar Simulation standards. Finally, we developed a method to mimic solar radiation at different angles and intensities.

Objective1: develop the cost-effective solar simulator to study the impact of solar radiation on human-scale study

Question 2-1: how develop a solar simulator to meet minimum standards for human-scale facade study with low-cost lights and structures?

Objective2: to investigate a method to mimic solar radiation for different times of the day (angular radiation).

Question 2-1: how to mimic angular solar radiation and simultaneously keep the uniformity of solar irradiance on the target surface?

Section 3: A human-scale test bed for thermal analysis of building facade technologies in a multi sensory environment

In this study, we establish a framework for examining the interaction between thermal and visual stimuli in human-facade interaction studies. Following this framework, we introduce and evaluate a tool and test bed to study various facade technologies on a human scale. To accomplish this, a novel solar simulator was integrated into a controlled room to create a test bed for thermal studies of building facade technology. To assess the thermal performance of the solar simulator within this framework, we compare the solar radiation and air temperature at different heights to simulated data from building performance simulations.

Objective: Investigate compatibility of the human-scale solar simulator to be used for thermal analysis of facade systems in an integrated framework with building performance simulation.

Question 3-1 What is the method for replicating the solar heat gain of facade systems in a controlled indoor multi-sensory environment?

Question 3-2 Is replicating the solar heat gain of the facade in the test comparable to the simulated heat gain produced by building performance tools?

0.3 Research Outline

Chapter 1: This chapter starts with a comprehensive review of current knowledge and understanding of human facade interaction. It examines the internal and external factors that affect comfort and behavior related to facades, including visual and thermal stimuli. The chapter also explores the methods and tools currently used to study the impact of these factors on human facade interaction. This literature review highlights the current gaps in knowledge related to the main research question and underscores important elements that are crucial to the present dissertation and the field as a whole. Chapter 2: This chapter reviews current knowledge and understanding of human facade interaction. It examines the internal and external factors that impact comfort and behavior related to facades, including visual and thermal stimuli. The chapter explores the methods and tools used to study the impact of these factors on human facade interaction. Additionally, it identifies gaps in current knowledge that are related to the main research question and highlights important elements that are relevant to the present thesis and the field. Chapter 3: This chapter focuses on the examination of dynamic solar simulators as a novel technology that can mimic solar radiation at different times and seasons. The chapter investigates the application of the solar simulator as a means of simulating solar radiation with varying intensities and angles and examines its ability to be used to study facades on a human scale. The thermal performance of the solar simulator is analyzed by measuring its spectral match and uniformity based on industry standards and by optimizing its solar intensity based on the solar angle. The results of this research introduce tools that can be used to study human behavior under the influence of different facade systems. Chapter 4: This chapter assesses the compatibility of the solar simulator within an integrated framework for studying the impact of solar radiation as a thermal stimulus on human facade interaction. The effectiveness of the solar simulator for thermal analysis is evaluated by comparing the solar heat gain of the test bed, which is equipped with the solar simulator, with simulated heat gain data from building performance tools. The results of this evaluation will indicate the usefulness of the solar simulator as a complementary tool for studying the impact of solar radiation on facade technologies in human facade interaction studies

A REVIEW OF METHODS AND TOOLS APPLIED IN HUMAN FACADE INTERACTION ASSESSMENT

0.1 Abstract

Human Facade Interaction (HFI) plays a crucial role in energy consumption, comfort, and well-being. In recent years, significant advancements have been made in facade systems, the design process, and the application of new technologies such as sensors, adaptive shading, and lighting systems [6]. However, despite these improvements, buildings equipped with dynamic facade systems do not perform more efficiently than conventional buildings, and there is a discrepancy between predicted and actual energy performance [7, 8, 9, 10, 11, 12, 13]. Furthermore, occupants are often unsatisfied with these systems due to conflicting requirements like energy efficiency and comfort [14]. To address these conflicts and understand HFI, researchers from various disciplines have studied human behavior and decision-making processes in response to dynamic facade systems [15]. This paper reviews the different methods and tools used to investigate HFI and examines recent research findings. The review identifies the external and internal factors that impact human behavior and examines how these factors have been applied in each method (Physical Prototyping and Acclimatized Chamber, Immersive Virtual Reality, and Hybrid Reality). Finally, The paper provides insight on the current practices and future trends in the field of Human Facade Interaction (HFI) and delves into the potential avenues for further research. The review highlights the gaps and limitations of various approaches to studying HFI, causing ambiguity in the models predicting occupants' behavior and affecting the precision of assessments on human comfort and energy consumption in buildings.

0.2 Introduction

Dynamic facade technologies (shading devices, external shading system, responsive glazing and facades, switchable glazing) are the components of advanced fenestration systems that allow occupants to interact and regulate the environment based on their comfort and preferences while reducing energy consumption. These envelope systems impact lighting and HVAC loads, accounting for more than 30% of energy use in U.S commercial buildings [16]. In the past decade, modern advancements in facade systems have led to high-energy performative buildings. However, as a considerable amount of study indicates, there are significant gaps between the expected and actual energy consumption in buildings [7, 17, 9, 10, 11, 12, 13]. The discrepancy between the design phase and operation phase in buildings has been linked to occupant behavior, leading to uncertainty in building simulation and the limited effectiveness of facade control solutions [18, 19]. The human behavior in the building is divided into occupancy (presence or absence of occupants) and occupants' Interactions [20]. The Human-facade interaction (HFI) is the main part of human behavior, which defines the relationship between occupant behavior and facade systems in the perimeter zone. As the occupants regulate the environment by the Interaction with dynamic facades (changing the facade status), comfort, wellbeing, and also energy consumption are simultaneously affected [21, 22, 23]. Therefore, the occupants' facade-related behavior directly impacts the lighting load by regulating the daylight in space. Besides, it affects the HVAC system's energy consumption by influencing solar heat gain on the internal cooling and heating loads [24]. Studying human facade interaction reveals stimulus-response relationships between occupants and facade systems that address human behavior impact on facade performance in the controlling at the operation phase and simulation at the design phase.

Researchers have increasingly emphasized the importance of understanding the factors of interaction between users in energy research, as it becomes increasingly

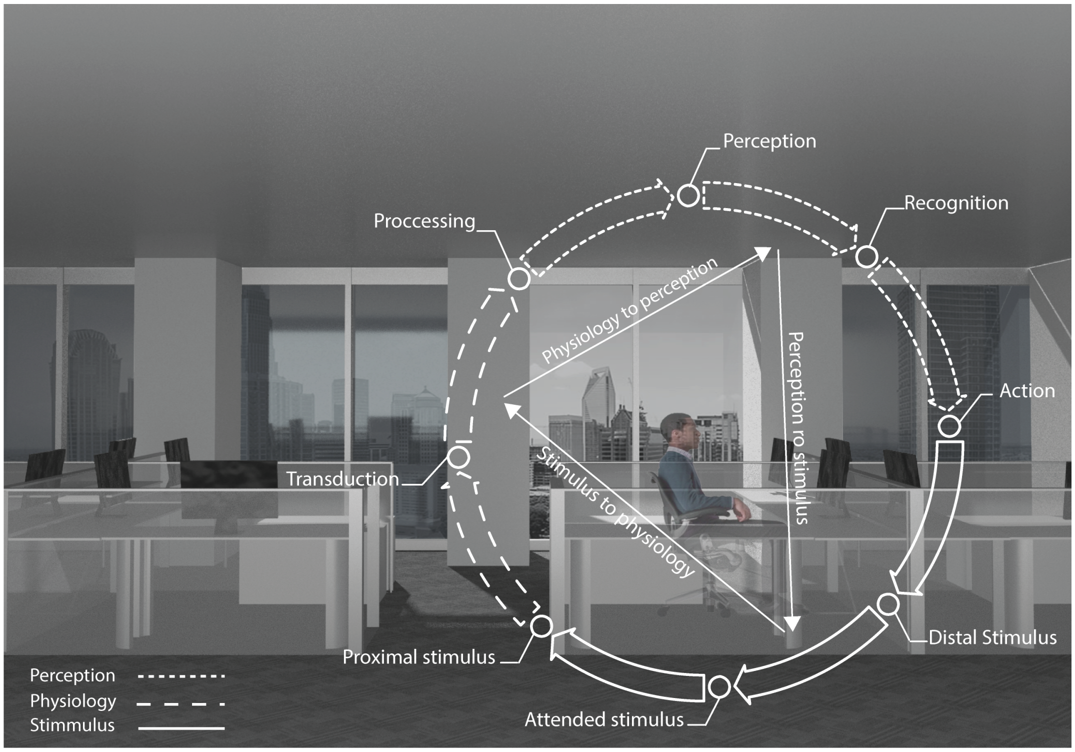

Figure 1: human decision-making process

user-centered. They have proposed integrating physiological and psychological science from the lens of engineering. [25, 26, 27, 28, 29, 30, 31]. However, the Investigation of HFI is a challenging task and has caused a lot of areas of uncertainties. The human facade interaction is a complex human decision-making process that is defined in three steps: sensation, perception, and facade related behavior in the environment to select a specific course of action among available alternatives and options [32, 33, 34], The process of human decision-making, as outlined by Goldstein, is seen as an ongoing sequence of processing steps, as depicted in Figure 1. At a high level, the iterative perceptual process is broken down into three stages: 1) the transformation of external stimuli into physiological responses, 2) the perceptual interpretation of these signals, and 3) the behavioral actions that arise from our perceptions and impact the external world, creating a never-ending cycle that represents our actual experience [32].

To fully comprehend human facade interaction and determine the underlying factors, it is necessary to examine all three steps of the human decision-making process.

Recently, studies have concentrated on investigating the impact of external factors, such as the environment, and internal factors, such as the physiological and psychological state of the occupants, on their perceptions and interactions with facades [35]. Despite these efforts, a comprehensive examination of the complexity of the interaction between occupants, smart facades, and automation systems has not been conducted. This study aims to highlight the current state of the field by providing a thorough overview of previous research and evaluating the different methodologies and tools utilized to understand the relationship between users, relevant factors, and energy consumption. We believe this review offers valuable insight and a significant contribution to the field.

0.2.1 Goals and Organization

To examine the method and tools of human facade interaction, our objectives are as follows: 1. Identify the influencing factors that have been used to characterize occupant interaction with facades. 2. Provide an overview of the research methods, instruments, and tools used to study human interactions in response to various factors. 3. Highlight existing gaps in research and provide general suggestions for future research. This literature review is organized according to internal and external factors that the researchers have investigated in their single or multi-sensory experiments. A multi-sensory study refers to a study that considers and accounts for more than one factor, both in its current and intended usage [36]. The rest of the paper is structured as follows:

- Section 2 provides an overview of the literature review methodology and the classification criteria
- Section 3 Identifies various factors that affect human behavior and interaction in relation to a facade system.
- Section 4 provides a comprehensive overview of the methods, means, and tools

employed in studies of HFI and assesses how the identified factors are applied.

- Section 5 addresses current gaps in existing research and provides suggestions for further research in this area.
- Section 6 Concluding remarks.

0.3 Approach and selection criteria

For this paper, we conducted a literature search within the last 30 years for relevant studies. Within this timeframe, there have been prominent technological developments and improvements in the HFI domain. To understand how occupants interact with facade systems, the purpose of this study was to identify studies that have used different methods, means, and tools to consider one or more Influencing factors. The following databases were used for the literature search: Science Direct, Taylor and Francis, Academic Search Complete, and Google Scholar. Multiple keyword combinations were used in the search string (representing multi-character truncated search terms or wildcards):

- Facade system-related keywords (Blind, Window, Dynamic shading, Shading, glazing, Automated, Envelope. Adaptive, switchable glazing)
- Building system related keywords (IoT Building, Control strategies, Built environment)
- Occupant-related keywords (Human, physiological, psychological, occupant, employee, individual, personal, comfort, wellbeing, perception, sensation).
- Interaction-related keywords (Interaction, Response, Behavior, Action).
- labels of enumerations
- Energy-related keywords (energy, consumption, efficiency).

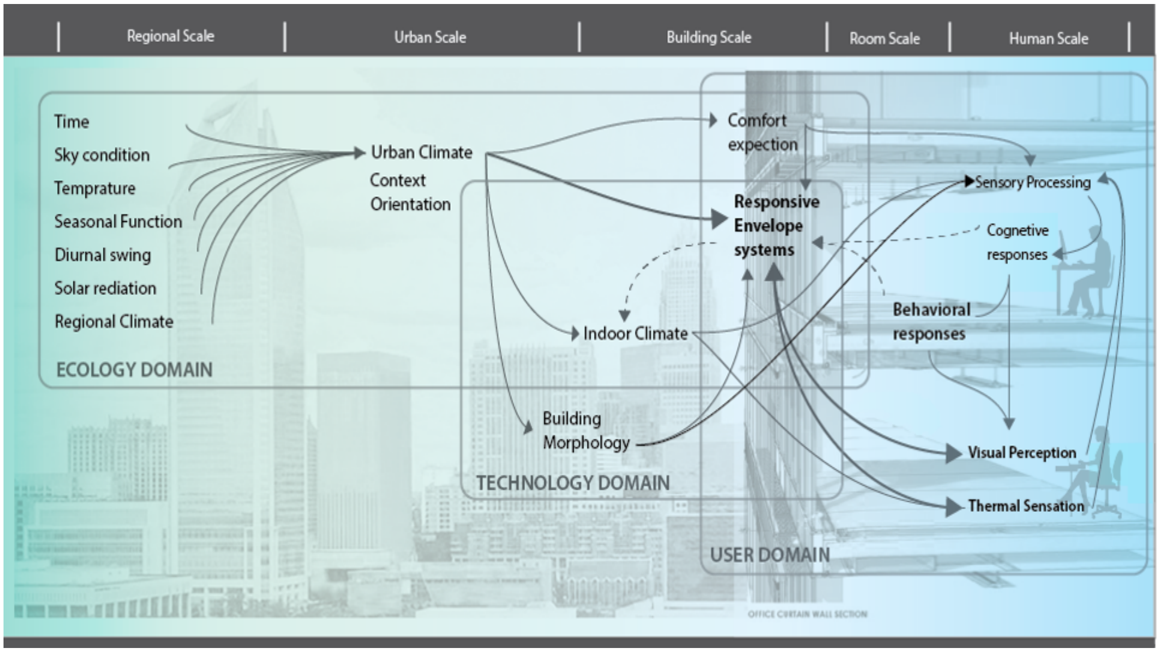

Figure 2: External and internal factors that impact on human facade interaction

In the search process, we reviewed 152 articles and included 106 while excluding 46. We focused on studies that explicitly examined the impact of internal and external factors on occupant comfort and excluded those that did not specifically explore this relationship. We excluded most literature reviews and systematic reviews, as well as studies that did not mention the term "interaction" in relation to occupant comfort. In some cases, the discussion of feedback mechanisms lacked an explanation of their influence on occupants' behavior.

0.4 Summary of key influential factors identified

This section identifies influencing factors during our review to provide a high-level perspective on Inter-scalar factors with interdependence relationships. While a multitude of external and internal factors exist across different human-building interactions, this review focuses on 17 factors that appear in our studies(Figure 2).

The existing forces in ecology, technology, and user domains are in the feedback loop that shapes the human perception of comfort and behavior [21, 37]. Most studies focused on ecology and the role of technology (external factors). Nevertheless, the occupant's experience in the perimeter zone of the building is a multi-sensory experience influenced by human factors that need to be considered in the modeling and collecting data approach. In the past decade, a significant amount of studies have been conducted to indicate the primary factors that impact energy consumption in the building. According to these studies, we categorize five main influencing factors on a range of scales that could affect occupant behavior and total energy use: (1) Regional factors, (2) Urban factors, (3) Building factors, (4) Facade factors,(5) Human scale.

0.4.1 Regional-scale

0.4.1.1 Daylight

The series of occupant surveys in the office buildings show, most participants close their Shading devices (blinds) to prevent heat and glare on their computer screens [20]. The study found that most occupants in private offices closed their blinds to protect their workstations and screens from glare (27.4%) or reduce heat (27.4%). Only 12.3% reported using them for privacy and security [38]. The research also shows that the values of blind occlusion were highly dependent on sky conditions. The study showed that the incidence of solar radiation on the facade caused significant differences in blind usage among different sky conditions. Moreover, the long-term perception of solar irradiance can impact the use of the blind [39]. Although the incidence of solar radiation on the facade could explain the facade interactions, solar penetration depth can describe the interaction more accurately [40]. Penetration depth refers to the distance from the facade to the point where solar radiation reaches the work plane. Studies suggest that the highest level of interaction occurs when the illuminance on the work plane is between 200 lux and 1200 lux [41]. Studies indicate that the threshold for exterior vertical illuminance is between 50 and 250 lux, at which point occupants tend to change the blind status from open to closed [40]. In addition to illuminance, there are also other physical factors that explain human facade interaction in the luminous environment. Several studies have indicated that the daylight glare probabilities and the index had the highest correlation with the occupantâs facade interaction [42]. Other variables, including daylight work plane illuminance [41, 43], vertical illuminance on the computer screen [44], and solar altitude, are also considered important factors in the occupants' visual motivations for interacting with the facade. Daylight Perception also thought about non-physical examples that affect residents indirectly. According to studies, occupants exposed to light during the workweek increased their physical activities and sleep duration [45]. As previous studies show, occupants also believed that daylight was better than artificial lighting [46]. Therefore, occupants tend to choose seats close to windows, even if it means tolerating visual or thermal discomfort [47]. The quality of light and color temperature not only impact human health but also influence occupant comfort [48]. Research has shown that color temperature has a significant effect on thermal perception during short exposures, which can drive heat discomfort. The interrelation between thermal and visual factors will be discussed in further detail in the following sections:

0.4.1.2 Solar radiation

In addition to visual factors, solar heat radiation is another factor that affects heat discomfort index. Solar radiation impacts thermal comfort through both direct (local body temperature) and indirect (ambient temperature) effects on thermoception [49]. The human body absorbs heat from solar radiation that reaches clothing or skin, and exchanges heat with the indoor environment through convection, which influences both physiological and psychological responses [50].The cross-effect between thermal and visual comfort has been reported as a significant interaction between these two stimuli. It has been examined how the thermal environment affects visual perception and how the visual environment affects thermal perception[51]. It is generally accepted that light conditions are more comfortable when the temperature is perceived as comfortable. Previous research has found that the highest levels of visual comfort are reported during neutral temperature, which is also the thermally most comfortable condition. Under these conditions, light intensity is also perceived as natural (neither dark nor bright). The results show a strong relationship between ambient temperature and the perceived color temperature of light. As ambient temperature increases, the light is perceived as warmer in color. For instance, exposure to 5800 K (bluish) is perceived as the coolest color during cool conditions, while the highest correlated color temperature was most comfortable during high temperature [52, 53]. Thermal perception can be influenced by both visual and quantitative factors. This highlights the importance of considering the whole indoor environment, including all visual and thermal stimuli, in shaping our multi-sensory spatial experience. Solar radiation plays a crucial role in human facade interaction, as demonstrated by studies that show how a threshold of 150 w/m2 solar radiation can trigger occupants to change the facade status due to discomfort [54, 55]. They used the sunshine index to measure solar radiation based on horizontal global radiation and time of day, but only observed maximum values during sunny midday conditions. This approach leads to inconsistencies with other studies. Solar radiation is widely recognized as a key predictor of HFI that affects occupants' energy-related behavior. [55, 42, 38, 46, 56].

0.4.1.3 Outdoor Temperature

The outdoor temperature impacts the windows' surface, and it can cause discomfort for the occupants. In the winter, due to temperature asymmetry between room and window surfaces, occupants experience discomfort. In that case, people prefer to have solar radiation to compensate for their heat loss. In the summer, occupants could experience temperatures above 60 (40) in perimeter zones due to solar gain from the direct transmission and radiated heat of windows. Since occupants experience discomfort, the possibility of their facade interaction is increased. Therefore, our outdoor temperature could indirectly be considered as an influencing factor in human facade interaction. New high-performance buildings provide better comfort for the occupants by reducing the heat loss or heat gain, leading to lower heating and cooling and even lighting costs [57].

0.4.1.4 Times of day

The different studies analyzed the influence of time of day on occupants ' energy-related behavior. The participants' interactions varied based on different times throughout the day. The occupant's actions are influenced by variations of the sunlight, solar intensity, and glare at different times of the day. As the study indicated, the time of day could impact energy consumption by 10% due to the variation of occupants' interactions [58].

0.4.1.5 Season

Seasonal effects also have been investigated to understand occupant interaction between different seasons. However, only a few studies have examined seasonal effects. Mahdavi surveyed three office buildings in a different season [59]. His research revealed people are more likely to deploy more shading during the cooling season (up to 30% higher). Another field measurement study in 26 European buildings also indicates that 15 - 20% occlusion occurred in winter compared to 30 - 35% for autumn and 35 - 40% for spring and summer [60]. However, the findings from some studies reported the effect on seasonal changes depending on the indoor physical variables such as temperature, daylight levels [61]. Thus they found the contribution of seasonal effect statistically insignificant. Generally, there are still no conclusive results regarding the role of the season on the HFI. These findings suggest that considering the proper variable as the trigger, one might be able to HFI throughout the year; however, further investigation is required.

0.4.1.6 Urban scale

The facade related behavior of occupants does not only depend on the characteristics of the building itself; the microclimate at the urban scale does have an important effect on the occupants' comfort and behavior [62]. Buildings in an urban context are exposed to urban heat due to increased maximum air temperatures and the heat island effect. For example, the lower wind speed due to the wind sheltering effect of buildings altered and reflected solar heat gain due to building shadowing. [63, 64]. The urban scale factors provide the specific microclimate, which is different from the regional climate. Therefore, the environmental stimuli are not directly and come from regional factors, and microclimate modifies the intensity and quality of thermal, visual, air, and acoustic stimuli. However, only a few studies consider these factors in their HFI studies.

0.4.1.7 View

The interaction of occupants with facade systems can also be explained by view as another context factor that cannot be measured with typical sensors. The view and connection to the outside are non-physical reasons for occupants to interact with the envelope[65, 42] reported that most occupants tend to sit close to the widow, although the sit was exposed to a high amount of solar radiation and glare [66]. This finding is interpreted that the majority of occupants prefer the quality of view at the expense of visual and thermal comfort. The facade and shading devices may block the view at different levels. Nevertheless, many researchers [38, 56, 55] have mentioned the view to outside as a possible trigger for HFI, yet the relation between view and the facade is not conclusive.

0.4.2 Building Scale

0.4.2.1 Typologies of Facade Systems

The dynamic facade (Dynamic shading facade + smart window) is categorized based on its ability to adapt or change its geometry or properties in response to environmental stimuli and occupantsâ comfort and preferences [67]. The significant difference between the dynamic facade system and the fixed one is the ability to change according to external and internal factors to maintain occupantsâ comfort and needs. On the other hand, the fixed shade is mainly designed to reduce the buildingâs thermal loads during the cooling season. A series of recent studies have indicated, the dynamic facade is categorized based on the type of morphologies (blind, louvers, Dynamic Egg-Crate, etc.), type of actuation (Manual or Automated), mode of actuation (Intrinsic material properties, remote control, environmental sensing, Occupant-centered), and interfaces that could adapt to control and manage lighting, daylight, and solar heat radiation on a building facade. As the few long-term studies show, different facade morphologies significantly impact comfort and energy consumption. However, despite the significant differences among facade typologies, only a few studies have considered the impact of facade typologies on occupantsâ choices and energy-related behavior. Human interaction with each facade typology is also dependent on the control systems, Interfaces, and the way they incorporate the occupantsâ feedback in the loop. The control and interface are affected by the user decision-making process in HFI. Recently, automated systems, including automated facades, have been introduced to regulate indoor environments. However, studies have shown that these facades have led to a high level of dissatisfaction among occupants, who frequently override the automation systems [40]. For instance, Reinhart and Voss (2003) found that out of 1,433 times the facade attempted to close according to its algorithm, it was overridden by occupants 1,263 times (88%). Leaman and Bordass (2001) noted that excluding occupants from the control loop leads to dissatisfaction [68]. Other studies [23, 69, 70] also confirm the desire of occupants to have some level of control and ability to customize the indoor climate condition. However, some research reported, providing some level of control does not necessarily lead to occupantsâ satisfaction. As occupantsâ tolerance of comfort increases, the level of satisfaction improves. Studies [23, 69, 70] have confirmed that occupants desire a level of control over indoor climate conditions. However, research has shown that having control does not always lead to satisfaction. Occupant comfort and satisfaction increase as their tolerance of comfort increases. There is a correlation between occupants' perception of control over their environment and their productivity [68], so having a user-friendly interface and ease of control over comfort delivery systems is believed to increase the likelihood of occupants interacting with building facades to improve comfort [54]. The facade interface also affects user interaction, offering occupants various options for adjusting their environment to meet their preferences and comfort needs [71]. The type of facade interface can vary. Depending on the type of system and control logic, interfaces provide information and control to occupants. The design and implementation of these interfaces affect how occupants perceive and interact with them. Interfaces are classified based on the level of interaction. Direct interactions refer to requests for action, feedback, or information display made directly between two physical components [72]. Indirect interaction occurs through intermediaries, such as sensing devices, between two physical components. Direct interaction can be further divided into control actions, feedback requests, and display of information. Similarly, indirect interactions (performed automatically through sensing) are categorized according to the purpose of the sensing action, such as sensing of occupants (e.g. physiological or facial characteristics), monitoring of occupant behavior, sensing of indoor and outdoor environments, and sensing of building facades Studies indicate that each interface has a significant impact on occupants' interactions with building facades, but there has yet to be a comprehensive study that compares these interfaces and assesses their relative contributions to occupant behavior related to facades [54].

0.4.2.2 Orientation

Facade orientation is critical in affecting the distribution of sunlight and solar heat gains. For example, the north facade receives minimal solar gain in the northern hemisphere, while the south facade is exposed to solar radiation in the winter. The solar penetration on east and west facades varies based on the time of day, but it varies even more for the south facade due to seasonal changes, making it more prone to higher indoor temperatures [38]. Studies [60, 73, 74, ?, 75] have shown that facade occlusion is lowest on the north facade and highest on the south facade. According to Zhang and Barrett [56], the occlusion rate for east and west facades is between that of the north and south facades, but closer to the south facade due to higher solar penetration during working hours. Studies have also revealed a significant diurnal pattern for the east and west facades. Occupants in east-facing offices tend to close shading in the morning and gradually open it throughout the day, while occupants in west-facing offices open the facade in the morning and close it at the end of the day. Occupant interaction with the facade is heavily influenced by its orientation.

0.4.2.3 HVAC and Indoor Temperature

The HVAC system's operation can impact how occupants interact with facade systems. The energy consumption of HVAC systems is directly influenced by the control of natural lighting. Solar heat gain and internal cooling and heating loads can affect the indoor environment. According to studies [76], an office with air conditioning had a 30% shade occlusion rate while an office without air conditioning had a 49% rate. However, these results cannot be generalized and must be considered in the context of the specific building. The impact of temperature and solar radiation at different orientations is dependent on the air conditioner's control of the zone

0.4.2.4 Interior design and office layout

Occupant interaction in offices varies depending on the office layout. According to researchers, the frequency of changing the facade status is higher in private offices than in shared open offices due to social constraints. In open-plan offices, the arrangement of workstations and configurations also affects occupant comfort and energy-related behaviors. Previous studies have shown that partitions in open-plan office spaces offer employees privacy, but their role in improving daylight distribution and occupant visual comfort cannot be ignored [74, 13]. The attributes of the occupant's location, such as the office arrangement, height of partitions, material, and orientation to windows, play a crucial role in ensuring visual comfort [13]. However, the impact of interior design strategies on the performance of facade systems has received little attention[77]. While the understanding of occupant behavior regarding external factors has increased, only a few studies have considered the contribution of both internal and external factors in the investigation of human-facade integration [2]. And there has been limited attention paid to measuring and quantifying the role of physiological and psychological parameters in occupant energy-related behavior.

0.4.3 Human Scale

Occupants may interact with the facade to alleviate discomfort caused by factors such as temperature, solar radiation, glare, and lack of daylight availability [78]. While external variables play a role in human-facade interaction, internal drivers also play a role in explaining this interaction. According to Cabanac, "a given external stimulus can be perceived as either pleasant or unpleasant depending on signals coming from within the body" [79]. Humans naturally strive for pleasant conditions and avoid unpleasant ones [80]. If a change leads to discomfort, occupants react to restore their comfort. However, due to differences in psychology and physiology, people do not react to stimuli in the same way[81].

0.4.3.1 Psychological factors

Psychological factors refer to thoughts, feelings, and other cognitive characteristics that impact attitudes, behaviors, and mental functions [79]. Recent studies have shown that individual differences, preferences, and personality traits can result in variations in environmental perception and behavior among occupants exposed to the same conditions. For instance, Heydarian found that extroverted individuals are significantly more likely to prefer maximum lighting than others [82]. Additionally, psychological factors are influenced and altered by physiological factors.

0.4.3.2 Physiological factors

Physiological factors are all those aspects "relating to the branch of biology that deals with the normal functions of living organisms and their parts" and have been related to the occurrence of an occupants' action inside a building [82]. Physiological factors (age, gender, level of health, acclimatization, psychological state, etc.) significantly influence the indoor environmental quality, overall building energy performance, the effectiveness of control strategies, and, eventually, on occupants' satisfaction and productivity. Several studies have considered the physiological factors in human comfort. For instance, as several studies show, compared to men, women are more sensitive to light (illuminance) and feel more uncomfortable than men at high and low-temperature extremes [83, 84, 85, 86]. Nevertheless, there are very few observational and experimental studies to evaluate the role of each specific physiological parameter on the HFI. Additionally, subjective perceptions and measured environmental data have been used in many studies of human comfort. However, the questionnaire is not a sufficient means to measure the occupants' comfort and behavior. Due to biological differences, the classification of perception is varied, which has led to uncertainty in human comfort and behavior. Therefore, it is essential to investigate overall human comfort and behavior by combining objective data with subjective data [87], As the literature review shows using physiological indicators in the study of thermal comfort during the last ten years. It can be observed that most articles examined thermal comfort, followed by skin temperature, heart rate, blood pressure, and other related physiological parameters, including skin conductance and oxygen saturation. As the previous studies indicate, the physiological indicators investigated in lighting research are pupil size, eye movement, gaze direction, and degree of eye-opening in terms of visual comfort. Studies show that eye movement and gaze direction are the most important parameters among all visual indicators that correlate with the subjective evaluation of the existing visual comfort metric [88]. The physiological indicators could reveal the relationship between the perception of comfort and the sensation that led to occupants' specific actions with the dynamic facade.

0.5 The Method, means, and tools employed in studies of HFI

Occupants' behavior in a built environment is a multi-sensory experience that involves a range of factors in different scales, requiring appropriate data collecting approaches to study human facade interaction.

Occupants' perceptual comfort is dominantly influenced by the visual and thermal performance of the facade that shapes the human facade interactions. However, this has been a complex challenge for designers and engineers to collect occupants' data (sensational, perceptional, and behavioral) under both visual and thermal stimuli. There are different approaches and means to collect and evaluate the impact of the facade systems on the environment and occupants. The purpose of this section is to summarize how the various external and internal factors mentioned in the previous section were used to understand the occupants' interaction with different faÃ§ade systems. We have classified the identified research studies based on different tools and methods to clearly determine how these factors have been applied. As a result, in the following subsections, we articulate an overview of the applied factors explaining occupant interactions by physical prototyping and acclimatized chamber, immersive virtual reality, and Mixed reality. Within each subsection, we give an overview of methodologies, data collection techniques, and general findings.

0.5.1 Physical Prototyping (chamber and real settings

Physical mock-up is a common means to measure and use users' data in experimental studies that provide a realistic situation to study external and internal factors on human behavior. These experimental studies offer the opportunity to measure the changes and behaviors in response to different variables. It provides a tool for researchers to cover visual facade-related variables, such as interface, morphologies, etc. However, to cover other building factors such as (HVAC, interior) and collect thermal and visual comfort and behavioral data, we need to create acclimatized climate chambers or use actual buildings as testbeds [89, 90, 91]. Although the acclimatized chamber could provide the thermal, visual, and acoustic stimuli to study occupants' comfort and behavior, it cannot cover most of factors in urban scale (building shadowing, view) and building scale such as building orientation, indoor design, etc.[92]. Therefore, the lack of urban scale factors and building factors could impact our perceptual interpretation of physiological signals in the second step of the iterative process interaction (sensation, perception, and behavior). The majority of these factors play their major role in visual stimuli rather than thermal stimuli. Because a lab acclimatized chamber has the ability to simulate the thermal condition and interior thermal condition could be adjusted to temperature and humidity. The real setting testbed has the superiority to offer the real building, environment, and contextual factors for long-term occupants' data collection to understand how temporal factors impact user behavior. However, the drawbacks of the former method are a limitation of environmental factors, high cost, and the fact that the method is time-consuming. The study is limited to certain building and facade designs that the researcher cannot change. Moreover, the physical prototype (scale 1:1) has to be built to examine the variety of design status in different early design stages, which requires substantial

Lab type	Lab name	Time of days	Season	Temperature	VISUAL(Daylight and glare)	Solar radiation	Wind	View	Building shadowing	Hvac Operation	Interior design/ Office layout	Orientation	Building Morphology	Facade system and typologies	Psychology	Physiology
Indoor Test Room	BPS Test Facade, TU Eindhoven	✓	✓	✓	✓	✓	x	x	✓	✓	✓	x	x	✓	x	x
	SinBerBEST Test Bed, BEARS, Singapor	✓	✓	✓	✓	x	x	x	x	✓	x	✓	✓	✓	x	x
	Experience room, SenseLab, TU Delft	✓	✓	✓	✓	✓	x	x	x	✓	✓	✓	x	✓	x	✓
	LESO Building Physics Lab, EPFL	✓	x	x	✓	x	x	x	x	x	✓	✓	x	x	✓	✓
	Laboratory, South china University of Technology, Guangdong, China	✓	✓	x	✓	x	✓	x	x	✓	x	x	x	x	x	✓
	Controlled Environmental Chamber, University of California, Berkeley	✓	✓	✓	✓	✓	✓	x	x	✓	✓	x	x	x	✓	✓
	Two Test rooms within the HiLo Living Lab.	✓	✓	✓	✓	✓	✓	x	x	✓	✓	✓	x	x	✓	✓
Outdoor test room	TRIUMF Laboratory Two Room Indoor Environment & Energy Universal Façade	✓	✓	✓	✓	✓	x	x	x	✓	x	x	x	✓	x	x
	LOBSTER, KIT, Karlsruhe, Germany	✓	✓	✓	✓	✓	x	x	x	✓	x	x	x	✓	x	x
	Demona, EPFL, Lausanne, Switzerlan	✓	✓	✓	✓	✓	x	x	x	✓	x	✓	x	✓	x	✓
	FlexLab, LBNL, Berkeley, USA	✓	✓	✓	✓	✓	x	x	x	✓	✓	✓	x	✓	x	x
	VERU, Fraunhofer Institute, Stuttgart, Germany	✓	✓	✓	✓	✓	✓	x	x	✓	✓	✓	✓	✓	x	x
	The Cube, Aalborg University, Aalborg, Denmark	✓	✓	✓	✓	✓	✓	x	x	✓	x	x	x	x	x	✓
	Facade System Interactions Lab, EURAC, Bozen, Italy	✓	✓	✓	✓	✓	✓	x	x	✓	x	✓	x	x	x	x
	FACT, CEA – INES, Le Bourget du Lac, France	✓	✓	✓	✓	✓	✓	x	x	✓	✓	✓	✓	✓	✓	x
	Danish Daylight laboratory, Copenhagen, Denmark	✓	✓	✓	✓	✓	✓	x	x	x	✓	✓	x	✓	✓	x
Virtual reality	Virtual office space sothern California university	✓	✓	✓	✓	✓	x	x	✓	x	✓	x	✓	✓	✓	✓
	VR Lab, Yonsei University	x	x	x	✓	x	x	✓	✓	x	✓	✓	✓	✓	x	✓
	QUT Design Lab	x	x	x	✓	✓	x	✓	✓	x	✓	✓	✓	✓	x	✓
	LESO laboratory	x	x	x	✓	x	x	✓	✓	x	✓	✓	✓	✓	✓	✓
	Testing office layout. Department of Construction Management, Louisiana State University,	✓	x	✓	✓	x	x	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Laboratory of Integrated Performance in Design (LIPID)	✓	✓	x	✓	x	x	✓	✓	x	✓	✓	✓	✓	✓	x
	École polytechnique fédérale de Lausanne (EPFL)	✓	✓	x	✓	x	x	✓	✓	x	✓	✓	✓	✓	✓	x
Hybrid Reality	Center for Architecture Science and Ecology / Skidmore Owings & Merrill LLP (SOM)	x	x	x	✓	x	x	✓	✓	x	x	✓	✓	✓	x	✓
	Virtual office space Southern California university	✓	✓	✓	✓	x	x	✓	✓	✓	✓	✓	✓	✓	✓	x
site	High Performance Environments Lab (HiPE), School of Architecture & Environment, University of Oregon, Eugene, OR, USA	✓	✓	✓	✓	✓	x	x	x	✓	x	x	x	✓	x	x

Figure 3: Application of important Internal and external factors in different tools and methods

resources. Furthermore, the feasibility might not be justified in many cases [93].

0.5.2 Use of Immersive Virtual Environments in HFI

The virtual environment offers egocentric multimodal sensory (i.e., visual, haptic, auditory, thermal, gustatory) experience controlled by computer, visual, auditory, and kinesthetic parameters[94, 95]. Researchers have used virtual environments widely in many different disciplines to study human experience, including social psychology [53], medicine [96], education and training [97, 98], design [98], and engineering [99]. The virtual environment provides an experimental opportunity to isolate exogenous factors and stimuli, making it a suitable alternative venue for human behavioral studies. It can also model, control, and test scenarios more easily and cost-effectively compared to physical mock-ups, especially in the case of built environments. Several studies have used immersive virtual environments (IVEs) as a tool to simulate facade performance in the built environment and evaluate occupants' behavior with regards to facades in single-sensory and multi-sensory environments [81, 100, 101, 102, 103, 104].

0.5.3 Single sensory and Virtual reality

Most research in the built environment and facade systems considers only a single sensory discomfort model (daylight). For instance, Heydarian provides the single sensory approach of collecting end-user preference in the design stage; in this study, visual factors such as (lighting intensity, interior design, and environmental view) are models to study the relation of personality and lighting in a built environment. Heydarian found that participants significantly prefer to have more daylight (have all shade open), which increases their performance [81]. Although integrating end-user preference information during the design phase provides a better understanding of occupant energy-related behavior, in this single sensory study, the lighting as stimuli is considered, and the effect of the thermal condition is not considered [105]. In that sense, the human sensation and perception of space can not represent the real setting of an office environment. Consequently, they could not be an appropriate alternative to study internal factors (physiological) and human behavior.

0.5.4 Multi-Sensory and hybrid reality

To model the multi-sensory environment, it is essential to ensure the adequacy of stimuli represents the real setting. As previously mentioned, using a virtual environment for lighting and behavioral research has been proven effective. However, the occupant behavior in a multi-sensory environment that involves both solar heat radiation and daylight has not been thoroughly investigated. Only a few studies have used mixed reality to address the simultaneous effect of visual conditions (such as work plan illuminance, perceived illuminance, and glare) and thermal conditions (such as indoor temperature) [106, 107]. These studies divided the thermal stimuli into three categories: fan, air conditioner, and solar gain. To model solar gain, the ambient temperature was increased by 2-3 degrees and an electrical heating panel was used to simulate solar radiation. However, this simplified method of simulating solar radiation (using an electrical panel) is not calibrated with solar intensity and angle, and is not integrated with the facade pattern. As a result, participants' sensations and perceptions rely more on ambient and local body temperatures, neglecting the impact of solar radiation on the body. The local thermal effect of solar gain and the cross-effects of visual and thermal perception are two important factors that highlight the role of solar radiation as an important stimuli in human perception of comfort and behavior. Most psychophysiological research on modeling solar radiation is based on predicting the thermal sensation of the entire body [108, 109]. A uniform environment generally corresponds well with sensation and comfort, and a neutral sensation is considered the ideal comfort condition. However, this relationship between sensation and comfort becomes more complex in non-uniform or transient environments [110]. For example, local thermal comfort can affect overall comfort sensation. Studies have shown that when thermal stimuli are applied to specific body parts (such as the hand or head), the perception of comfort changes from "pleasant" to "very pleasant." In that sense, rooms with cold or hot surfaces, solar gain, or temperature stratification create asymmetrical thermal environments that change over time [110]. As solar radiation can hit occupants in different patterns and intensities in perimeter zones, incoming short-wave radiation is crucial for human comfort and energy-related behavior [111, 112]. Solar radiation impacts human sensation and affects visual perception due to the cross-effect between thermal and visual comfort. Studies have shown a significant interaction between thermal and visual comfort. The cross-effects between the thermal environment and visual perception, as well as the visual environment and thermal perception, have been investigated. The effect of the thermal environment on visual perception in general shows that as temperature is perceived as more comfortable, the light conditions are also perceived as more comfortable. Research has shown that the highest visual comfort is reported during the thermoneutral condition and that light intensity is perceived as close to natural (neither too dark nor too bright). The results indicate a robust effect of ambient temperature on light color temperature: as ambient temperature increases, the color of light is perceived as warmer. For example, 5800 K exposures (bluish) are perceived as the coolest color during cool conditions, while the highest correlated color temperature (CCT) is considered most comfortable during high temperature [113, 114]. As a result, thermal perception can be influenced by visual quantitative and qualitative parameters.

0.6 Discussion and directions for future research

The trend towards dynamic facades that balance comfort and health benefits is driving the development of human-centric design in the facade industry. The increasing demand for personalized, responsive, and interactive built environments is fueled by awareness of the impact of the environment on productivity, well-being, and energy consumption. A user-centered approach to facade design provides opportunities for engineers and designers to incorporate user needs and preferences from the early stages of design. The use of virtual and mixed reality technologies is a cost-effective way to incorporate users into the design process. However, although many studies have used virtual reality for lighting-based facade design research, there is a need for further research on multi-sensory tests to develop standard methods and tools for user-centered facade design.

0.6.1 Limitation of virtual lab

Several studies have demonstrated the practicality of VR for the subjective study of daylighting, as well as the adequacy of subjective perceptions regarding perceived pleasantness, interest, excitement, complexity, and satisfaction with the amount of view in the space. On the evaluated evaluations, there was no significant difference between the real and virtual environments as far as perceptual accuracy was concerned. [114]. According to precedent research, there is promising potential to study the impact of daylight availability of space. The static current method of tone mapping can decrease the human perception while the dynamic behavior would correspond more precisely [115] [115, 116]. The use of newer devices, such as the Oculus Rift CV1, provides higher resolution and refresh rate but can also negatively impact occupants' perceptions of glare [114]. Another gap in current studies is that most of them focused on the blinds. Automatic blinds are a more common dynamic facade type. However, today we have various dynamic facades with different morphology, patterns, control systems, and interfaces that are less addressed. The new research shows a cross effect among different stimuli, as the facade with a different pattern can have a completely different effect on the iterative decision-making process (sensation, perception, and action). In addition to the morphology of the facades, different control systems are used to regulate the interior space, which differs in how different external and internal factors affection different facades. Although a significant amount of research on blinds has played an undeniable role in our understanding of the impact of environmental factors on different scales, this research could not be generalized to all facades systems and assumed the same impact of different types of the facade on humans. It is necessary for researchers to investigate more on the effect of varying facade types in users' decision-making process.

The study on the identified internal and external factors emphasizes that human facade interaction should not be considered isolation. The cross effect between stimuli indicated how user perception and behavior could be different in the lab compared to real settings. Researchers and designers should consider the indoor environment as a whole with all the visual and thermal sensory stimuli, which simultaneously incorporate to shape our multi-sensory spatial experience. Because of the complexity of human facade interaction, it deals with a variety of disciplines. To study this topic, on the one hand, we need to look at how different factors affect the facade system and built environment. On the other hand, we need to evaluate the effect of those factors on human physiology and psychology. Therefore, we need researchers and engineers in the field of building science, computers, physiologists, and psychologists to investigate human facade interaction holistically, especially in the design stage.

0.6.2 Conclusion

In this study, we reviewed and categorized the interscalar factors that were used to study occupant behavior and interactions with the facade system. This section provides an overview of the various factors our literature review identified (section 3) and how different methods and tools have been employed to explain occupants' interactions with varying building systems (section 4). We have identified the current state and gaps associated with using the factors in occupant facade interaction in commercial buildings: Although lighting is the primary external factor, some factors have been less studied: Building shadow, microclimate in urban scale, View, and season.The impact of solar radiation on the local body temperature is marginalized while it has a significant role in the overall perception of thermal comfort that it could also change our visual comfort perception due to the cross effect between thermal and visual perception. The new facade technologies with different patterns and interfaces required more studies, and the findings from certain types of facades cannot be generalized to all facade systems. The majority of existing research in this area focuses on external factors, and only a few studies consider the internal factors in HFI studies. Considering the iterative cycle process, The missing link in recent research is the relationship between sensation and interaction, which has been less discussed. As the pervasiveness of intrusive sensors and IoT systems grows, it has become possible for researchers to use physiological indicators in HFI studies to understand occupant facade-related behavior better.

Although chambers and prototypes provide realistic environments and stimuli, they could not offer contextual factors. Virtual reality and mixed reality provide the cost-effective tool to study human facade interaction in the different built environments and facade systems. Most recent research focuses on the single sensory environment (lighting), and other aspects of built environments (thermal and acoustic conditions) have been less considered. Since the actual experience of occupants is multi-sensory that deals with different external factors in the environment; it is necessary to conduct multi-sensory research to have a comprehensive perspective regarding users' interactions. In conclusion, we hope that this literature review will motivate more researchers to conduct interdisciplinary studies based on a holistic approach to collect data to better understand the role occupant behavior plays in the operation of facade systems.

DEVELOPMENT OF A LOW-COST LARGE-SCALE SOLAR SIMULATOR WITH FLEXIBLE MOUNTING

0.1 Abstract

The dynamic solar simulator has been developed to characterize and define the photovoltaic, solar thermal, advanced evacuated glazing, thermal comfort technologies, and human-based solar tests. The simulator lamp array consists of 6 rows of 500 W halogen lamps with a built-in paraboloidal reflector. Light intensity is controlled through a microcontroller (ESP 32) and five sets of four-channel dimmer modules, allowing the dimming of each lamp. Intensities of light up to 800 Wm-2 can be achieved on a maximum illuminated area of 90 cm x 150 cm with a variable target distance from the simulator of 40 cm to 180 cm. The lamp array is mounted on a frame that allows tilt adjustment in the range of 0 to 90 degrees from horizontal to vertical with 5-degree steps. Hydraulic height adjustment of the apparatus is from ground-level to 34 1/2 inches height. The simulator is equipped with heavy-duty caster wheels, which allows the unit to move in different directions. A unique dimming feature enables the simulator to achieve up to 82% uniform light intensity on vertical, horizontal, and inclined surfaces. The feature provides solar incidence angles between 0 and 90 degree to be simulated for the technologies under examination. This device is a cost-effective halogen lamp-based solar simulator that can therefore be used to test solar cells, investigate different heat-sensitive materials, and conduct thermal studies in human-based research. In this paper, the design and construction of a large-scale solar simulator under $5,000 will be described and its accuracy will be validated against the similar testing capabilities offered by more expensive, high-flux research simulators specially for angular sunlight experiments.

0.2 Introduction

Exposure to sunlight is affected by weather, time of day, geography, and other environmental factors. These factors have made it difficult to use sunlight in a stable, repeatable, and controllable way for experiments that test performance. That is, without the ability to strictly control the variables, it is virtually impossible to meet the minimum requirements of scientific research. Therefore, the solar simulator is utilized as an adjustable device to artificially simulate the physical properties of sunlight, including total radiation, spectral distribution, radiation uniformity, and radiation stability under different conditions [117, 118]. Based on the relative path length, where direct sunlight passes through the atmosphere, the AM1.5G and AM1.5D are defined as the standard spectrum [119]. The American Society for Testing and Materials (ASTM) and the Japanese Industrial Standards (JIS) have classified the standard of the solar simulator as Spectral match, spatial non-uniformity, and temporal instability. However, a significant amount of solar simulators are either expensive, or cannot provide the complex conditions of outdoor lighting because it is difficult to detect the intensity of light outdoors, and researchers prefer to use optical models for simulation [120, 121, 122].

As the solar orientation changes, the angle of incident-light on the device also changes. When measuring solar radiation at different angles, the difference between distal and proximal light sources, such as flashlights, clearly affects the accuracy of the results according to [123]. IEC 61853-2 (2016) stipulates that the simulation of the sun at different angles must have a higher non-uniformity than class B. Therefore, the majority of the solid angle, commercial, solar, systems have to be performed at the level of a small measurement, in order to maintain their uniformity. On the other hand, those simulators that can simulate sunlight from different angles are not affordable, especially on a large scale. Despite their high accuracy and efficiency, these light sources are expensive and require complex, expensive construction, making them unaffordable for industry and academia.

Arc xenon and metal halide are preferred due to their spectral range and color temperature which are comparable to the sun's. However, these light sources are expensive, especially for large-scale solar simulators. The halogen lamp, as a cost-effective alternative, has been used for single and multi-light sources for large solar simulators [124].

Halogen has been utilized for different solar simulators for a long time due to its spectral interval (which is near natural sunlight), easy availability and manipulation, high light intensity, low cost, and usability [125]. Although the inferred light in the spectral distribution of halogen is higher than ultraviolet, in comparison to natural sunlight, the wavelength range (360 - 2500 nm) is similar to sunlight, especially in terms of radiation. The halogen lamp can also radiate a black body temperature of 3200 K, which is quite close to natural sunlight, with a temperature of 5600 K [126, 127, 128, 125].

Halogen lamps have many advantages, but few studies have used them to simulate angular sunlight. The purpose of this paper is to describe the design, development, characterization, and testing of a cost-effective, dynamic solar simulator that can simulate angular sunlight. In this project, we developed and constructed a solar simulator that was large enough to simulate angular sunlight, but cost less than $5,000 and would have similar testing capabilities as high-flux research simulators.

0.3 Methodology

Simulator using international standards. The experimental design of the IFS is divided into three components: light sources, frames, and control systems.

0.3.0.1 Light Source

We use halogen 500W 120V double-ended capsule light bulbs with parabolic reflectors. Figure 1 shows the luminous intensity distributions of halogen lamps compared to other light sources (leg, LED, halogen, xenon). The Sunlite Q500T3 is used for this simulator lamp array. Table 1 shows the specification of the employed lamp. Each of the halogen lamps is equipped with a paraboloidal reflector, which plays the role of a collimator for the emitted light.

0.4 Control

The control mechanism is divided into mechanical and electrical parts.

0.4.1 Mechanical Control

The mechanical adjustment enables the solar simulator to be adjusted at different heights, angles, and XY positions. On the other hand, the control unit adjusts the light to maintain light uniformity in the target area. A hydraulic table provides height adjustment of the lamp array from the ground level to one meter above the ground. The frame can move on heavy-duty caster wheels to test the various technologies at the different locations in the laboratory space. The aluminum box allows tilt adjustment in the range of 0 to 90 degrees from horizontal to vertical with 5-degree steps. To provide the mechanism for angle adjustment, an aluminum plate had been drilled every 5 degrees so that the user could choose the desired angle by placing the Pull Pin-Handle at the specified angle. Since the intensity of light is changed when the array of lamps is tilted based on the desired angle, the irradiance uniformity on the target area is also changed. To keep the uniformity, the control unit is designed to control the light intensity.

0.4.2 Electrical Control

The control unit comprises two parts: the first floor of the distribution blocks, and the second floor of the microcontroller and dimmers (RobotDyn 4 Channel Arduino Light Dimmer, Arduino Dimmer).

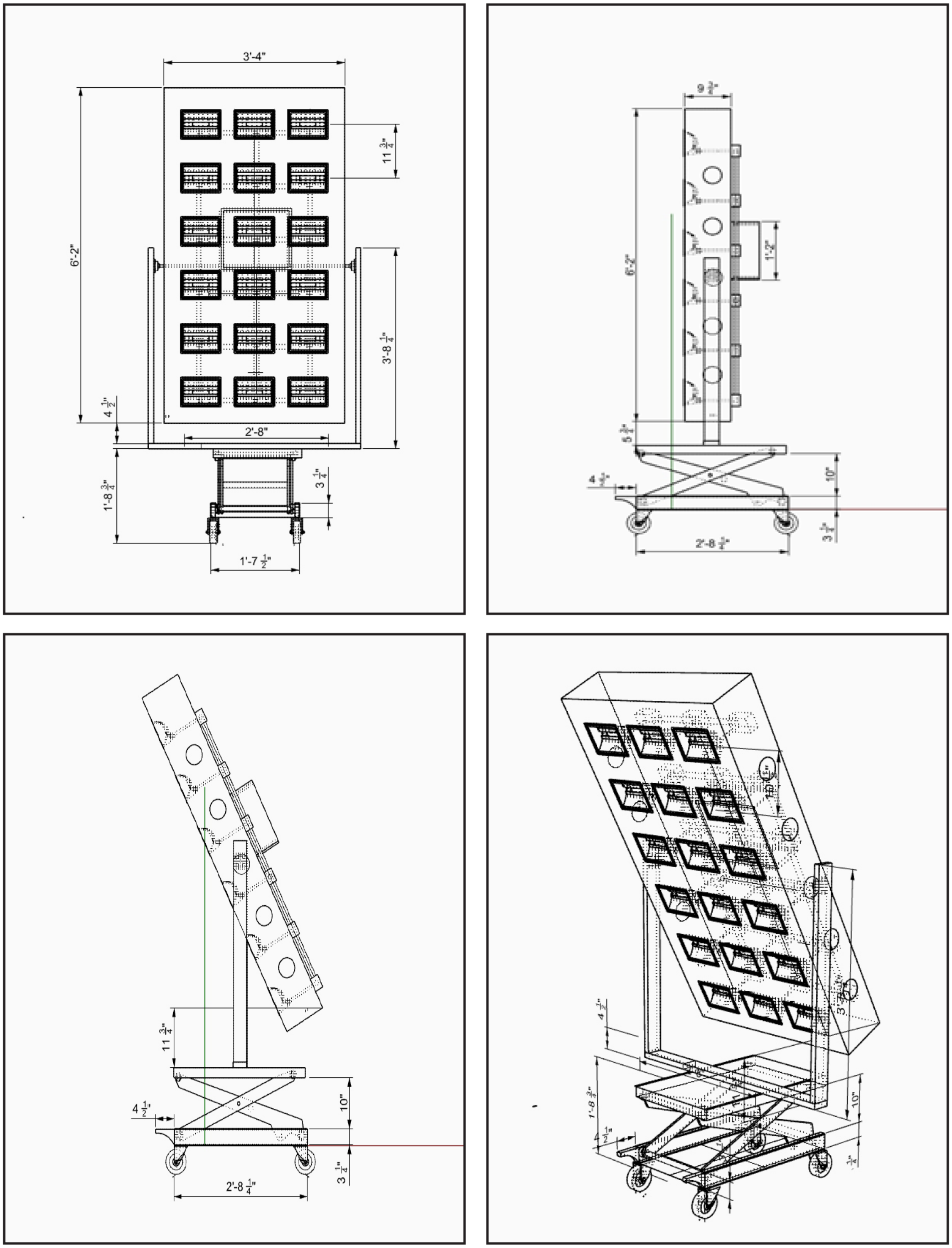

Figure 4: Solar Simulator Drawings

Figure 5: Solar Simulator,Control Unit

0.4.2.1 Electrical Distribution blocks

On the first floor of the electrical box, a series of terminal blocks are located. Each modular, insulated block is used to connect wiring to the ground and connect electrical power (inputs) and lamp wires (outputs) to dimmers, safely. The control unit is made up of two parts on the floor: the first floor of the distribution blocks and the second floor of the microcontroller and dimmers (RobotDyn 4 Channel Arduino Light Dimmer, Arduino Dimmer).

0.4.2.2 Dimmers

AC Dimmer controls the voltage of alternating current, which can transfer up to 300V (8A) (TRIAC BTA16 for 600V/16A). In this case, a dimmer is used to control the intensity of lamps and turn the power on/off. In order to prevent high current disruption to a microcontroller, the power portion of the dimmer is isolated from the control portion. Two digital pins connect the Dimmer to the Arduino controller. The first (Zero) controls the passing of Phase Null of AC, which initiates the interrupt signal. Controlling (dim) current with the second (DIM/PSM). As Zero is tied to microcontroller interrupts, it needs to be connected to designated microcontroller pins,

The control unit provided includes all the mentioned electronic components, controls and monitoring features, which allow maximum control and operational flexibility for maximum control. The control units provide two models of operation (manual and automatic). In the manual mode, the user has the ability to set the light intensity of all the lamps in each individual row or lamp. The dimming feature allows the user to set the intensity for different purposes and experimental tests. In the automatic mode, the user can set the desired intensity and angle and distance while the control unit would be used to set up all the required specifications for the outpower output of each lamp to achieve a specified light intensity with maximum uniformity.

0.5 Testing Characterization

0.5.1 Analysis of qualification of the solar simulator

In order to examine and optimize the solar simulation, we used ASTM E927 (Standard Specifications for Solar Simulation for Terrestrial Photovoltaic Testing), and IEC 60904-9, which define simulation performances of solar simulators under three classes: Class A, Class B and Class C [129, 130, 131].

In order to test Spectral Match (SM), the spectroradiometer is used to measure the spectrum of the simulator. In order to calculate the required percentage of irradiance, the actual percentage of irradiance must be compared to the actual percentage of irradiance [132, ?]. The spectral match of the simulator is in Class B, wich is calculated by the equation below:

SM= (Actual Irradiance in the interval) / (Required Irradiance in the interval) [132]

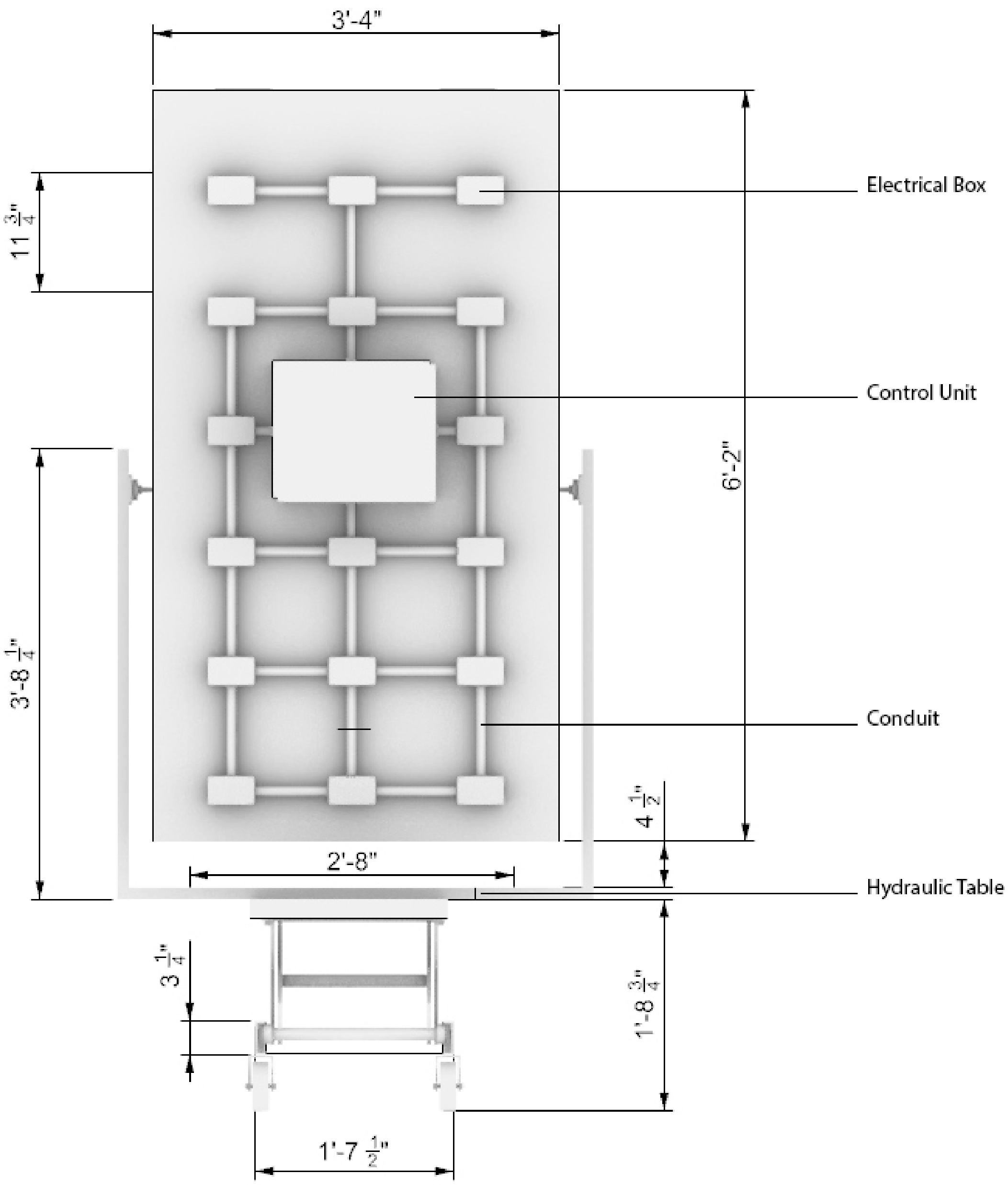

Figure 6: Solar Simulator Component

Power	600V - 16A
AC frequency	50/60 Hz
TRIAC	BTA16 - 600B
Isolation	Optocoupler
Logic level	3.3V/5V
Zero point	Logic level
Modulation (PWM with trigger)	logic level ON/OFF TRIAC
Signal current	>10mA
Environment:	? For indoor and outdoor use ? Operating temperatures: -20°C to 80°C
Operating humidity	Dry environment only
ROHS3	Compliant

Figure 7: Dimmer Specification

$$\text{SNU}= \frac{(E\ max - E\ min)}{(E\ max - E\ min)} \times \%100$$

Figure 8: Spatial non-uniformity (SNU)

$$\text{Temporal Instability (\%)} = \frac{(Max\ irridiance - Min\ irridiance)}{(Max\ irridiance + Min\ irridiance)} \times \%100$$

Figure 9: Temporal Instability

The setup for Spectral Match (SM) test Spatial non-uniformity (SNU)

To measure the uniformity of the test area irradiance, measurements are taken on a uniform rectangular grid by a precision Li-Cor pyranometer [133]. The test area of the solar simulator is 90 * 160, which is close to the sitting positions of the human dimension that will be tested under the simulator. The SNU is calculated using Emax and Emin, where Emax represents the maximum intensity on a test section and Emin represents the minimum intensity on a given equation. The Uniformity of this solar simulator is 4.6, which is defined as uniformity class B.

To measure temporal instability, the irradiance of the simulator beam over the specified time period is measured and the following equation is used to calculate the instability. The temporal instability class for this simulator is in class A.

Solar simulators are evaluated according to their non-uniformity in dispersion of irradiance. A solar simulator would with insignificant non-uniformity value, showing that the irradiance from the light-source is dispersed uniformly onto the testing area. Measurement of non-uniformity is conducted using irradiance mapping. The test is run at different distances between the panel (array of lamps) and the mapping area

Spectral Match		Spatial non-uniformity		Temporal instability	
Spectral Match	Class	% Uniformity	Uniformity Class	%Temporal Instability	Temporal Instability Class
1,010 W·m−2	**B**	**4.6**	**B**	**1.25**	**A**

Figure 10: Light Standards

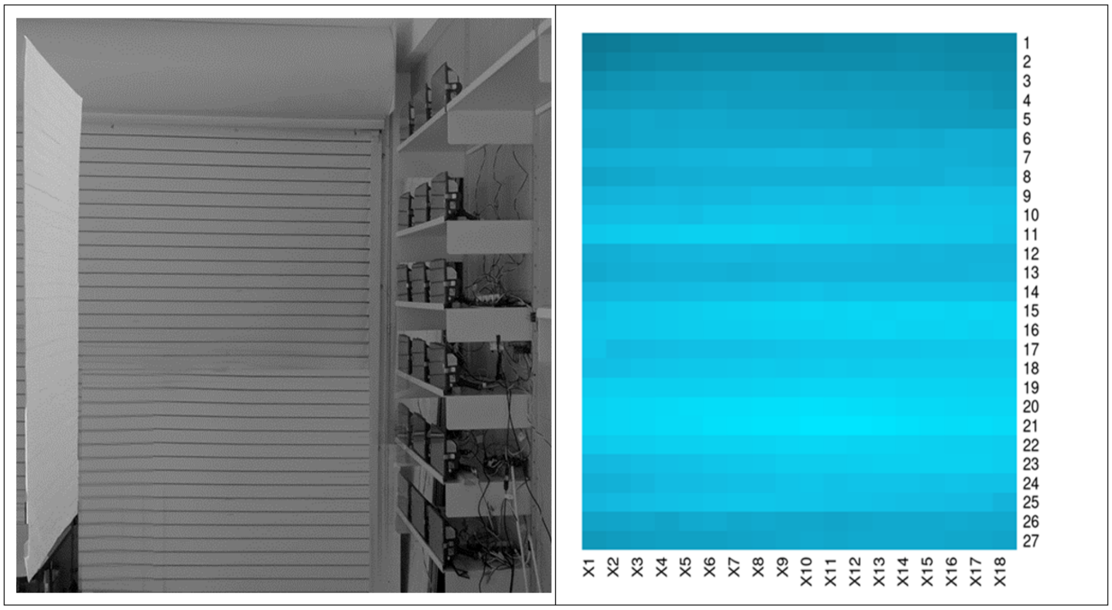

Figure 11: left test set up, Right: test result

(40,60, 80,100,120, 140, 160, 180). A unit of the Li-Cor brand Pyranometer is located in the mapped grid area. The area of the mapping grid is 90cm*160cm, which is equivalent to the surface area of a sitting person. The mapping area has 18 rows, and each row has 32 columns. As shown in Figure 5, there are 576 sections in the mapped area. After irradiance intensity had stabilized, readings were taken with the pyranometer. In order to measure all sections, the pyranometer is shifted from one to another. Each intensity value is mapped three times for each setting of irradiance intensity. It is necessary to repeat the mapping at each level of intensity value to ensure repeatability.

If the solar simulator passes the required test, the facade layers are added and the performance of IFS in different solar angles and patterns is examined. Since the angle of the solar simulator is not perpendicular to different hours, the challenge is to find a uniform condition for different times of day and seasons. To that end, the relationship between distance and intensity is obtained, and then the optimum intensity of halogen lamps for each row is calculated.

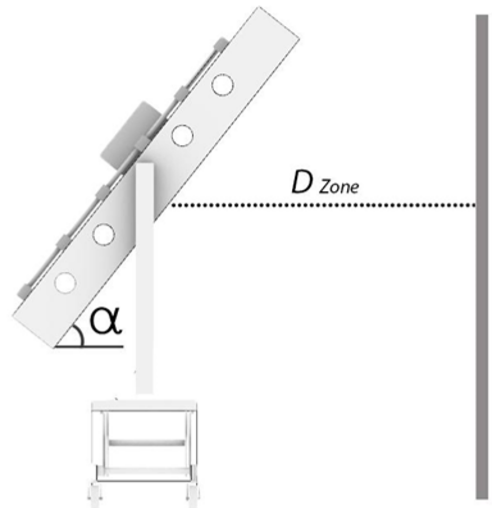

Figure 12: Tilted solar simulator diagram

0.5.2 Angular Measurement

To maintain uniformity at different angles, we hypothesize that there is a correlation between distance and light intensity (Figure 4). In that sense, each light has a corresponding zone on the target surface, such that as the angle changes, the distance between each zone on the target surface and the light source, also changes in varied angular directions. Therefore, if the relation between light intensity and distance is obtained, we could predict the amount of required dimming level for each light in angular position to keep the uniformity. In this method, first the different intensities (minimum to maximum) in the range of distance were explored, and then the corresponding relationship between distance and magnitude was obtained by numerical calculations. Finally, the light intensity on the target surface at different angles could be predicted based on the dimming level and distance. In order to validate the predictions, we measured light intensities on the target surface in different angular positions and observed the minimum required uniformity for each angle.

In this process, first we assume a hypothetical line from the light source, perpendicular to the target surface. According to the range and light radius of each lamp (based on the type of lamp and reflector used), we consider its corresponding zone

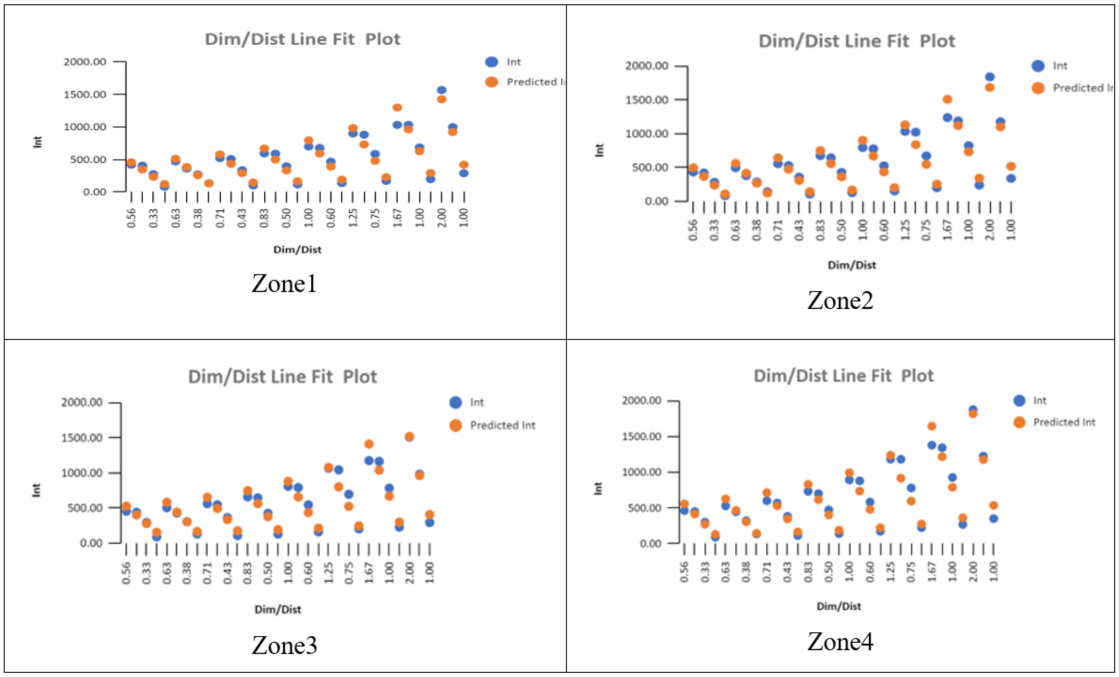

Figure 13: Tilted solar simulator diagram

$$\frac{((Tint * D) - Coe1 \;-\; (Coe1\ X\ 0.1))}{Coe2} - 01\ X\ \frac{((Tint * D) - Coe1 \;-\; (Coe1\ X\ 0.1))}{Coe2}$$

T_{int} : Target Intensity
D : Lamp Dis to Target
Coe : Zone Coefficients

on the target surface. As the figure shows, there are 18 zones, each one containing 6 x 6 cells. Then, we measure the light intensity on the target surface for each zone from 40 to 180cm and different percentages of dimming magnitude: 20 to 100, which was described in the testing and characterization portion of the study. Finally, after drawing the equation of the existing trend line for distance and light intensity, we obtain the corresponding points as follows:

0.6 Validation

For the validation of the extracted formula, we have compared the predicted and measured intensity in seven random points, which are selected from different distances

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Multiple R	0.965447	0.969517	0.963809	0.965814	0.969318	0.969540
R Square	0.932089	0.939964	0.928927	0.932796	0.939578	0.940008
Adjusted R Square	0.927238	0.935676	0.923850	0.927996	0.935262	0.935723
Standard Error	92.78298	103.77975	100.85875	123.11696	95.82151	111.78320
Observations	31	31	31	31	31	31

Figure 14: Regression analysis

DIS	Dim	Int	Prediction Z1	Delta Z1	Accuracy Z1	Prediction Z2	Delta Z2	Accuracy Z2	Prediction Z3	Delta Z3	Accuracy Z3	Prediction Z4	Delta Z4	Accuracy Z4	Prediction Z5	Delta Z5	Accuracy Z5	Prediction Z6	Delta Z6	Accuracy Z6
130	50	219.61	188.99	13.94%	86.06%	230.56	4.98%	95.02%	258.76	17.83%	82.17%	258.76	17.83%	82.17%	211.22	3.82%	96.18%	270.12	23.00%	77.00%
150	40	94.39	93.63	0.80%	99.20%	126.89	34.43%	65.57%	134.50	42.50%	57.50%	134.50	42.50%	57.50%	108.86	15.33%	84.67%	150.30	59.24%	40.76%
90	50	323.36	272.99	15.58%	84.42%	333.03	2.99%	97.01%	373.77	15.59%	84.41%	373.77	15.59%	84.41%	305.09	5.65%	94.35%	390.18	20.66%	79.34%
110	65	484.11	366.86	24.22%	75.78%	421.65	12.90%	87.10%	489.41	1.09%	98.91%	489.41	1.09%	98.91%	401.39	17.09%	82.91%	490.66	1.35%	98.65%
130	90	544.33	512.80	5.79%	94.21%	567.15	4.19%	95.81%	673.03	23.64%	76.36%	673.03	23.64%	76.36%	553.66	1.71%	98.29%	656.93	20.68%	79.32%
170	70	348.86	268.33	23.08%	76.92%	305.01	12.57%	87.43%	356.28	2.13%	97.87%	356.28	2.13%	97.87%	292.45	16.17%	83.83%	354.46	1.60%	98.40%
150	70	414.81	304.11	26.69%	73.31%	345.67	16.67%	83.33%	403.78	2.66%	97.34%	403.78	2.66%	97.34%	331.45	20.10%	79.90%	401.72	3.15%	96.85%
			Average		84.27%						84.94%			84.94%			88.59%			81.47%

Figure 15: Accuracy of predication based on the measured data

from the simulator and different dimming levels. The intensity difference and prediction accuracy are calculated in addition to the average prediction accuracy in each zone. As we can see in the Table below, the maximum average accuracy is 88.59% for Zone Five and the minimum accuracy is 81.47% for Zone Six.

0.7 Conclusion

A novel and thoroughly researched approach is deployed for human-based solar tests using The dynamic Solar Simulator, whereby a prototype was modeled and built according to specifications, to ensure the most accurate and efficient sun-like conditions in a controlled testing environment. The physical mechanisms of the Simulator allow for varying conditions of and degrees of light exposure, which mimic conditions in the natural environment. For example, the lamp array is mounted on a frame that allows tilt adjustment in the range of 0 to 90 degrees from horizontal to vertical with 5-degree iterations. Hydraulic height adjustment elevated the apparatus from ground-level up to 34 1/2 inches height. The simulator is equipped with heavy-duty caster wheels, which. that allows the unit to move in different directions. A unique dimming feature enables the simulator to achieve up to 82% uniform light intensity on vertical, horizontal, and inclined surfaces. Again, in order to maintain uniformity at different angles, we hypothesize that there is a correlation between distance and light intensity. In that sense, each light has a corresponding zone on the target surface, such that as the angle changes, the distance between each zone on the target surface, and the light source, also changes. This device is designed as a cost-effective halogen lamp-based solar simulator that can therefore be used to test solar cells, investigate different heat-sensitive materials, and conduct thermal studies in human-based research. As noted, the design and construction of a large-scale solar simulator that costs less than $5,000 as described, indicates its accuracy and is fully validated against the similar testing capabilities offered by more expensive, high-flux research simulators especially for angular sunlight experiments.

THERMAL ASSESSMENT OF TESTBED EQUIPPED WITH THE INDOOR SOLAR SIMULATOR TO BE UTILIZED FOR HYBRID

0.1 Abstract

Lack of an empirical tool to investigate human facade interaction as a multi-sensory study in the early stage of design is one of the main causes of uncertainty in the estimation of facade performance. Recently immersive virtual reality has become the common tool for staying human facade interaction. The affordability, flexibility to simulate visual qualities in a short amount of time, and its ability to be integrated with building performance simulation made this tool an empirical to study human facade interaction. however, visual stimuli are not the only driver for human facade interaction. Other stimuli, such as thermal stimuli (solar radiation and ambient temperature), also play a significant role in occupants' facade-related behavior, which is overshadowed by the single sensory study of immersive virtual realities. In this study, we examine the adequacy of the novel use of a solar simulator to provide the solar radiation for the (multi-sensory) hybrid environment in an integrated framework with Performance Simulations (BPS). to that end, we compare three states of a dynamic facade on the temperature stratification from ankle to head of siting man in physical environment with simulated data in building performance simulation tools. The obtained experimental and simulated results for different dynamic facade states showed that the temperature gradient difference (angle to head) using one C/m corresponds to the standard recommendations. Comparing globe temperature experimental data and simulated data showed a maximum difference of 1 centigrade. This study proves the indoor solar simulator could be a sufficient alternative to provide thermal stimuli for the hybrid multi-sensory environment that could be integrated into building

performance tools

0.2 Introduction

Since physical Prototyping to study the impact of the facade on occupants can be costly and time-consuming, building performance simulation (BPS) platforms are often deployed to visualize the architectural and daylighting effects and measure occupants' comfort and energy performance of different facade systems [37]. In that sense, architects and engineers are able to model the external physical factors (e.g., outside weather, daylighting, indoor and outdoor temperature, etc.), building attributions, the Facade systems, and interior design to predict the building energy consumption [134]. However, a lack of understanding of human behavior under the co-presence of daylighting and solar radiation causes nonconformities and simplifications in modeling and simulation that lead to considerable uncertainties [135]. Building and facade systems not only have unique characteristics in their designs and functionality but are also used by occupants with a unique perception of comfort and behaviors that current BPS does not address this individual information to provide a realistic outcome. In fact, using stochastic humans behavior model in the buildings perimeter zone has caused a lack of accuracy in performance simulations during the design phase and also occupants' dissatisfaction during the operation phase [136, 137, 102]. Researchers use observational and experimental studies in immersive virtual environments (IVE) to address these limitations in collecting occupant data.

0.2.1 Use of Immersive Virtual Environments in HFI

The virtual environment offers egocentric multimodal sensory (i.e., visual, haptic, auditory, thermal, gustatory) experience that, by the use of computer, visual, auditory, and kinesthetic parameters are controlled.[138][, In comparison with mundane reality in situ-controlled experiments, the virtual environment provides the experimental opportunity to isolate the exogenous factors and stimuli and apply human behavior observed in virtual environments to the physical environments. Several studies investigated human comfort and behavior in relation to the facade by the use of IVE as a tool to simulate facade performance in the built environment. [139, 81, 100, 101, 134, 103, 104]. However, Most of the research in the built environment and facade systems consider only a single sensory discomfort model based on the different daylight circumstances. Although integrating end-user preference information during the design phase provides a better understanding of occupant energy-related behavior, in this single sensory study, the lighting as stimuli is considered, and the effect of the thermal condition is not considered. In that sense, the human sensation and perception of space can not represent the real setting of an office environment. Consequently, they could not be an appropriate alternative to studying the built environment's impact on humans.

0.2.2 Multi-sensory environment and the impact of solar radiation

In order to model the multisensory environment, it is essential to ensure the stimuli's adequacy represents the real setting. As mentioned above, the use of a virtual environment for lighting and behavioral research is proven. However, the occupant behavior in a multisensory environment (solar heat radiation and daylight) has not been investigated. Recently Only a few studies) by the use of mixed reality has addressed the simultaneous effect of visual conditions (e.g., work plane illuminance, perceived illuminance, glare), and thermal conditions (e.g., indoor temperature)[140, 141, 142] In these studies, the thermal stimuli are divided into a fan, air conditioner, and solar gain. In order to model solar gain, the ambient temperature was increased (2-3 degrees), and by the use of electrical heating, the panel attempted to provide the solar radiation. However, the simplified solar radiation stimuli (electrical panel) are not calibrated with solar intensity and angles. .Moreover, the panel is not integrated with the facade pattern. Therefore, the participants' sensation and their perceptions rely more on the ambient temperature and local body temperature and landed solar radiation on occupants' bodies is undermined. The local thermal effect of solar gain and cross effects of visual and thermal perception are two major important factors that highlight the role of solar radiation as the important stimuli on human perception of comfort and behavior. The majority of psychophysiological research on modeling solar radiation is based on the prediction of the thermal sensation of the entire body [107, 108, 143, 144]. In fact, sensation and comfort are correlated quite well in a uniform environment [145]. A neutral sensation corresponds to the ideal comfort condition that a warmer or cooler sensation reduces comfort [109]. However, the relationship between sensation and comfort is more complex in the non-uniform or transient environment. For example, the local thermal comfort could change the overall comfort sensation of humans. As the studies show, when thermal stimuli are applied to local body parts (e.g., hand, head), the perception of comfort changes from "pleasant" to 'very pleasant.' In that sense, the room with cold/hot surfaces, solar gain, or temperature stratification Changes the uniform environment into asymmetrical thermal environments that change over time [146]. As solar radiation could land on occupants with different patterns and intensity in perimeter zones, the incoming shortwave radiation is one the most crucial drivers for human comfort and energy-related behavior

0.3 Method

In order to test the capability of solar simulators to be used for a hybrid reality in an integrated framework with Building Performance Simulations (BPS) [147], an experiment was conducted to compare the impact of the dynamic facades on indoor temperature between the physical test bed and building performance simulation data. To that end, we model the physical and virtual environment for the physical environment. We used a control room as the test bed and integrated the physical dynamic facade prototype. The facade has three different states (open, Semi-open, and close) that manually could be adjusted to the desired angle. To collect the data, the solar

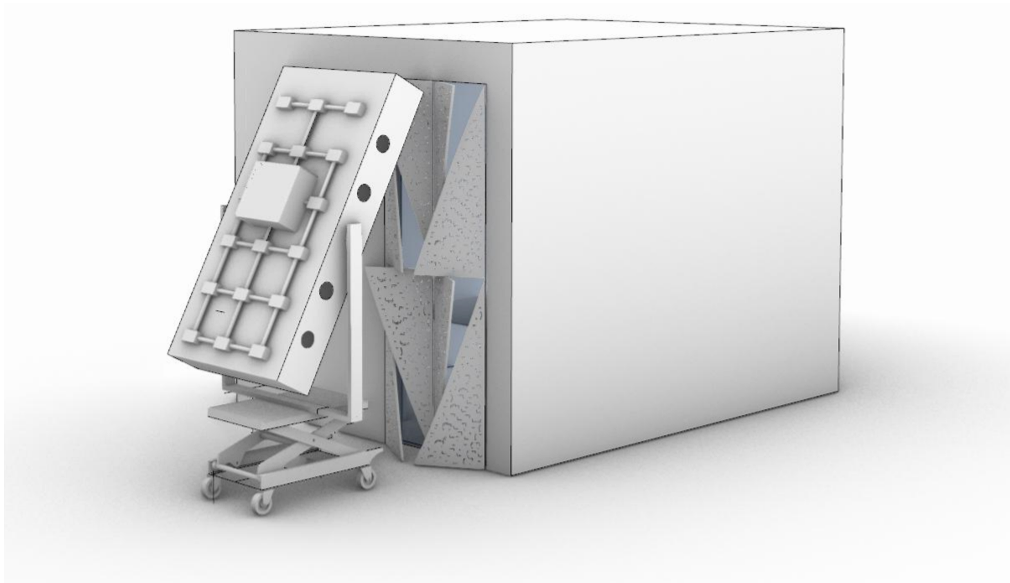

Figure 16: Testbed Setting: Solar simulator, Facade prototype and controlling room

simulator's angle was set to 30 degrees, and 450 solar intensity on the assumed target surface represents 4pm June 16 in Charlotte. We allocate 45 minutes for each facade state. During every 1 minute, the air temperature and humidity were recorded using a HOBO data logger. All this data was used to assemble a profile of the operative temperature of space from ankle to head that distance between each sensor is 30 cm except for the first sensor, which is10 cm above the ground, in order to simulate the physical setting. We modeled the geometry of the room by Rhino and used the ladybug and honey bee package to model the exact thermal aspect of the test bed. In this process, we used the Com Recipe component and modified it to record the data in a certain time frame we already used for the testbed.

0.3.1 Testbed

As the figure 15 and 18 shows the indoor test bed only has a windows in one side , which are fully glazed to the point that they can usually create a thermal gradient across the room from south to north. The testbed also has an air conditioner (SPT Portable Air Conditioner), by which the research team can change the indoor temperature from 19 Â°C to 35 Â°C. In the experiments, the room temperature

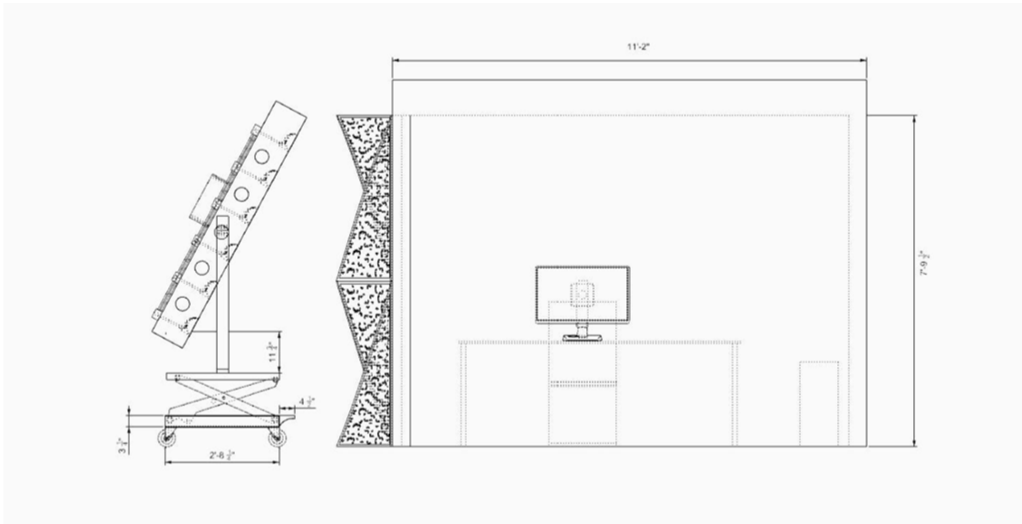

Figure 17: Testbed Section

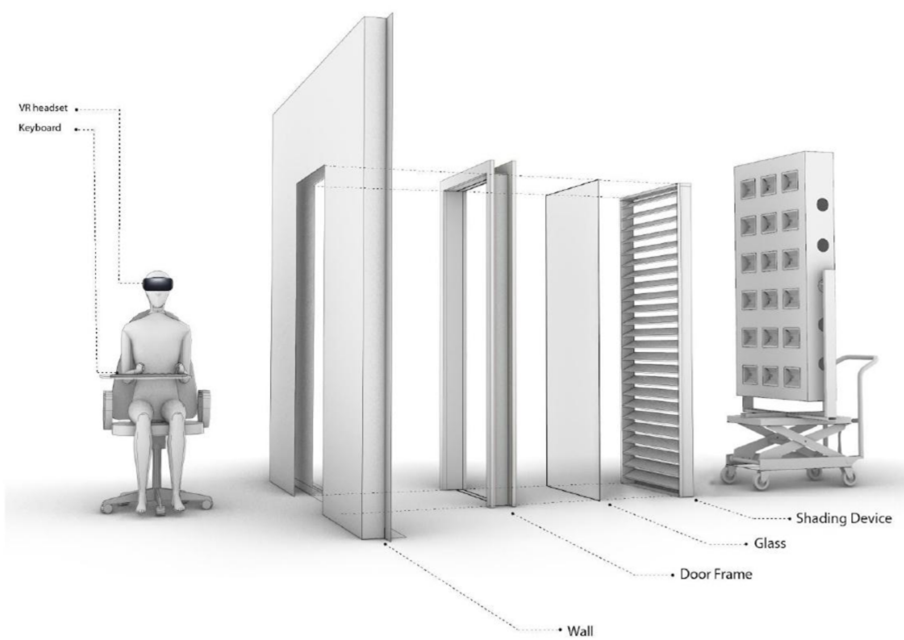

Figure 18: Testbed Components

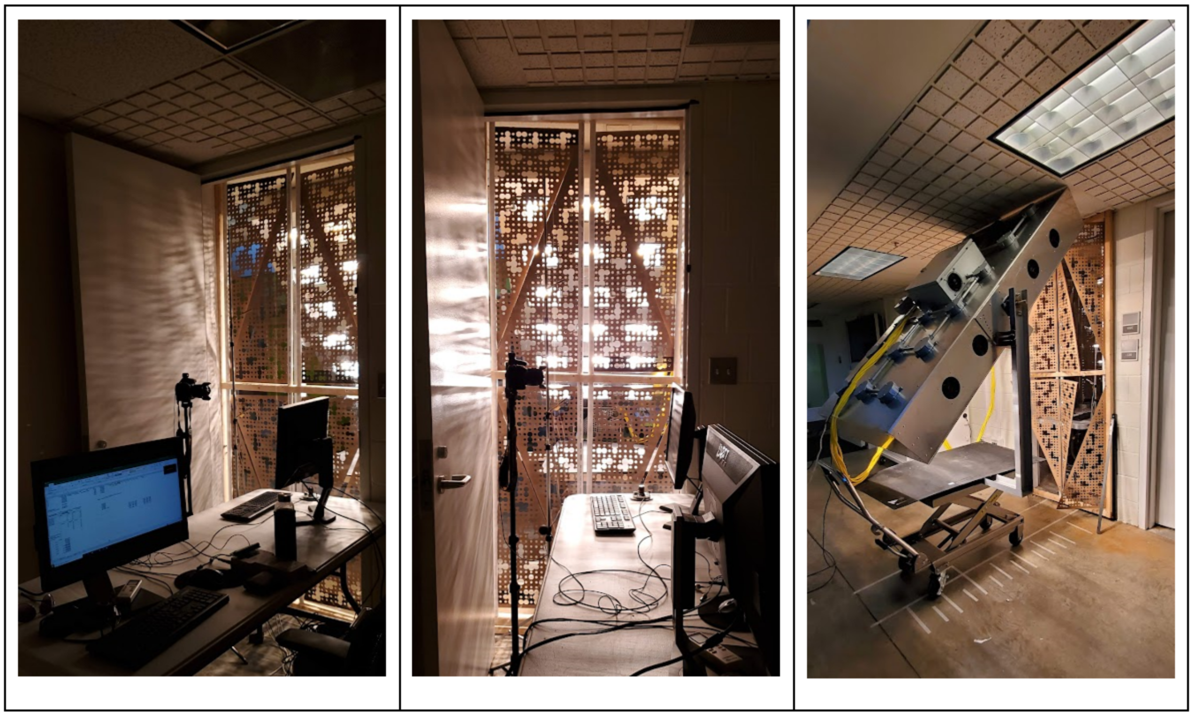

Figure 19: Testbed Interior

is between 72 Â°F, which conforms to typical indoor conditions controlled by the mechanical HVAC system. The test bed was equipped with a novel solar simulator that could mimic solar radiation at different times and intensities. The Dynamic solar simulator has been developed to characterize photovoltaic, solar thermal, advanced evacuated glazing, thermal comfort technologies, and human-based solar test. The simulator lamp array consists of 6 rows of 500 W halogen lamps with a built-in paraboloidal reflector. Light intensity is controlled through a micro control (ESP 32) and five sets of 4 channel dimmer modules. The lamp array is mounted on a frame that allows tilt adjustment in the range of 0 to 90 degrees from horizontal to vertical with 5-degree steps figure 4

0.4 Result

After convergence, Tecplot was used to extract the temperature profiles at different positions and compare them with the testbed temperature profiles. In Fig. 5. According to the simulations, the temperature estimates agree well with the experimental

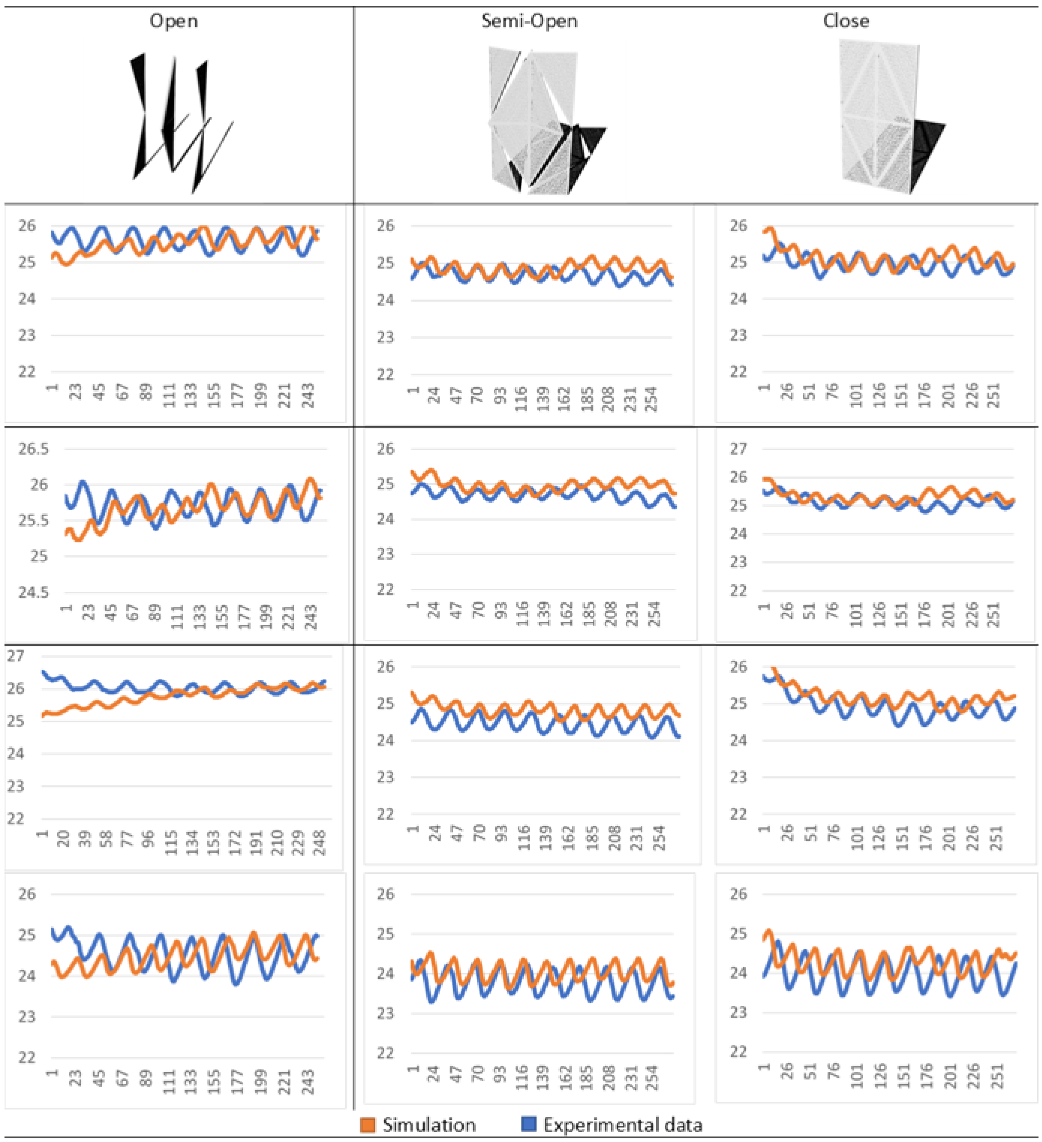

Figure 20: Comparison of experimental data with Simulation Data

measurements. The maximum temperature difference between simulation results and sensor data is about

$$\Delta tmax = 0.2CatPositionB. \quad (1)$$

.

The relative error ranges from 0.2% to 1.3%. Based on the ASHARE thermal comfort standard, seated occupants' temperatures should not differ more than three degrees between their ankles and heads (Nielsen, 2015). According to this analysis, the temperature difference between the ankle and head levels ranges from 0.5 to 1.5. Celsius, which complies with the thermal comfort standard.

0.5 Conclusion

A novel and thoroughly researched approach is deployed for human-based solar tests using The dynamic Solar Simulator, whereby a prototype was modeled and built according to specifications, to ensure the most accurate and efficacy sun-like conditions in a controlled testing environment. The physical mechanisms of the Simulator allow for varying conditions of and degrees of light exposure, which mimic conditions in the natural environment. For example, the lamp array is mounted on a frame that allows tilt adjustment in the range of 0 to 90 degrees from horizontal to vertical with 5-degree iterations. Hydraulic height adjustment elevated the apparatus from ground-level up to 34 1/2 inches height. The simulator is equipped with heavy-duty caster wheels, which. that allows the unit to move in different directions. A unique dimming feature enables the simulator to achieve up to 82

CONCLUSION

Human facade interaction is a new interdisciplinary field of study that impacts the building efficiency and occupant's comfort and wellbeing. The lack of empirical means and tools to study human facade interaction has led to uncertainty for facade modeling in building performance simulations and also the operation of dynamic facades due to relying on unrealistic predictions of human interaction. As the literature review shows there are different numbers of internal and external factors that impact occupantsâ facade-related behavior. Although lighting is the primary external factor, some factors have been less studied: Building shadow microclimate on an urban scale, View, and season. The impact of solar radiation on the local body temperature is also marginalized while it has a significant role in the overall perception of thermal comfort that it could also change our visual comfort perception due to the cross effect between thermal and visual perception. Moreover, the new facade technologies with different patterns and interfaces required more studies, and the findings from certain types of facades cannot be generalized to all facade systems. The majority of existing research in this area focuses on external factors, and only a few studies consider the internal factors in HFI studies. Those few studies that investigate the internal factors focus on the single sensory environment (lighting), and other aspects of built environments thermal stimuli have been less considered. Since the experience of occupants is multisensory that deals with different external factors in the environment; it is necessary to conduct multisensory research to have a comprehensive perspective regarding users' interactions. In this dissertation, we developed a novel test bed equipped with a solar simulator to provide the thermal stimuli (solar radiation and temperature) for human facade interaction that can be integrated with immersive virtual reality (visual stimuli) and building performance simulation. The first step to test the adequacy of this tool was examining the solar simulator based on the standard. The dynamic Solar Simulator was modeled and built according to specifications, to ensure the most accurate and efficacy sun-like conditions in a controlled testing environment. The physical mechanisms of the Simulator allow for varying conditions and degrees of light intensity and angle, which replicate the solar conditions in the natural environment. to replicate the solar radiation at a different angle. It is hypothesized that there is a correlation between distance and light intensity. In that sense, each light has a corresponding zone on the target surface, such that as the angle changes, the distance between each zone on the target surface, and the light source, also change. This device is designed as a cost-effective (less than $5,000) halogen lamp-based solar simulator that can therefore be used for thermal studies in human-based research. The next step to examine the adequacy of this tool was to investigate the ability of an indoor test bed to provide accurate thermal stimuli and examined its compatibility to be utilized as a complementary tool for building performance simulation to incorporate human facade-related behavior in energy estimation potentially. The test bed, which is equipped with a novel solar simulator, tests a dynamic facade prototype regarding the solar heat gain and ambient temperature in three different facade states (open, close, and semi-open). At the same time, we virtually made the thermal model based on the testbed. after the comparison of the experimental and simulation datasets. The dynamic solar simulation was found to be an alternative that could provide the standard thermal stimuli which could be utilized in the hybrid reality test bed for facade technologies studies. Moreover, this study confirms that the solar simulation has the compatibility to be integrated with the building performance tool.

REFERENCES

[1] U. D. U. D. o. Energy, u. Washington, u. DC, and u. 2015, "Quadrennial technology review 2015,"

[2] A. Heydarian, C. McIlvennie, L. Arpan, S. Yousefi, M. Syndicus, M. Schweiker, F. Jazizadeh, R. Rissetto, A. L. Pisello, C. Piselli, *et al.*, "What drives our behaviors in buildings? a review on occupant interactions with building systems from the lens of behavioral theories," *Building and Environment*, vol. 179, p. 106928, 2020.

[3] E. Delzendeh, S. Wu, A. Lee, and Y. Zhou, "The impact of occupantsâ behaviours on building energy analysis: A research review," 2017.

[4] S. Li, L. Liu, and C. Peng, "A review of performance-oriented architectural design and optimization in the context of sustainability: Dividends and challenges," *Sustainability*, vol. 12, no. 4, p. 1427, 2020.

[5] G. Chinazzo, J. Wienold, and M. Andersen, "Daylight affects human thermal perception," *Scientific reports*, vol. 9, no. 1, p. 13690, 2019.

[6] S. Attia, R. Lioure, and Q. Declaude, "Future trends and main concepts of adaptive facade systems," *Energy Science & Engineering*, vol. 8, no. 9, pp. 3255–3272, 2020.

[7] M. Sunikka-Blank and R. Galvin, "Introducing the prebound effect: the gap between performance and actual energy consumption," *Building Research & Information*, vol. 40, no. 3, pp. 260–273, 2012.

[8] I. Gaetani, P.-J. Hoes, and J. L. Hensen, "Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy," *Energy and Buildings*, vol. 121, pp. 188–204, 2016.

[9] L. Norford, R. H. Socolow, E. S. Hsieh, and G. Spadaro, "Two-to-one discrepancy between measured and predicted performance of a low-energyâoffice building: insights from a reconciliation based on the doe-2 model," *Energy and buildings*, vol. 21, no. 2, pp. 121–131, 1994.

[10] E. Azar and C. C. Menassa, "Agent-based modeling of occupants and their impact on energy use in commercial buildings," *Journal of Computing in Civil Engineering*, vol. 26, no. 4, pp. 506–518, 2012.

[11] M. Jia, R. S. Srinivasan, and A. A. Raheem, "From occupancy to occupant behavior: An analytical survey of data acquisition technologies, modeling methodologies and simulation coupling mechanisms for building energy efficiency," *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 525–540, 2017.

[12] K. Schakib-Ekbatan, F. Z. Cakıcı, M. Schweiker, and A. Wagner, "Does the occupant behavior match the energy concept of the building?–analysis of a german naturally ventilated office building," *Building and Environment*, vol. 84, pp. 142–150, 2015.

[13] M. Modaresnezhad and A. Nezamdoost, "Daylight-based Partition Design in Side-lit Open Plan Offices," tech. rep.

[14] Q. Li, L. Zhang, L. Zhang, and X. Wu, "Optimizing energy efficiency and thermal comfort in building green retrofit," *Energy*, vol. 237, p. 121509, 2021.

[15] S. Moghtadernejad, L. E. Chouinard, and M. S. Mirza, "Design strategies using multi-criteria decision-making tools to enhance the performance of building façades," *Journal of Building Engineering*, vol. 30, p. 101274, 2020.

[16] U. EIA, "Commercial buildings energy consumption survey," *United Sates Department of Energy, Ed., ed*, 2012.

[17] I. Gaetani, P. J. Hoes, and J. L. Hensen, "Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy," *Energy and Buildings*, vol. 121, pp. 188–204, 6 2016.

[18] C. M. Clevenger, J. R. Haymaker, and M. Jalili, "Demonstrating the impact of the occupant on building performance," *Journal of computing in civil engineering*, vol. 28, no. 1, pp. 99–102, 2014.

[19] M. Bonte, F. Thellier, and B. Lartigue, "Impact of occupant's actions on energy building performance and thermal sensation," *Energy and Buildings*, vol. 76, pp. 219–227, 2014.

[20] S. A. Sadeghi, "VISUAL PREFERENCES AND HUMAN INTERACTIONS WITH SHADING AND ELECTRIC LIGHTING SYSTEMS," tech. rep., 2018.

[21] K. Konis and S. Selkowitz, "The challenge of effective daylighting," in *Effective Daylighting with High-Performance Facades*, pp. 1–31, Springer, 2017.

[22] A. Boerstra, M. Loomans, and J. Hensen, "Personal control over indoor climate and productivity," in *13th International Conference on Indoor Air Quality and Climate (Indoor Air 2014), June 7-12, 2014, Hong Kong*, pp. 1–8, ISIAQ, 2014.

[23] R. J. Cole and Z. Brown, "Reconciling human and automated intelligence in the provision of occupant comfort," *Intelligent buildings international*, vol. 1, no. 1, pp. 39–55, 2009.

[24] A. Tzempelikos and A. K. Athienitis, "The impact of shading design and control on building cooling and lighting demand," *Solar energy*, vol. 81, no. 3, pp. 369–382, 2007.

[25] T. Jackson, "Motivating sustainable consumption," *Sustainable Development Research Network*, vol. 29, no. 1, pp. 30–40, 2005.

[26] M. Moezzi and L. Lutzenhiser, "Whatâs missing in theories of the residential energy user," 2010.

[27] N. D. Sintov and P. W. Schultz, "Unlocking the potential of smart grid technologies with behavioral science," *Frontiers in psychology*, vol. 6, p. 410, 2015.

[28] C. Wilson and H. Dowlatabadi, "Models of decision making and residential energy use," *Annu. Rev. Environ. Resour.*, vol. 32, pp. 169–203, 2007.

[29] A. Heydarian, E. Pantazis, J. P. Carneiro, D. Gerber, and B. Becerik-Gerber, "Lights, building, action: Impact of default lighting settings on occupant behaviour," *Journal of Environmental Psychology*, vol. 48, pp. 212–223, 2016.

[30] S. Khashe, A. Heydarian, B. Becerik-Gerber, and W. Wood, "Exploring the effectiveness of social messages on promoting energy conservation behavior in buildings," *Building and Environment*, vol. 102, pp. 83–94, 2016.

[31] V. Fabi, R. V. Andersen, S. Corgnati, and B. W. Olesen, "Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models," *Building and Environment*, vol. 58, pp. 188–198, 2012.

[32] E. Goldstein and J. Brockmole, *Sensation and perception.* 2016.

[33] R. Wilson and F. Keil, *The MIT encyclopedia of the cognitive sciences.* 2001.

[34] J. Jerald, "Human-Centered Design for Virtual Reality," tech. rep.

[35] X. Zhang, H. Zhang, Y. Wang, and X. Shi, "Adaptive façades: Review of designs, performance evaluation, and control systems," *Buildings*, vol. 12, no. 12, p. 2112, 2022.

[36] G. Volpe and M. Gori, "Multisensory interactive technologies for primary education: From science to technology," *Frontiers in psychology*, vol. 10, p. 1076, 2019.

[37] B. Krietemeyer, B. Andow, and A. Dyson, "A computational design framework supporting human interaction with environmentally-responsive building envelopes," *International Journal of Architectural Computing*, vol. 13, no. 1, pp. 1–24, 2015.

[38] V. Inkarojrit, "Balancing comfort: occupants' control of window blinds in private offices," 2005.

[39] M. S. Rea, "Window Blind Occlusion: a Pilot Study," Tech. Rep. 2, 1984.

[40] C. F. Reinhart and K. Voss, "Monitoring manual control of electric lighting and blinds," *Lighting research & technology*, vol. 35, no. 3, pp. 243–258, 2003.

[41] F. Haldi and D. Robinson, "Adaptive actions on shading devices in response to local visual stimuli," *Journal of Building Performance Simulation*, vol. 3, pp. 135–153, 6 2010.

[42] A. Inoue, K. Ohtera, A.-P. Tsai, and T. Masumoto, "Aluminum-based amorphous alloys with tensile strength above 980 mpa (100 kg/mm2)," *Japanese Journal of Applied Physics*, vol. 27, no. 4A, p. L479, 1988.

[43] P. C. da Silva, V. Leal, and M. Andersen, "Occupants interaction with electric lighting and shading systems in real single-occupied offices: Results from a monitoring campaign," *Building and Environment*, vol. 64, pp. 152–168, 2013.

[44] G. W. Hunt, N. A. Reay, and T. Y. Yoshimura, "LOCAL DIFFEOMORPHISMS IN THE BIFURCATIONAL MANIFESTATIONS OF THE UMBILIC CATASTROPHES.," *Proceedings of The Royal Society of London, Series A: Mathematical and Physical Sciences*, vol. 369, no. 1736, pp. 47–65, 1979.

[45] R. G. Vine, "Optical fibre connector with moveable insert," May 26 1998. US Patent 5,757,996.

[46] Y. Sutter, D. Dumortier, and M. Fontoynont, "The use of shading systems in vdu task offices: A pilot study," *Energy and Buildings*, vol. 38, no. 7, pp. 780–789, 2006.

[47] J. A. Veitch, D. W. Hine, and R. Gifford, "END USERSâ KNOWLEDGE, BELIEFS, and PREFERENCES FOR LIGHTING," *Journal of Interior Design*, vol. 19, pp. 15–26, 9 1993.

[48] M. Boubekri, I. N. Cheung, K. J. Reid, C.-H. Wang, and P. C. Zee, "Impact of windows and daylight exposure on overall health and sleep quality of office workers: a case-control pilot study," *Journal of clinical sleep medicine*, vol. 10, no. 6, pp. 603–611, 2014.

[49] S. G. Hodder and K. Parsons, "The effects of solar radiation on thermal comfort," *International journal of biometeorology*, vol. 51, no. 3, pp. 233–250, 2007.

[50] S. Torresin, G. Pernigotto, F. Cappelletti, and A. Gasparella, "Combined effects of environmental factors on human perception and objective performance: A review of experimental laboratory works," 7 2018.

[51] E. Arens, T. Hoyt, X. Zhou, L. Huang, H. Zhang, and S. Schiavon, "Modeling the comfort effects of short-wave solar radiation indoors," *Building and Environment*, vol. 88, pp. 3–9, 6 2015.

[52] "TARGET ARTICLE: Immersive Virtual Environment Technology as a Methodological Tool for Social Psychology: Psychological Inquiry: Vol 13, No 2."

[53] S. Bassetti, L. Wolfisberg, B. Jaussi, R. Frei, M. F. Kuntze, M. Battegay, and A. F. Widmer, "Carriage of staphylococcus aureus among injection drug users: lower prevalence in an injection heroin maintenance program than in an oral methadone program," *Infection Control & Hospital Epidemiology*, vol. 25, no. 2, pp. 133–137, 2004.

[54] M. Foster and T. Oreszczyn, "Occupant control of passive systems: The use of Venetian blinds," *Building and Environment*, vol. 36, pp. 149–155, 2 2001.

[55] A. Mahdavi, L. Ferreira, C. Sundback, J. W. Nichol, E. P. Chan, D. J. Carter, C. J. Bettinger, S. Patanavanich, L. Chignozha, E. Ben-Joseph, A. Galakatos, H. Pryor, I. Pomerantseva, P. T. Masiakos, W. Faquin, A. Zumbuehl, S. Hong, J. Borenstein, J. Vacanti, R. Langer, and J. M. Karp, "A biodegradable and biocompatible gecko-inspired tissue adhesive," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 105, pp. 2307–2312, 2 2008.

[56] Y. Zhang and P. Barrett, "Factors influencing occupantsâ blind-control behaviour in a naturally ventilated office building," *Building and Environment*, vol. 54, pp. 137–147, 2012.

[57] P. R. Lyons, D. Arasteh, and C. Huizenga, "Window performance for human thermal comfort," *Transactions-American Society of Heating Refrigerating and Air Conditioning Engineers*, vol. 106, no. 1, pp. 594–604, 2000.

[58] J. P. Carneiro, A. Aryal, and B. Becerik-Gerber, "Understanding the influence of orientation, time-of-day and blind use on userâs lighting choices and energy consumption using immersive virtual environments," *Advances in Building Energy Research*, vol. 15, no. 5, pp. 603–629, 2021.

[59] A. Mahdavi, A. Mohammadi, E. Kabir, and L. Lambeva, "Occupants' operation of lighting and shading systems in office buildings," *Journal of building performance simulation*, vol. 1, no. 1, pp. 57–65, 2008.

[60] F. Nicol, M. Wilson, and C. Chiancarella, "Using field measurements of desktop illuminance in European offices to investigate its dependence on outdoor conditions and its effect on occupant satisfaction, and the use of lights and blinds," *Energy and Buildings*, vol. 38, pp. 802–813, 7 2006.

[61] S. A. Sadeghi, P. Karava, I. Konstantzos, and A. Tzempelikos, "Occupant interactions with shading and lighting systems using different control interfaces: A pilot field study," *Building and Environment*, vol. 97, pp. 177–195, 2016.

[62] A. Rasheed, "Multiscale modelling of urban climate," tech. rep., EPFL, 2009.

[63] M. Kolokotroni, I. Giannitsaris, and R. Watkins, "The effect of the london urban heat island on building summer cooling demand and night ventilation strategies," *Solar energy*, vol. 80, no. 4, pp. 383–392, 2006.

[64] C. Ghiaus, F. Allard, M. Santamouris, C. Georgakis, and F. Nicol, "Urban environment influence on natural ventilation potential," *Building and environment*, vol. 41, no. 4, pp. 395–406, 2006.

[65] C. F. Reinhart and J. Wienold, "The daylighting dashboard - A simulation-based design analysis for daylit spaces," *Building and Environment*, vol. 46, pp. 386–396, 2 2011.

[66] S. Mirzabeigi, B. K. Nasr, A. G. Mainini, J. D. B. Cadena, and G. Lobaccaro, "Tailored wbgt as a heat stress index to assess the direct solar radiation effect on indoor thermal comfort," *Energy and Buildings*, vol. 242, p. 110974, 2021.

[67] C. Kasinalis, R. C. Loonen, D. Cóstola, and J. Hensen, "Framework for assessing the performance potential of seasonally adaptable facades using multi-objective optimization," *Energy and Buildings*, vol. 79, pp. 106–113, 2014.

[68] S. Borgeson and G. Brager, "Occupant control of windows: Accounting for human behaviour in building simulation. Centre for the Built Environment," 2008.

[69] M. Slater and M. Usoh, "Representations Systems, Perceptual Position, and Presence in Immersive Virtual Environments," *Presence: Teleoperators and Virtual Environments*, vol. 2, pp. 221–233, 1 1993.

[70] A. Luna-Navarro, R. C. G. M. Loonen, S. Attia, M. Juaristi, A. Monge-Barrio, M. Donato, R. Rabenseifer, and M. Overend, "Occupant-Adaptive Façade Interaction: Relationships and Conflicts," tech. rep.

[71] J. K. Day, C. McIlvennie, C. Brackley, M. Tarantini, C. Piselli, J. Hahn, W. O'Brien, V. S. Rajus, M. De Simone, M. B. Kjærgaard, *et al.*, "A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort," *Building and environment*, vol. 178, p. 106920, 2020.

[72] A. Luna-Navarro, R. Loonen, M. Juaristi, A. Monge-Barrio, S. Attia, and M. Overend, "Occupant-facade interaction: a review and classification scheme," *Building and Environment*, vol. 177, p. 106880, 2020.

[73] V. Inkarojrit, "Monitoring and modelling of manually-controlled venetian blinds in private offices: a pilot study," *Journal of Building Performance Simulation*, vol. 1, no. 2, pp. 75–89, 2008.

[74] M. Eilers, J. Reed, and T. Works, "Behavioral aspects of lighting and occupancy sensors in private offices: a case study of a university office building," in *Summer Study on Energy Efficiency in Buildings*, 1996.

[75] A. H. Zarrabi, M. Azarbayjani, J. Day, E. Thariyan, E. Stearns, and B. Dale, "VISUAL QUALITIES AND PERCEIVED THERMAL COMFORT-RESULTS OF SURVEY STUDIES IN A LEED PLATINUM OFFICE BUILDING," 2017.

[76] A. Tzempelikos and A. K. Athienitis, "The impact of shading design and control on building cooling and lighting demand," *Solar Energy*, vol. 81, pp. 369–382, 3 2007.

[77] W. O'Brien, K. Kapsis, and A. K. Athienitis, "Manually-operated window shade patterns in office buildings: A critical review," 2 2013.

[78] N. Sumpi and H. J. Amukugo, "Paradigmatic perspectives of a psychosocial educational programme to facilitate the reintegration of incarcerated women who had dumped babies and / or committed infanticide in Namibia," *http://www.sciencepubco.com/index.php/IJH/article/view/6129*, 2016.

[79] M. Cabanac, "Physiological role of pleasure," *Science*, vol. 173, no. 4002, pp. 1103–1107, 1971.

[80] P. Bluyssen, *The indoor environment handbook: how to make buildings healthy and comfortable.* 2009.

[81] A. Heydarian, E. Pantazis, A. Wang, D. Gerber, and B. Becerik-Gerber, "Towards user centered building design: Identifying end-user lighting preferences via immersive virtual environments," *Automation in Construction*, vol. 81, pp. 56–66, 9 2017.

[82] A. Stevenson, *Oxford dictionary of English.* 2010.

[83] Amir H. Zarrabi (University of North Carolina at Charlottel), Mona Azarbayjani (University of North Carolina at Charlottel), Julia Day (Kansas State University), Elizabeth Thariyan (University of North Carolina at Charlottel), Elizabeth Stearns (University of North Carolina at Charlottel), and Brentrup Dale (University of North Carolina at Charlottel), "Visual Qualities and Perceived Thermal Comfort-results of Survey Studies in a LEED Platinum Office Building | Building Research Information Knowledgebase."

[84] J.-H. Choi and J. Moon, "Impacts of human and spatial factors on user satisfaction in office environments," *Building and Environment*, vol. 114, pp. 23–35, 2017.

[85] S. L. Chellappa, R. Steiner, P. Oelhafen, and C. Cajochen, "Sex differences in light sensitivity impact on brightness perception, vigilant attention and sleep in humans," *Scientific reports*, vol. 7, no. 1, pp. 1–9, 2017.

[86] J.-H. Choi, V. Loftness, and A. Aziz, "Post-occupancy evaluation of 20 office buildings as basis for future ieq standards and guidelines," *Energy and buildings*, vol. 46, pp. 167–175, 2012.

[87] M. Schweiker, F. Haldi, M. Shukuya, and D. Robinson, “Verification of stochastic models of window opening behaviour for residential buildings,” *Journal of Building Performance Simulation*, vol. 5, no. 1, pp. 55–74, 2012.

[88] M. Taj-Eldin, C. Ryan, B. Oâflynn, and P. Galvin, “A review of wearable solutions for physiological and emotional monitoring for use by people with autism spectrum disorder and their caregivers,” 12 2018.

[89] D. A. McIntyre, “Chamber studies-reductio ad absurdum?,” *Energy and Buildings*, vol. 5, no. 2, pp. 89–96, 1982.

[90] R. J. de Dear, T. Akimoto, E. A. Arens, G. Brager, C. Candido, K. W. D. Cheong, B. Li, N. Nishihara, S. C. Sekhar, S. Tanabe, J. Toftum, H. Zhang, and Y. Zhu, “Progress in thermal comfort research over the last twenty years,” *Indoor Air*, vol. 23, pp. 442–461, 12 2013.

[91] R. J. de Dear and M. E. Fountain, “UC Berkeley Indoor Environmental Quality (IEQ) Title Field experiments on occupant comfort and office thermal environments in a hot-humid climate Publication Date FIELD EXPERIMENTS ON OCCUPANT COMFORT AND OFFICE THERMAL ENVIRONMENTS IN A HOT-HUMID CLIMATE,” tech. rep., 1994.

[92] K. Cena and R. De Dear, “Thermal comfort and behavioural strategies in office buildings located in a hot-arid climate,” *Journal of Thermal Biology*, vol. 26, no. 4-5, pp. 409–414, 2001.

[93] R. J. de Dear, T. Akimoto, E. A. Arens, G. Brager, C. Candido, K. W. D. Cheong, B. Li, N. Nishihara, S. C. Sekhar, S. Tanabe, J. Toftum, H. Zhang, and Y. Zhu, “Progress in thermal comfort research over the last twenty years,” *Indoor Air*, vol. 23, pp. 442–461, 12 2013.

[94] M. Slater, A. Antley, A. Davison, D. Swapp, C. Guger, C. Barker, N. Pistrang, and M. V. Sanchez-Vives, “A virtual reprise of the stanley milgram obedience experiments,” *PloS one*, vol. 1, no. 1, 2006.

[95] B. G. Witmer and M. J. Singer, “Measuring presence in virtual environments: A presence questionnaire,” *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 3, pp. 225–240, 1998.

[96] K. F. Hew, “Use of audio podcast in k-12 and higher education: A review of research topics and methodologies,” *Educational Technology Research and Development*, vol. 57, no. 3, pp. 333–357, 2009.

[97] J. Goulding, W. Nadim, P. Petridis, and M. Alshawi, “Construction industry off-site production: A virtual reality interactive training environment prototype,” *Advanced Engineering Informatics*, vol. 26, pp. 103–116, 1 2012.

[98] H.-J. Bullinger, D. Spath, H.-J. Warnecke, and E. Westkämper, *Handbuch unternehmensorganisation: strategien, planung, umsetzung*. Springer-Verlag, 2009.

[99] S. Woksepp and T. Olofsson, "Credibility and applicability of virtual reality models in design and construction," *Advanced Engineering Informatics*, vol. 22, pp. 520–528, 10 2008.

[100] S. F. Kuliga, T. Thrash, R. C. Dalton, and C. Hölscher, "Virtual reality as an empirical research tool - Exploring user experience in a real building and a corresponding virtual model," *Computers, Environment and Urban Systems*, vol. 54, pp. 363–375, 11 2015.

[101] S. Niu, W. Pan, and Y. Zhao, "A virtual reality integrated design approach to improving occupancy information integrity for closing the building energy performance gap," *Sustainable Cities and Society*, vol. 27, pp. 275–286, 2016.

[102] D. Yan, W. O'Brien, T. Hong, X. Feng, H. Burak Gunay, F. Tahmasebi, and A. Mahdavi, "Occupant behavior modeling for building performance simulation: Current state and future challenges," *Energy and Buildings*, vol. 107, pp. 264–278, 2015.

[103] T. Hong, M. Lee, S. Yeom, and K. Jeong, "Occupant responses on satisfaction with window size in physical and virtual built environments," *Building and Environment*, vol. 166, no. August, p. 106409, 2019.

[104] J. Wienold, "Façade and sunlight pattern geometry and their influence on occupants View project On the sensitivity of buildings to climate: the interaction of weather and building envelopes in determining future building energy consumption View project Giorgia Chinazz," tech. rep., 2019.

[105] E. Yandri, "Uniformity characteristic and calibration of simple low cost compact halogen solar simulator for indoor experiments," *International Journal of Low-Carbon Technologies*, vol. 13, no. 3, pp. 218–230, 2018.

[106] J. P. Carneiro, A. Aryal, and B. Becerik-Gerber, "Understanding the influence of orientation, time-of-day and blind use on userâs lighting choices and energy consumption using immersive virtual environments," *Advances in Building Energy Research*, pp. 1–27, 2019.

[107] Y. Guan, M. Hosni, B. J. A. . . . , and u. 2003, "Investigation of human thermal comfort under highly transient conditions for automotive applications-part 2: Thermal sensation modeling," *search.proquest.com*.

[108] D. Fiala, "Dynamic Simulation of Human Heat Transfer and Thermal Comfort," tech. rep., 1998.

[109] A. P. Gagge, J. A. Stolwijk, and J. D. Hardy, "Comfort and thermal sensations and associated physiological responses at various ambient temperatures," *Environmental Research*, vol. 1, no. 1, pp. 1–20, 1967.

[110] V. Esen, Ş. Sağlam, and B. Oral, "Light sources of solar simulators for photovoltaic devices: A review," *Renewable and Sustainable Energy Reviews*, vol. 77, pp. 1240–1250, 2017.

[111] C. Marino, A. Nucara, and M. Pietrafesa, "Thermal comfort in indoor environment: Effect of the solar radiation on the radiant temperature asymmetry," *Solar Energy*, vol. 144, pp. 295–309, 2017.

[112] H. Nakamura and M. Oki, "Influence of Air Temperature on Preference for Color Temperature of General Lighting in the Room," *Journal of the Human-Environment System*, vol. 4, no. 1, pp. 41–47, 2000.

[113] M. te Kulve, L. Schlangen, and W. van Marken Lichtenbelt, "Interactions between the perception of light and temperature," *Indoor Air*, vol. 28, pp. 881–891, 11 2018.

[114] K. Chamilothori, J. Wienold, and M. Andersen, "Adequacy of immersive virtual reality for the perception of daylit spaces: comparison of real and virtual environments," *Leukos*, vol. 15, no. 2-3, pp. 203–226, 2019.

[115] M. J. Murdoch, M. G. Stokkermans, and M. Lambooij, "Towards perceptual accuracy in 3d visualizations of illuminated indoor environments," *Journal of Solid State Lighting*, vol. 2, no. 1, pp. 1–19, 2015.

[116] B. Salters, M. Murdoch, D. Sekulovksi, S.-H. Chen, and P. Seuntiens, "An evaluation of different setups for simulating lighting characteristics," in *Human Vision and Electronic Imaging XVII*, vol. 8291, pp. 477–489, SPIE, 2012.

[117] C. A. Gueymard, "The smarts spectral irradiance model after 25 years: New developments and validation of reference spectra," *Solar Energy*, vol. 187, pp. 233–253, 2019.

[118] J. Jin, Y. Hao, and H. Jin, "A universal solar simulator for focused and quasi-collimated beams," *Applied energy*, vol. 235, pp. 1266–1276, 2019.

[119] Q. Chen, X. Jin, and L. Xue, "Modeling and optimization for selecting led to synthesize solar spectrum using residual-guided evolution algorithms," *Optik*, vol. 182, pp. 95–104, 2019.

[120] C. A. Gueymard, "Revised composite extraterrestrial spectrum based on recent solar irradiance observations," *Solar Energy*, vol. 169, pp. 434–440, 2018.

[121] D. R. Myers, "Direct beam and hemispherical terrestrial solar spectral distributions derived from broadband hourly solar radiation data," *Solar Energy*, vol. 86, no. 9, pp. 2771–2782, 2012.

[122] J. Polo, F. Antonanzas-Torres, J. Vindel, and L. Ramirez, “Sensitivity of satellite-based methods for deriving solar radiation to different choice of aerosol input and models,” *Renewable energy*, vol. 68, pp. 785–792, 2014.

[123] J. Balenzategui and F. Chenlo, “Measurement and analysis of angular response of bare and encapsulated silicon solar cells,” *Solar Energy Materials and Solar Cells*, vol. 86, no. 1, pp. 53–83, 2005.

[124] D. S. Codd, A. Carlson, J. Rees, and A. H. Slocum, “A low cost high flux solar simulator,” *Solar energy*, vol. 84, no. 12, pp. 2202–2212, 2010.

[125] M. Tawfik, X. Tonnellier, and C. Sansom, “Light source selection for a solar simulator for thermal applications: A review,” 7 2018.

[126] W. Leiner, K. Altfeld, E. Aranovich, and B. Gillett, “Design of a solar simulator with reduced thermal radiation to be used as a component of a test facility for air heating collectors,” 1982.

[127] W. Gillett, “Solar simulators and indoor testing,” in *Meeting of the International Solar Society, UK Section-April*, 1977.

[128] M. Shatat, S. Riffat, and F. Agyenim, “Experimental testing method for solar light simulator with an attached evacuated solar collector,” 2013.

[129] M. Shimotomai, Y. Shinohara, and S. Igari, “The development of the iv measurement by pulsed multi-flash, and the effectiveness,” in *2006 IEEE 4th World Conference on Photovoltaic Energy Conference*, vol. 2, pp. 2223–2226, IEEE, 2006.

[130] K. A. Kim, N. Dostart, J. Huynh, and P. T. Krein, “Low-cost solar simulator design for multi-junction solar cells in space applications,” in *2014 Power and Energy Conference at Illinois (PECI)*, pp. 1–6, IEEE, 2014.

[131] A. Y. Liu, S. Shao, and S. Chang, “Using various pulse durations and reference cells on long-pulse solar simulator for cigs thin-film pv module performance measurements,” in *2012 Spring Congress on Engineering and Technology*, pp. 1–4, IEEE, 2012.

[132] M. A. Mohan, J. Pavithran, K. L. Osten, A. Jinumon, and C. Mrinalini, “Simulation of spectral match and spatial non-uniformity for led solar simulator,” in *2014 IEEE Global Humanitarian Technology Conference-South Asia Satellite (GHTC-SAS)*, pp. 111–117, IEEE, 2014.

[133] F. Hussain, M. Y. Othman, B. Yatim, H. Ruslan, K. Sopian, Z. Anuar, and S. Khairuddin, “Fabrication and irradiance mapping of a low cost solar simulator for indoor testing of solar collector,” *Journal of Solar Energy Engineering, Transactions of the ASME*, vol. 133, no. 4, 2011.

[134] D. Yan, W. OâBrien, T. Hong, X. Feng, H. B. Gunay, F. Tahmasebi, and A. Mahdavi, "Occupant behavior modeling for building performance simulation: Current state and future challenges," *Energy and Buildings*, vol. 107, pp. 264–278, 2015.

[135] I. A. Macdonald, "Quantifying the Effects of Uncertainty in Building Simulation," tech. rep.

[136] E. Lindbladh and C. H. Lyttkens, "Habit versus choice: The process of decision-making in health-related behaviour," *Social Science and Medicine*, vol. 55, no. 3, pp. 451–465, 2002.

[137] Z. Yu, B. C. Fung, F. Haghighat, H. Yoshino, and E. Morofsky, "A systematic procedure to study the influence of occupant behavior on building energy consumption," *Energy and Buildings*, vol. 43, no. 6, pp. 1409–1417, 2011.

[138] J. Blascovich, J. Loomis, A. C. Beall, K. R. Swinth, C. L. Hoyt, and J. N. Bailenson, "Immersive virtual environment technology as a methodological tool for social psychology," *Psychological Inquiry*, vol. 13, no. 2, pp. 103–124, 2002.

[139] A. Heydarian, J. P. Carneiro, D. Gerber, B. Becerik-Gerber, T. Hayes, and W. Wood, "Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations," *Automation in Construction*, vol. 54, pp. 116–126, 2015.

[140] G. Ozcelik and B. Becerik-Gerber, "Benchmarking thermoception in virtual environments to physical environments for understanding human-building interactions," *Advanced Engineering Informatics*, vol. 36, pp. 254–263, 4 2018.

[141] J. P. Carneiro, A. Aryal, and B. Becerik-Gerber, "Advances in Building Energy Research Understanding the influence of orientation, time-of-day and blind use on user's lighting choices and energy consumption using immersive virtual environments," 2019.

[142] C. Chokwitthaya, S. Saeidi, . Yimin Zhu, R. Kooima, and P. D. Student, "The Impact of Lighting Simulation Discrepancies on Human Visual Perception and Energy Behavior Simulations in Immersive Virtual Environment," tech. rep.

[143] D. Fiala, K. Lomas, M. S. A. Transactions, and u. 2003, "First principles modeling of thermal sensation responses in steady-state and transient conditions," *search.proquest.com*.

[144] X. Wang, "Thermal comfort and sensation under transient conditions," 1994.

[145] M. Veselỳ and W. Zeiler, "Personalized conditioning and its impact on thermal comfort and energy performance–a review," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 401–408, 2014.

[146] H. Zhang, E. Arens, C. Huizenga, and T. Han, "Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts," *Building and Environment*, vol. 45, pp. 389–398, 2 2010.

[147] S. Norouziasl, A. Jafari, and Y. Zhu, "Modeling and simulation of energy-related human-building interaction: A systematic review," *Journal of Building Engineering*, vol. 44, p. 102928, 2021.