HIDE & SEEK: THERMAL ALLIESTHESIA INSIDE SOLAR SCREENED PERIMETER OFFICES

by

NIYATI S. NAIK

A DISSERTATION

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Student: Niyati S. Naik

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This dissertation has been accepted and approved in partial fulfilment of the requirements for the Doctor of Philosophy degree in the Department of Architecture by:

Ihab Elzeyadi	Chair
Virginia Cartwright	Core Member
Jun-Hak Lee	Core Member
Christopher Minson	Institutional Representative
and	
Andy Karduna	Interim Vice Provost for Graduate Studies

Original approval signatures are on file with the University of Oregon Division of Graduate Studies.

Degree awarded June 2021.

DISSERTATION ABSTRACT

Niyati S. Naik

Doctor of Philosophy

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Title: HIDE & SEEK: Thermal Alliesthesia inside Solar Screened Perimeter Offices

It is the need of the day to design indoor environments that are not only comfortable but also pleasurable for the occupants. Passive yet dynamic architectural strategies have been widely acknowledged for their influence on thermal pleasure. However, this influence has not been adequately investigated. Dynamic solar screens of building facades are passive strategies that can potentially provide thermal comfort and pleasure. This dissertation research explored thermal pleasure in office spaces using dynamic solar screens as the tools to control the indoor environments. The study responds to these questions, (i) what typologies of dynamic solar screens are the most suitable in controlling indoor thermal environments for thermal pleasure? (ii) how to design dynamic solar screens for thermal pleasure? (iii) what is the relationship of thermal pleasure with indoor thermal environmental parameters and human physiological variables inside dynamic-movable and static-stationary screened spaces? (iv) what is the impact of sky conditions on thermal pleasure inside dynamic and static screened spaces, and (v) what is the significance of dynamic over static screens in influencing thermal pleasure under different sky conditions?

The research employed a multi-method approach of five inter-related studies, as follows: (i) meta-analysis of solar screen performance from previous studies, (ii) observational field study, (ii) computational simulations, (iii) indoor environmental monitoring, and (iv) within and between-subjects experiments involving human participants inside the experimental perimeter offices with dynamic and static screen shading. It was found that the dynamic screens, designed to create variability in the indoor thermal environment within the limits of the thermal comfort zone may influence thermal pleasure. The findings provide experimental evidence that expands the application of the thermal alliesthesia framework to building perimeter offices. They

demonstrate the importance of indoor thermal environmental variability for occupant pleasure and well-being. This research contributes to occupant-centric building research by describing an approach to design shading systems that cater to occupant's thermal pleasure and multi-comfort. This work will be of interest to scholars, architects, building designers, engineers, and students interested in research on thermal comfort, indoor environmental quality, adaptive shading, and passive architecture.

This dissertation includes previously published/unpublished material.

CURRICULUM VITAE

NAME OF AUTHOR: Niyati S. Naik

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene
University of Wisconsin-Milwaukee
The Maharaja Sayajirao University of Baroda, India

DEGREES AWARDED:

Doctor of Philosophy, Architecture, 2021, University of Oregon
Master of Architecture, 2014, University of Wisconsin-Milwaukee
Bachelor of Architecture, 2010, The Maharaja Sayajirao University of Baroda

AREAS OF SPECIAL INTEREST:

Thermal Comfort-Pleasure in Buildings
Passive Cooling Strategies in Building Design
Solar Screens
Indoor Environmental Quality
Environmental Psychophysiology
Net-Zero and Net-Positive Buildings
Historic Preservation and Adaptive Re-use of Buildings

PROFESSIONAL EXPERIENCE:

Graduate Teaching and Research Fellow, Architecture, 2016 to present
Associate Architect, TATA Ecofirst, Mumbai, India, 2014-2016
Assistant Architect, Karan Grover Associates, Vadodara, India, 2010-2012

GRANTS, AWARDS, AND HONORS:

ARCC King Student Medal, 2021
ARCC Graduate Students Scholarship, 2021
College of Design Dissertation Research Fellowship, 2020-21
Jeffrey Cook Memorial PLEA Scholarship, 2020
Sushil Jajodia Indian Student Scholarship, 2019-2020
Society of Building Science Educators Travel Scholarship, 2017
Chancellor’s Graduate Student Award, UW-Milwaukee, 2013

PUBLICATIONS:

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Consortium (ARCC) conference held virtually in Tuscon, Arizona.

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Naik, N. & Elzeyadi, I. (2020). External Dynamic Screens for Thermal Delight and Alliesthesia. In the proceedings of *Associate Collegiate Schools of Architecture (ACSA) 108th Annual Meeting* held virtually in, San Diego, CA, USA

Naik, N. & Elzeyadi, I. (2020). Investigating the impacts of Solar Screens on Occupant's Thermal Comfort: An Observational Field Study. *ASHRAE Transactions*, 126 (1)

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CHAPTER I: INTRODUCTION

The existing thermal comfort standards for building indoor environments accept narrow limits of uniform thermal conditions as ‘comfortable’ (ASHRAE Standard-55; EN15251; ISO 7730). Aiming at “reducing the negative” aspects of the indoor environments to provide for thermal comfort deprives occupants of sensory experiences and climate variability (Brager et al., 2015; Brager, 2019). Scholars in occupant comfort research have observed that the standardized thermal and visual environments create “experiential monotony” and promote “dull-spaces”, which negatively impact occupant well-being (Brager, 2019; Reinhart, 2015). Thus, in current times, when design decisions are driven by standards, architects and building designers should respond by “enhancing the positives” of the indoor environments by making them engaging and pleasurable.

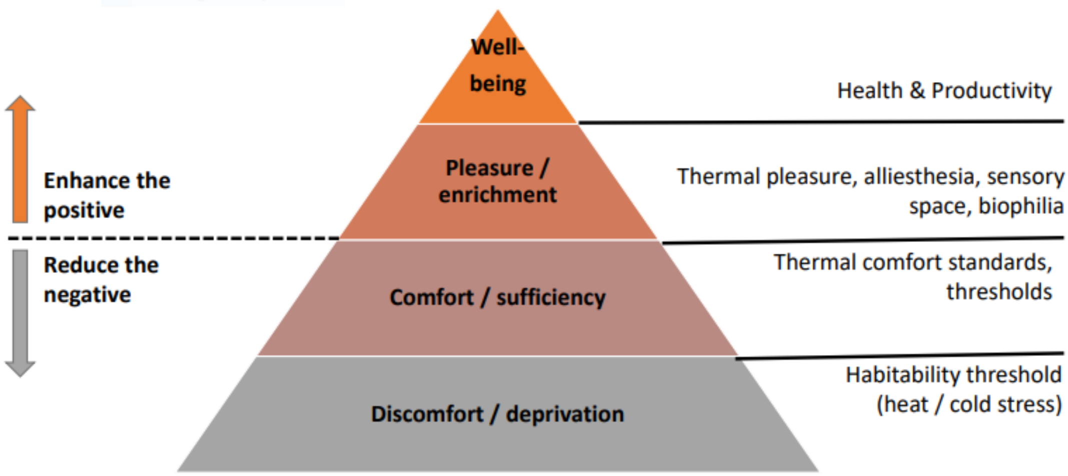


Figure 1.1 A theoretical understanding on aspects to focus on while designing engaging and pleasurable environments for occupant well-being. Modified after Vischer, J.C. (2007) and Brager (2019).

Provision for controlled non-uniform thermal conditions is advocated for designing thermally pleasurable indoor environments for office occupants (Brager, 2015; de Dear, 2012). The transient conditions like temperature changes from mildly high to low and/or changes in air velocity in a non-uniform thermal environment may be perceived as pleasurable and could garner higher occupant satisfaction. Human perception of thermal pleasure under exposure to indoor thermal non-uniformity can be explained by the framework of thermal alliesthesia (Cabanac, 1971). This framework explains that when a human body is in a slightly less comfortable (warm/cool) state it can experience pleasure due to a thermal stimulus that brings it towards comfort. Thermal pleasure is being explored inside building environments based on a space's programmatic use or through non-architectural interventions like personal comfort systems like hand-foot warmers, personal fans, and heated-cooled chairs, or temperature modulations created by HVAC systems (Pasut et al., 2015; Vargas et al., 2017; Traylor et al., 2019).

Passive architectural strategies have been widely acknowledged for their influence on thermal pleasure (Heschong, 1979; Reynolds, 2002; de Dear, 2014; Passe & Battaglia, 2015). However, this influence has not been investigated scientifically. Solar screen shading is a passive cooling strategy that is based on biophilic design principles. The nature of biophilic design is based on the central idea that aims at providing sensory pleasure to occupants (Ryan and Browning, 2020). Thus, solar screen shading can potentially provide for thermal as well as over-all sensory pleasure.

1.1 Research Goal and Questions

The goal, through this dissertation research, was to explore thermal pleasure in office spaces using solar screens as the tools to control the indoor environments. This work seeks to respond to questions such as, (i) what typologies of solar screens are the most suitable in controlling indoor thermal environments? (ii) how to design solar screens for thermal pleasure? (iii) what is the relationship of thermal pleasure with indoor thermal environmental parameters and human physiological variables inside dynamic (movable) and static (stationary) screened spaces? (iv) what is the significance of dynamic over static screens in influencing thermal pleasure under different sky conditions? (v) what is the impact of sky conditions and visual environment on thermal pleasure inside dynamic and static screened spaces?

1.2 Research Objectives

Thermal perception inside office spaces shaded by solar screens was explored by involving human-factors based design research. This exploration was carried out during the summer months of Eugene, Oregon (44.4 °N 123.5 °E), ASHRAE Climate Zone

(CZ)-4C. While this climate zone does not experience large thermal swings, buildings here do have substantial cooling loads during summers and as a design response to which solar shading of facades is a common practice.

Following objectives were addressed: (i) to determine suitable solar screen typologies for thermal environmental control, (ii) to design and fabricate dynamic and static screens that can influence thermal pleasure in ASHRAE-CZ-4C, (iii) to investigate the impact of dynamic and static screens on the indoor thermal environment and human physiological variables, (iv) to quantify the relationships of thermal pleasure with human physiological variables, and the thermal and visual environmental parameters inside the static and dynamic screened spaces, (v) to compare the impact of the dynamic versus the static screen in influencing thermal pleasure under different sky conditions, and (vi) to observe the impact of sky conditions and visual environment on thermal pleasure.

1.3 Dissertation Overview

The dissertation is structured as a series of chapters that address the research objectives towards attaining the research goal. The dissertation committee members have contributed and are listed as co-authors towards development of these chapters, each of which is composed of single or multiple research papers. Some of these papers are already published, in-review, or to be submitted for publication to peer-reviewed conference proceedings and/or journals. Brief detail on each chapter is discussed in the following paragraphs.

Chapter 2 addresses the question on the type of solar screens that are suitable for controlling indoor thermal environments. This chapter is a compilation of two papers, one of which is a literature review on previous work related to solar screens and the other reports on findings from an observational field study. The literature review was used to categorize the solar screens investigated in previous studies and conduct a meta-analysis of their performance in influencing building energy and indoor thermal-visual environment. The observational field study was conducted inside a solar screened building, where human behaviour in response to the thermal environment mediated by solar screens was observed under moderate climate conditions. The paper on the observational field-study is co-authored by Prof. Ihab Elzeyadi and has been published in American Society of Heating Refrigeration and Air-Conditioning (ASHRAE) conference proceedings. The literature review paper is co-authored by Prof. Ihab Elzeyadi and Prof. Virginia Cartwright and is to be submitted to a journal for publication.

Chapter 3 addresses the question on ways to design solar screens for thermal pleasure. This chapter is a compilation of two papers, one of which reports on findings from a computational study that was used to inform the design and fabrication of static and dynamic screen prototypes for thermal pleasure. The other paper reports on findings from a pilot study that was carried out inside full-scale, static, and dynamic screened experimental/mock-up offices. This study was used to design the thermal environment using static and dynamic screens for human exposure to the experimental office set-ups. Both the papers are co-authored by Prof. Ihab Elzeyadi and have been published in Association of Collegiate Schools of Architecture (ACSA) and Passive and Low Energy Architecture (PLEA) conference proceedings.

Chapter 4 addresses the question on the relationship of subjective reporting of thermal pleasure with indoor thermal environmental parameters and human physiological variables inside dynamic and static screened experimental, offices. It elaborates on thermal alliesthesia, its relevance inside buildings and discusses findings from the experiments that exposed human participants inside the static and dynamic screened experimental offices. Co-relations of subjective data with physical environmental variables and objective human related parameters have been quantified and compared with findings from previous work focusing on thermal pleasure inside buildings. This entire chapter has been submitted as a research paper to the journal, Building Research and Information (BRI) and is under peer-review. It has been co-authored by Prof. Ihab Elzeyadi, Prof. Christopher Minson, and Dr. Jun-Hak Lee.

Chapter 5 addresses the questions on the significance of dynamic over static screens in influencing thermal pleasure and the impact of sky conditions and visual environment on thermal pleasure. This chapter is a combination of two papers that report on more findings and in-depth analysis from experiments with human participants inside the static and dynamic screened experimental offices. One paper focuses on comparing the participants' overall thermal perception (pleasure, sensation, preference, comfort, and sensation of asymmetry), task performance, and general environmental perception between static and dynamic screened offices. This paper is prepared for submission to a peer-reviewed journal. The other paper focused on observing the impact of sky conditions on thermal pleasure and thermal sensation. This paper has been published in the proceedings of Architectural Research Centres Consortium (ARCC) conference and is co-authored by Prof. Ihab Elzeyadi and Prof. Virginia Cartwright.

Finally, Chapter 6 reports on the conclusions and the potential avenues for future work.

CHAPTER II: BACKGROUND AND PROBLEM STATEMENT

This chapter is a compilation of two papers, one reports on the findings from a critical review of literature on solar screens and the other is an observational field study. The literature review is co-authored by Prof. Ihab Elzeyadi and Prof. Virginia Cartwright and will be submitted to a journal for publication. The observational field study (Section 2.3) is co-authored by Prof. Ihab Elzeyadi and is published in American Society of Heating Refrigeration and Air-Conditioning (ASHRAE) Winter-2020 conference proceedings.

The chapter responds to the question that is what typologies of solar screens are the most suitable in controlling indoor thermal environments? The literature review was conducted to identify research gaps, highlight methodological limitations, and propose future application potentials to investigate the unexplored impacts of the solar screens. The observational field study was used to analyse human behaviour with respect to the thermal environment inside a solar screened building.

In the literature review process, solar screens were categorized into four parametric typologies termed as: (i) massive static, (ii) light-weight static, (iii) dense dynamic, and (iv) 3-D geometric dynamic. Massive static and dense dynamic screens essentially have higher number and smaller sized perforations in a unit area of thick shading panels. Whereas light-weight static and 3-D geometric dynamic screens have lower number and larger sized perforations in a unit shading area that is mounted on light-weight structures. Screen panel thickness is not accounted for in light-weight static and 3-D geometric dynamic screens.

The meta-analysis of the building and indoor environmental performance of these screen typologies revealed that their impact on occupant thermal perception was under-researched. It was found that massive static and deep dynamic screens can potentially increase 10-15% energy savings on building cooling and reduce solar heat gain by 20-25% compared to the light-weight static and 3-D geometric screens. Thus, massive static and dense dynamic screens are the suitable typologies for indoor thermal environmental control. For a balanced, thermal, daylighting, and visual comfort performance, the meta-analysis predicted that the dense dynamic screens, because of their ability to change in response to climate and occupant demand, could potentially perform better than the massive static screens.

The observations from the field study indicated that there is a need to revisit the massive static screen designs that are optimized to maintain thermally uniform conditions in the building perimeter areas. The measurements and observations from this study indicated occupant's preference of thermally non-uniform and dynamic environments; the requirement of which is advocated by Brager et.al, (2015) and Parkinson & de Dear (2015). The field study is suggestive towards different ways to design fenestrations like solar screens to achieve thermally dynamic indoors to enhance occupants' thermal experience. Realizing the importance of keeping occupants' experience and wellness at the top priority in building design, a set of hypotheses is proposed that describe approaches to design dense dynamic screens for occupant well-being. Moreover, suitable research methods to investigate dense dynamic screens for occupant well-being are discussed.

2.1. Introduction

Architects are eager to develop energy efficient building facades using high-performance shading and glazing components as design solutions to reduce the greenhouse gas emissions related to buildings (Brager et al., 2015). External dynamic façade shading system is a design strategy that enables facades to change their physical properties in response to hourly, daily, and seasonal variations in outdoor climate conditions as well as occupant demands. Dynamic facades are also termed as adaptive, climate responsive, kinetic, smart, and intelligent systems (Kunwar et al., 2018; Fiorito et al., 2016; Attia et al., 2015). Compared to non-shaded envelopes, manually controlled or automated dynamic facades can potentially reduce energy consumption by 33%, increase thermal comfort hours by 30%, achieve standardized daylighting sufficiency, and manage glare. (Elzeyadi, 2017; Cort & Johnson, 2017; Curcija et al., 2013; Elzeyadi et al., 2016).

External dynamic shading systems have been broadly categorized based on their geometry, material properties, and type of movement (Elzeyadi et al., 2016). The four main types of these systems are: (i) operable blinds and roller shades, (ii) dynamic egg-crates, (iii) dynamic optical and thermal elements, and (iv) dynamic solar screens. For this study, the authors focused on a meta-analysis and critical review of previous studies related to dynamic solar screens, which are denoted as 'dynamic screens' in the following text. As shown in the Figures 1 and 2, dynamic screens are operable versions of static-fixed solar screens that are designed using parametric processes. The solar screen perforations behave as miniature equivalents of a combined application of horizontal overhang and vertical fin shading. Thus, both, dynamic and static screens can control high and low sun angles effectively (Kamath and Daketi, 2016).

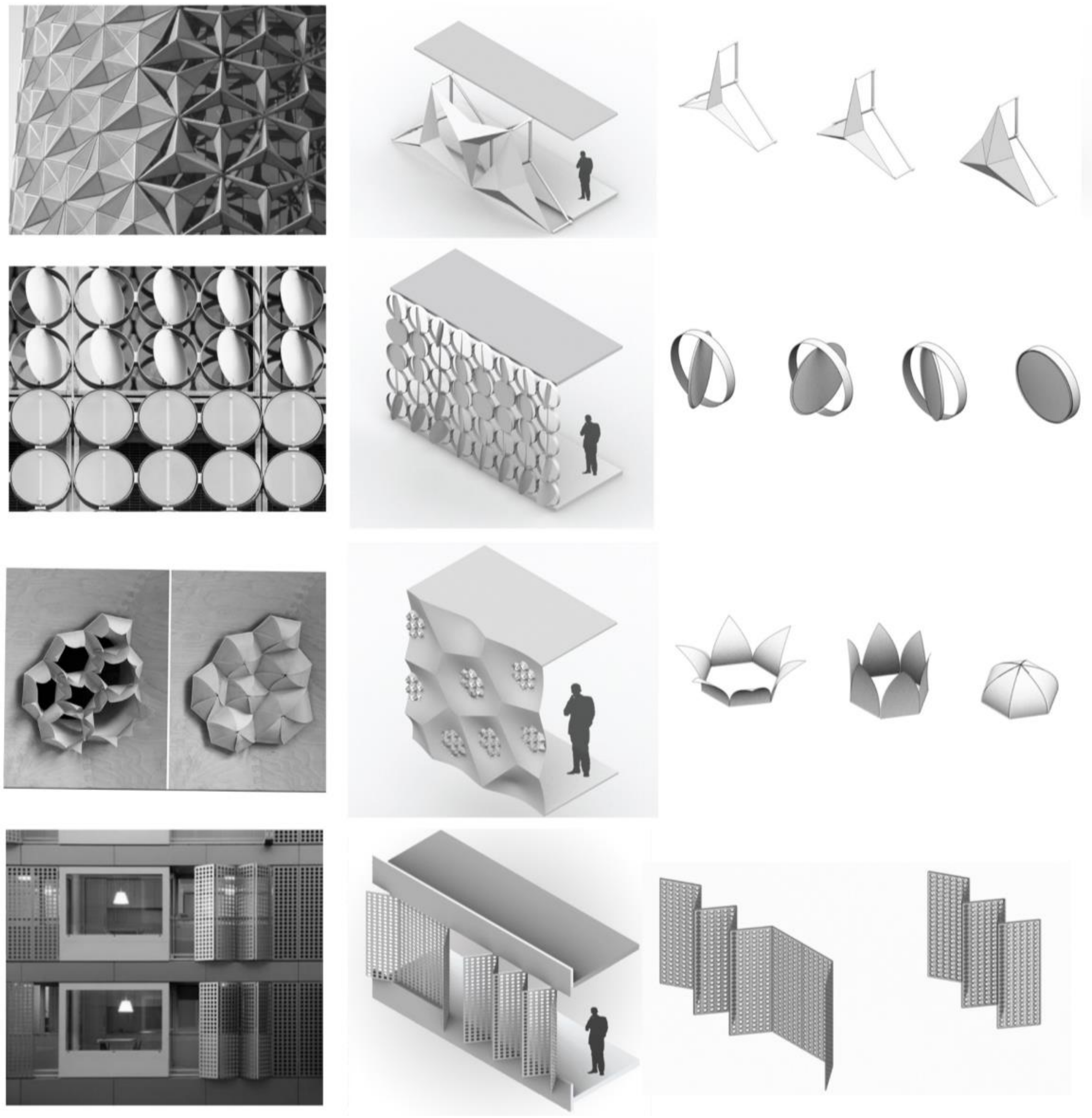


Figure 2.1 Dynamic screen applications: From top (1) Al Bahr Towers, UAE (leftmost image source: https://www.reddit.com/r/architecture/comments/5mflra/sunshades_on_the_al_bahr_towers_abu_dhabi/), (2) RMIT Design Hub, Australia (leftmost image source: https://www.photography-dj.com/apps/photos/photo?photoid=184403358), (3) Hygroskin Pavilion, Germany (leftmost image source: http://www.achimmenges.net/?p=5612), and (4) Ljubljana Student Housing, Slovenia

(leftmost image source: https://www.filt3rs.net/case/terrace-perforated-shutters-ljubljana-324).

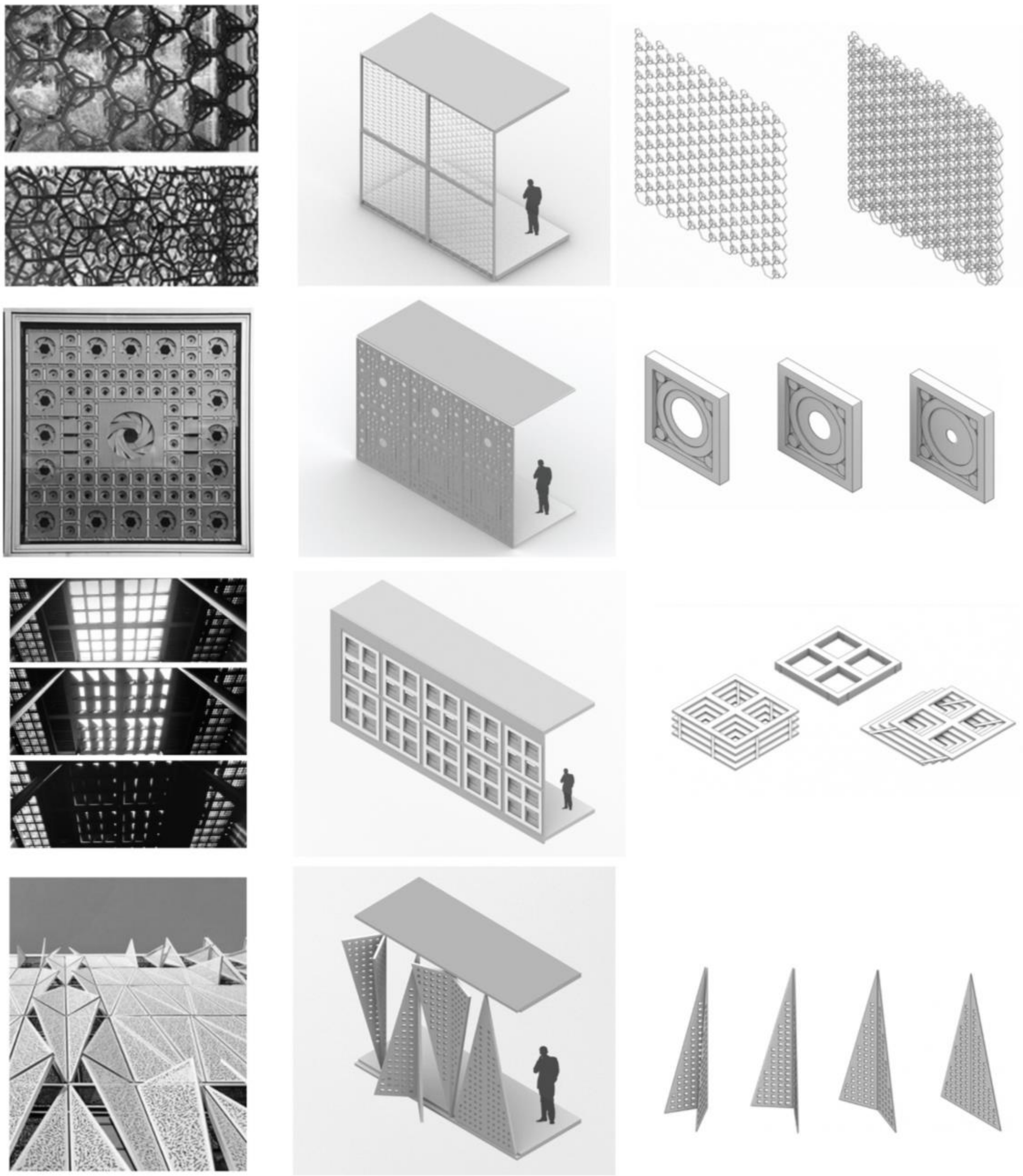


Figure 2.1 Dynamic screen applications: From top (5) Simon's Center for Geometry and Physics at Stony Brook University, USA (leftmost image source: https://tim-theincrediblemachine.tumblr.com/post/22973191687/tessellate-transforming-facade-simons-center-of) (6) Arab World Institute, France (leftmost image source: http://spacecollective.org/kbug/718/Architecture-The-Arab-World-Institute) (7) Alder Central Market, UAE (leftmost image source:http://design8-cheryl.blogspot.com/2011/09/climate-adaptive-building-shells.html) (8) Campus Kolding building at University of Southern Denmark, Denmark (leftmost image source: https://www.ribaj.com/products/campus-kolding-university-of-southern-denmark).

Recent studies related to dynamic façade shading systems concluded that while there is a continued interest in the use of dynamic screens, they have not received extensive market adoption (Attia et al., 2018). Dynamic screen applications to existing buildings contribute to the overall building's aesthetics and convey high-tech aspirations of their architects and owners (Attia et al., 2018; Elzeyadi, 2017). Despite their aesthetic appeal, studies documenting their performance are inconsistent with respect to the climate, building type, facade orientation, screen type under investigation, and research method of execution. This makes it challenging to conclude the building and environmental performance impacts of dynamic screens. Hence, the purpose of this investigation is to: (i) review research on dynamic screens conducted within the last two decades and summarize their impact on the building performance and indoor environmental quality, (ii) identify gaps in the existing studies in the methods employed to investigate their performance, and (iii) determine the vital yet unexplored impacts of dynamic screens for future studies.

2.1.1. Significance of dynamic screens and their vernacular precedents

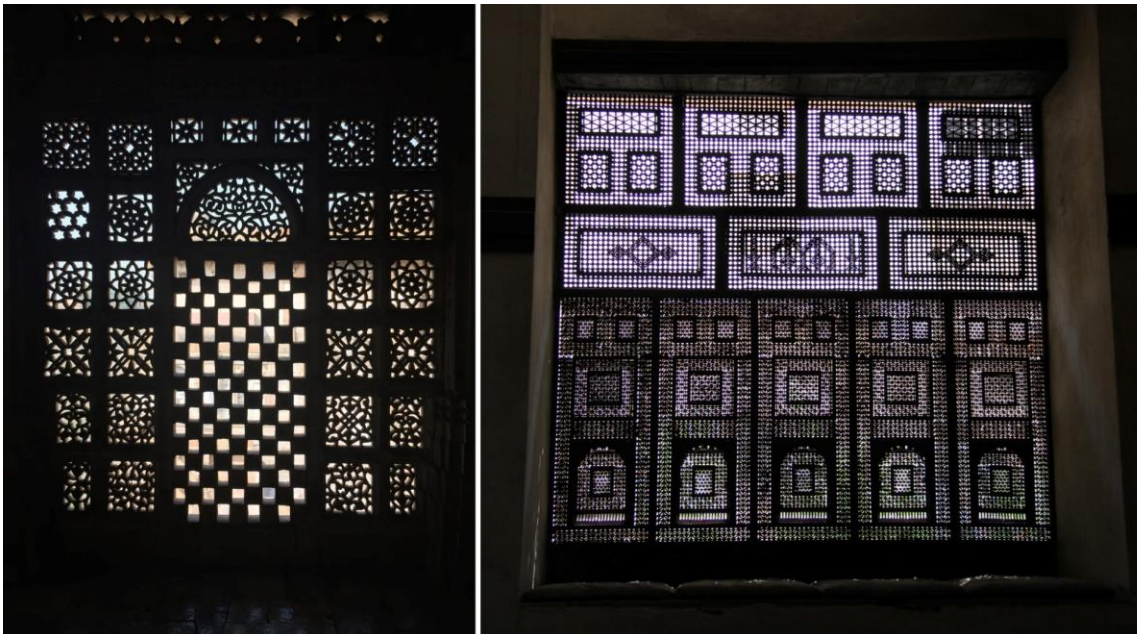


Figure 2.2 Vernacular solar screens: Jaalis carved in stone at Ahmedabad, India (Left, photograph by Niyati Naik) and Mashrabiyas in Cairo, Egypt constructed out of rounded wooden pieces (Right, photograph by Ihab Elzeyadi).

Table 1.1 Environmental, aesthetic, and cultural significance of traditional-static and dynamic screens. (Note that the description presented in the columns entitled vernacular screens and dynamic screens should not be viewed as a direct comparison between the two types)

	Vernacular Screens	Dynamic Screens
ASSOCIATED VARIABLES	*Geometric only*	*Geometric and Non-geometric*
	Perforation ratio (% of open) (PR), depth ratio (perforation depth/width) (DR), thickness, perforation shapes, non-uniformity, color, panel dimensions, perforation dimensions	Geometric variables same as those for traditional screens as well two additional variables 'movement' and 'control'
ENVIRONMENTAL SIGNIFICANCE	Light-weight static screens with PR of 70-90% and DR of 0.5-1 yield optimum daylighting performance and energy savings (Sherif et.al, 2012; Sabry et.al, 2014)	'Movement' with 'automated control' substantially reduces energy demand (University of Southern Denmark by Henning Larsen Architects (2015); Al Bahr Towers, Abu Dhabi by Aedas UK
	Massive static screens with parametric combinations of PR ranging from 30 to 50% and thickness ranging from 1 to 3" can lead to optimum thermal-visual comfort and energy savings (Gandhi et.al, 2014; Elzeyadi & Batool, 2017)	'Movement' with 'automated control' can lead to superior thermal comfort evaluations from occupants (Attia, 2017)
	Perforation shapes can affect daylighting performance, e.g., rhombus and square shaped perforations offered the best annual daylighting performance among the seven geometries, portrayed in Fig. 3, tested (Oghazian & Mahdavinejad, 2017; Chi et.al, 2017).	'Automated control' with the possibility of 'manual over-rides' is recommended for visual comfort and occupant satisfaction (Attia,2017; O'Brien etl.al, 2013)
	Non-uniformity of perforations (Fig. 3) in screens reduces glare (Oghazian & Mahdavinejad, 2017; Brotas and Rusovan, 2013)	Some amount of visual discomfort evaluated by glare metrics in dynamic screen shaded spaces is rated as "visual pleasure" by occupants (Mudri & Lenard, 2000)
AESTHETIC SIGNIFICANCE	Screen patterns demonstrate principles of 'complexity and order' that influence façade aesthetics (Nasar, 1994)	Dynamic screen precedents like Simon's Centre at Stony Brook foundation, Al Bahr Towers and Arab World Institute are inspired by the geometric patterns of traditional screens
	These screens are considered as "Biophilic" elements due to their earthen colors, material, texture, and geometric patterns being based on proportions of golden mean ratio which can reduce stress and enhance concentration (Ryan and Browning, 2014; Dabbour, 2012; Joye, 2007)	Their ability to change/move makes them aesthetically significant
CULTURAL SIGNIFICANCE	They allowed for a "controlled transparency" for women by providing one-way view and hence preserving their privacy (Kenzari and Elsheshtawy, 2003). Transparency/ view is attained when an observer stands closer to the screen and the observed is at a distance from the screen	Their application is not gender specific. Access to view and privacy are equally important. 'Degree of transparency' can be controlled by the observer.

Solar screens were widely used as passive and low energy shading systems of vernacular buildings in hot-arid, hot-dry, hot-humid, and moderate climates of Indian subcontinent, Middle East, and North Africa. The Mashrabeyas in Eqypt and Jaalis in

India are prototypical variations of these vernacular screens (Figure 2.3). These screens were used on the facades of residential and public buildings of the culturally rich geographic areas to control direct solar radiation and regulate visual communication (Elzeyadi and Batool, 2017). A brief analysis of the environmental, aesthetic, and cultural significance of vernacular and dynamic screens has been summarized in Table 2.1.

One major difference between the dynamic and the vernacular screens is that the former has a changeable geometry while the latter have static geometric parameters optimized for extreme weather conditions in the climate of their application. Architects have turned towards design patterns of vernacular solar screens for creating contemporary solar screened facades in their static or dynamic states. Compared to the static screens, dynamic screens can potentially offer better building and indoor environmental performance because their physical properties can be modified to respond to outdoor climatic conditions throughout the year to meet the building shading requirements and occupant demands.

2.2. Methods: A critical review of dynamic screens studies

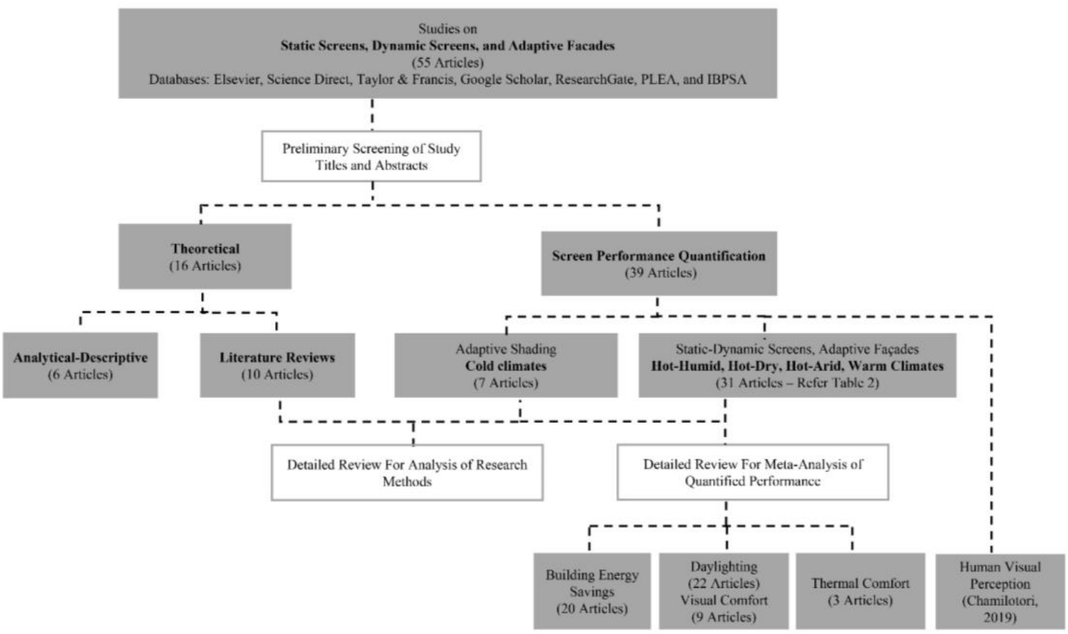


Figure 2.3 Literature selection process for the review.

Articles for the critical review were searched using primary keywords like: “Perforated screens”, “Solar Screens”, “Mashrabiyas”, “Jaalis”, “Dynamic screens”, “Dynamic shading”, “Adaptive facades”, and “Kinetic facades”. Aiming at the purpose of this study, phrases defining dynamic screen or the underlying building façade performance; like “Building Energy Savings”, “Indoor Environmental Quality”, “Visual Comfort”, “Thermal Comfort”, “View”, “Occupant Satisfaction”, “Occupant Pleasure”, and “Aesthetics” were added to the primary keywords during the detailed search. High-quality, peer-reviewed research and information papers from the databases of Elsevier, Science Direct, Taylor and Francis, Springer, Google Scholar, Research Gate, PLEA (Passive and Low Energy Architecture) and IBPSA (International Building Performance Simulation Association) were collected. Through the initial survey of abstracts of the collected articles it is observed that higher number of investigations were carried out on static screens compared to that of dynamic screens. Studies on other comparable dynamic shading like; operable horizontal blinds, operable vertical sails, and operable egg-crate systems, are also included to have a larger database of previous studies.

Fifty-five articles comprising studies on static and dynamic screens, and comparable adaptive facades are selected based on the initial review of the study titles and abstracts. The article screening and selection process are diagrammed in Figure 2.4. This collection of fifty-five papers includes, (i) investigative studies that employed quantitative methods to examine static or dynamic screen performance, and (ii) descriptive studies in which, static and dynamic screens, or adaptive shading applications were analysed using literature reviews or case studies through theoretical criticism approach. Critical analysis of important findings from the theoretical studies on solar screens (Alawad, 2017; Babaei et al., 2013; Crespi & Persiani, 2019; Kamath & Daketi, 2016; Kenzari & Elsheshtawy, 2003) is outside the scope of this work.

Table 2.2 Studies on dynamic and static screens and the performance variables that are considered for meta-analysis.

			Performance Variables Investigated				
	Studies By	**Proceedings Of**	**Energy Consumption**	**Daylighting Performance**	**Glare**	**Thermal Comfort**	**SHGC**
MASSIVE SCREENS	Blanco et al.	Energy and Buildings (2016)	*				
	Chi et al.	Building and Environment (2017)	*	*			
	Emami & Giles.	Nexus Network Journal (2016)		*	*		
	Alawadhi.	Building and Environment (2018)					*
	Alawadhi.	Journal of Solar Energy Engineering (2019)		*	*		*
	Batool & Elzeyadi.	PLEA (2014)	*	*			
	Lavin & Fiorito.	Procedia Engineering (2017)	*		*		
	Mousa et al.	Architectural Science Review (2017)	*			*	
	Gandhi et al.	Indian Architect & Builder (2014)		*			
	Elzeyadi & Batool.	IBPSA (2017)	*	*	*		*
LIGHTWEIGHT SCREENS	Brotas & Rusovan, 2013	PLEA (2013)	*	*	*		
	Hegazy et al.	IBPSA (2013)	*	*			
	Huang & Zhao.	Energies (2017)	*	*			
	Lai et al.	Solar Energy (2017)	*				*
	Sawyer et al.	Building Simulation (2011)	*	*			
	Sherif et al.	Energy and Buildings (2012)	*				
	Sabry et al.	Solar Energy (2014)	*	*			
	Oghazian & Mahdavinejad.	PLEA (2017)	*	*	*		
	Wagdy & Fathy.	PLEA (2016)	*	*			
	Fathy et.al.	PLEA (2017)	*	*			
DYNAMIC SCREENS	Elzeyadi.	Architectural Science Review (2017)	*	*	*		*
	Karamata et al.	PLEA (2014)		*			
	Attia.	Qscience Connect (2018)				*	*
	Mudri & Lenard.	PLEA (2000)			*		
	Hosseini et al.	Building and Environment (2019)		*	*		
	Elghazi et al.	IBPSA (2015)		*			
	Sabry et al.	Journal of American Science (2015)		*			
	Tabadkani et al.	Automation in Construction (2019)		*	*		
	Hammad, F. & Abu-Hijleh, B	Energy & Buildings (2010)	*				

		Performance Variables Investigated				
Studies By	Proceedings Of	Energy Consumption	Daylighting Performance	Glare	Thermal Comfort	SHGC
Yao, J.	Building and Environment (2014)	*	*		*	*
Grobman et al.	Architectural Science Review (2017)		*			
Total Studies						
31		19	23	10	3	6

2.2.1. Solar screen categorization and performance meta-analysis

The commonly investigated geometric properties of the screens constitute its parameters like perforation ratio (PR) that is the percentage of opening and depth ratio (DR) that is the ratio of perforation depth to its width. The basic non-geometric properties pertaining to dynamic screens are its movement and control. Based on the static and dynamic screens investigated in the previous studies, the authors categorized them into four types namely, (i) massive static, (ii) light-weight static, (iii) dense dynamic (Figure 2.2- 5,6,7), and (iv) 3-D geometric dynamic (Figure 2.1- 1,2,3). Massive static and dense dynamic screens essentially have higher number and smaller sized perforations in a unit area of thick shading panels. Whereas light-weight static and 3-D geometric dynamic screens have lower number and larger sized perforations in a unit shading area that is mounted on light-weight structures. To make them applicable to high-rise building facades, screen panel material thickness is not accounted for in light-weight static and 3-D geometric dynamic screens.

Massive static screens are heavy weight and typically crafted in stone, marble, terracotta, or brick and have 30-50% PR created in panels with 1-3” thicknesses while maintaining the perforation depth to width ratio (DR) as 1:1. Light-weight static screens have 70-90% PR and 1:1 *DR.* These geometric parameters of the massive and light-weight static screens were found to be optimal because they led to a balanced building energy and daylighting performance in tropical and warm climatic conditions (Sherif et.al, 2012; Elzeyadi & Batool, 2017, Chi et.al, 2017; Lai et.al, 2017). The dense dynamic screens have panels that can be operated by sliding and rotating mechanisms in two-dimensions to manage variability in PR, DR, and panel thickness (Figure 2.2 - 5, 6, 7). In this case the PR changes between 10% to 90%, DR between 0.5:1 and 1:1, and thicknesses between 1” and 3”. The 3-D geometric dynamic screens have light-weight foldable shutters that bring variability in *PR* and *DR* while in operation (Figure 2.1- 1, 2, 3). In this case, the PR changes between 10% and 90% and DR between 0.5:1 and 1:1.

The authors have listed thirty-one studies in Table 2.2, in which the screen categories and related performance variables investigated within each of them are highlighted. The screen performance variables researched in those studies constitute: energy consumption, daylighting, glare, thermal comfort, and solar heat gain. The meta-analysis of screen performance for this work is conducted with respect to the impact of the four categorized screen types on building energy, thermal, and visual comfort. Besides the geometric and non-geometric parameters of static and dynamic screens the other parameters controlled for in their performance meta-analysis are (i) building space type, (ii) climate type, (iii) window to wall ratio (WWR), and (iv) façade orientation. The screen performance meta-analysis for this study is for South and/or West facing solar screen applications on windows with WWR between 40 and 60%; for residential spaces and open-plan offices in tropical and warm climates (To be noted that South facing application is related to climates in northern latitudes and North facing application is related to climates in southern latitudes). Metrices to quantify each of their performance variables and indicators of their quality; as defined by standards; are listed in Table 2.3.

Table 2.3 Building performance variables and related metrics to evaluate the performance of dynamic screens.

Performance Variables			Performance Metrics	Indicators
BUILDING ENERGY	Building Heating-Cooling-Lighting Energy		EUI - kWhr/m^2/year	*Objective:* Building Internal Load Parameters *Objective + Observational: Building Energy Monitoring & Model Calibration*
INDOOR ENVIRONMENTAL QUALITY	Visual Comfort	Daylighting Distribution	spatial Daylight Autonomy (sDA) (IESNA, LM-83, 2012) Daylight Sufficiency = at least 55% space gets 300 lux for at least 50% of occupied hours	*Objective:* Work plane Illuminance
			Annual Solar Exposure (ASE) (IESNA, LM-83, 2012) Daylight Excessiveness > 1000 lux for at least 250 hours in 20% of the space	
			Uniform Daylight Illuminance (UDI) (Nabil & Mardeljevic, 2006) 100 - 2000 lux = Useful Daylight > 2000 lux = Exceeds Useful Range	
		Glare Occurrence	DGI Model (Daylight Glare Index) (Hopkinson, 1972) (Appendix, Eqn. 1) Imperceptible: < 16, Perceptible: 16-24 Disturbing: 24-28, Intolerable: < 24-28	*Objective:* Source Luminance (cd / m^2), Background Luminance (cd / m^2) *Subjective*: Occupant evaluations, Appraisals
			DGP Model (Discomfort Glare Probability) (Weinold & Christoffersen, 2006) (Appendix, Eqn.2) Imperceptible: < 0.35, Perceptible: 0.35 - 0.40 Disturbing: 0.40 - 0.45, Intolerable: > 0.45	*Objective:* Source Luminance (cd / m^2), Background Luminance (cd / m^2), Vertical Illuminance *Subjective*: Occupant evaluations, Appraisals
	Thermal Comfort		PMV Model (Predicted Mean Vote) (Fanger, 1970) (Appendix, Eqn.3) PPD Model (Predicted Percentage Dissatisfied) (Fanger, 1970) (Appendix, Eqn. 4) - 0.5 > PMV > 0.5, PPD < 20%	*Objective: Ambient Air Temperature, Mean Radiant Temperature, Relative Humidity, Air Speed, Occupant Clothing, Metabolic Rate, Mean Outdoor Temperature*
			Adaptive Comfort Model (McCartney & Nicol, 2002) (Appendix, Eqn. 5) PPD < 10 %	*Subjective: Occupant Thermal Satisfaction Likert Scale, Thermal Acceptability Votes, Thermal Preference Votes*

2.2.1.1.*Solar screens and building energy consumption*

Previous studies investigating energy performance of dynamic and static screens reported their impact on substantial savings in building cooling energy consumption (Elzeyadi, 2017). This meta-analysis is based on the data from studies corresponding to the column energy consumption in Table 2.2. It was found that compared to non-screened settings, screens could achieve up to 60% of building cooling energy savings. The meta-analysis of energy savings reported in previous studies for the four categories of static and dynamic screens is presented in Figure 2.5. The impact of solar screens on building energy savings is up to such an extent that the aggregate building heating, cooling, and lighting energy savings is always higher than that in the case of non-screened buildings. Massive static and dense dynamic screens with operable shutters promise superior thermal performance by potentially saving 35-43% and 27-48% of building energy use, respectively (Figure 2.5). Higher energy savings are achieved due to the screen panel thickness that effectively controls the conductive and radiative heat transfer to enhance the thermal performance of a massive static or dense dynamic screened façade (Naik & Elzeyadi, 2020).

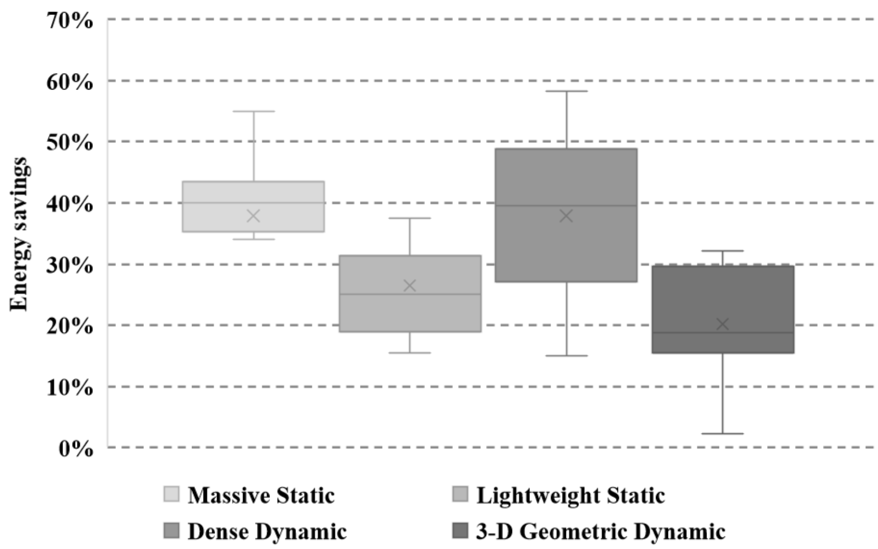


Figure 2.4 Energy Savings on application of dynamic and static screens compared to non-screened conditions.

2.2.1.2.Solar screens and visual comfort

Solar screens impact the horizontal and vertical illuminance in the indoor environment. Horizontal illuminance defines the amount of light falling on a horizontal work plane; the adequacy of which facilitates ease in an occupant's desk-based task performance. Vertical illuminance (Ev) falling on a vertical plane at an occupant's eye-level informs glare prediction models that determine an occupant's visual comfort in an indoor environment (Weinold & Christofferson, 2006). Meta-analysis of data from previous studies within which, the researchers reported daylighting performance of screens have been presented in Figure 2.6. This meta-analysis is based on the data from the studies corresponding to the column daylighting performance in Table 2.2. These results reveal that due to the application of dynamic and static screens, the area of spaces with useful daylighting (between 200-2000 lux) increases and the area with excessive daylighting (> 2000 lux) decreases compared to non-screened conditions. Because of the ability of the dense and 3-D geometric dynamic screens to switch between wide range of geometric parameters, they create larger variability in the daylighting conditions of a space.

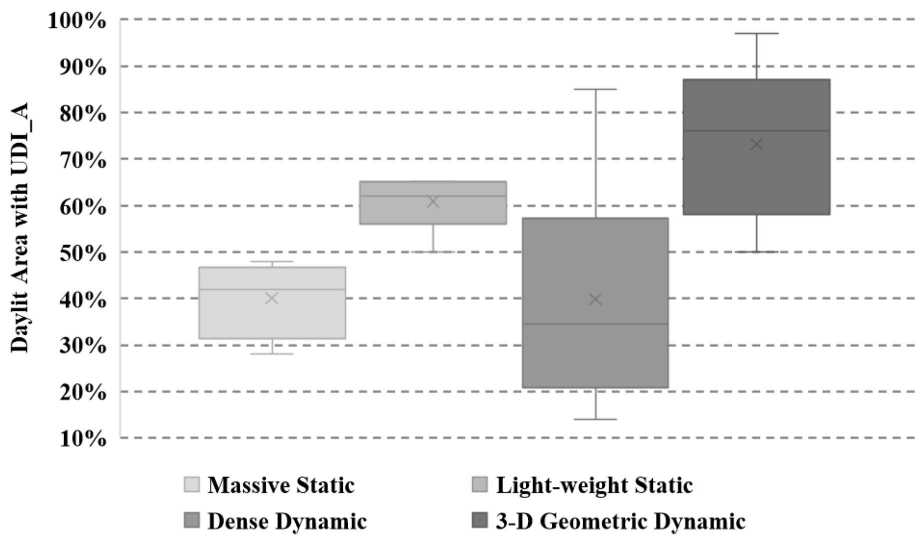


Figure 2.5 Area with useful daylight due to application of dynamic and static screens.

Excessive daylighting in office spaces is critical as it causes glare, which interrupts an occupant's task performance. The meta-analysis of findings from previous studies corresponding to the column *glare* in Table 2.2; within which the researchers investigated the impacts of dynamic and static screens on glare probability is presented in Figure 2.7. Glare was evaluated using the daylight glare probability (DGP) metric (Weinold & Christofferson, 2006). Note that the DGP value of 0.35 indicates that 35 percent of occupants would notice some glare in a scene, yet it will not be intolerable. On this basis, the DGP metric categorizes and sets glare thresholds of less than 0.35 as imperceptible to more than 0.45 as disturbing glare. Because of the higher density of perforations in thick panels; massive static and deep dynamic screens can manage glare effectively. Through this meta-analysis, the authors predict that application of light-weight static or 3-D geometric screens would not make any difference in reduction of visual discomfort in a non-screened space.

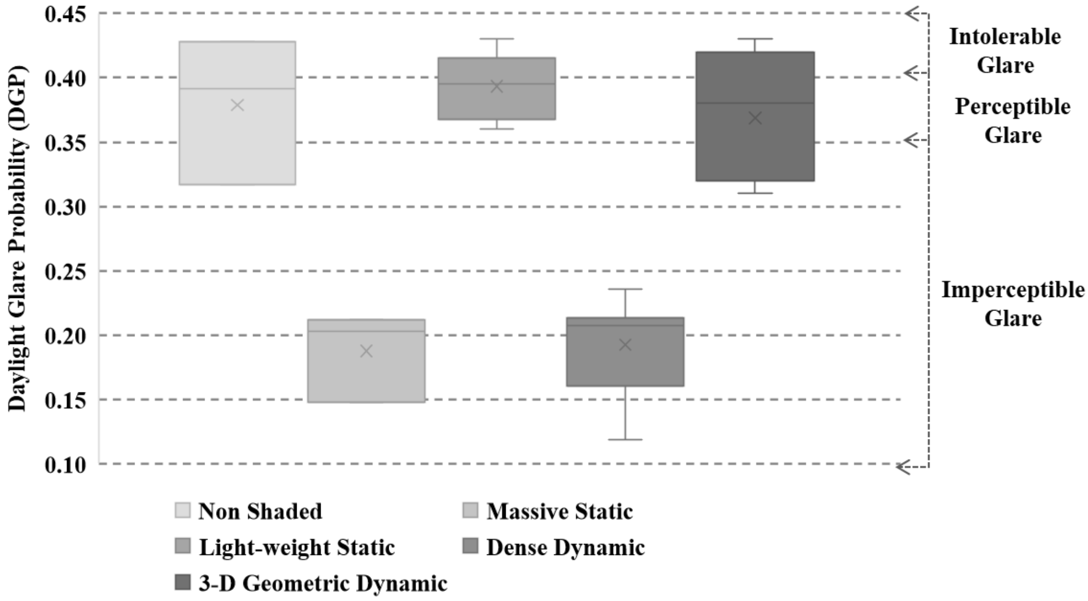


Figure 2.6 Instances of glare on application of dynamic and static screens.

2.2.1.3.Solar screens and thermal comfort

"Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." (ASHRAE Standard-55, 2017). Thermal comfort can be predicted using standardized metrics, which are listed in Table 2.3. Solar screens impact the indoor environment of building perimeter zones, within which locally discomforting environments prevail, as per the thermal comfort standards. These discomforting thermal conditions are characterized by radiant temperature asymmetries, floor temperature extremes, air drafts, etc. (Zelenay et al., 2011). In such environmental conditions, localized cooling/heating of individual body parts can lead to removal of some amount of thermal stress due to which occupants may perceive satisfaction (Arens et al., 2006b; Brager et al., 2015; Parkinson and De Dear, 2015). Moreover, temperature swings in the direction opposite to that of discomforting temperatures also offer occupant satisfaction. The geometric properties of solar screens like PR and thicknesses, and material properties are the main parameters that can impact thermal conditions within building perimeter spaces (Gandhi et al, 2015; Elzeyadi and Batool, 2017).

Mousa et al. (2017) compared the thermal performance of screened versus non-screened conditions and found that screens with 50% PR and 1” thickness resulted in 3.4 °F (1.8 °C) to 5.4° F (3 °C) drop in the indoor operative temperatures from outdoor temperatures in summer of extreme hot-dry climates. Further, it was found that while the massive static screens maintained thermal comfort during summer, they caused thermal discomfort due to overshading in moderate winters. While the findings from the previous studies; corresponding to the column *SHGC* in Table 2.2; show that solar screens substantially reduce the solar gain in building indoors, as observed in Figure 2.8. The impacts of both static and dynamic screens on occupant’s thermal comfort in building perimeter spaces is under-researched. In very few of the previous studies, did the researchers attempt to investigate subjective thermal perception under the impact of façade shading (Kunwar et al., 2018).

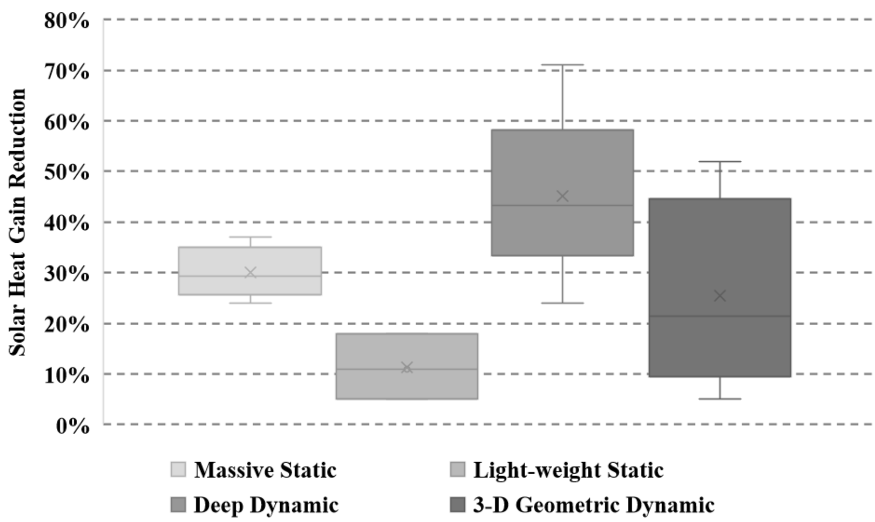


Figure 2.7 Reduction in indoor solar heat gain due to application of dynamic and static screens.

The meta-analysis revealed that the massive static and dense dynamic screens can potentially offer better cooling energy savings and solar gain control than the light-weight static and 3-D geometric screens, which otherwise create better daylighting conditions. However, the glare probability increases in creating better daylighting conditions using light-weight static and 3-D geometric screens. The meta-analysis indicates that the deep dynamic screens with operable shutters could potentially be the best façade shading devices if they are carefully designed to balance thermal performance with that of daylighting and glare management.

2.2.2. Review of research methods to evaluate performance of dynamic screens

The methods adopted in the thirty-nine studies to evaluate the building and environmental performance of dynamic screens and similar type of adaptive shading mainly include computational simulations, experiments, and field studies.

2.2.2.1.Design simulations in computational environments

Computational simulations are experimental methods employed in virtual environments that replicate real-world phenomena, where a building's outdoor and indoor environmental parameters can be controlled to carry out a focused investigation of the screen's performance parameters. These methods were employed in majority of studies on dynamic and static screens. Previous studies on solar screens used computational simulations to; (i) investigate the problem of optimizing one or more of the parameters like; PR, DR, perforation shapes, spread, and non-uniformity to achieve the most suitable static screen design with respect to energy and/or environmental performance standards (Chi et al., 2017; Lavin and Fiorito, 2017; Sabry et al., 2014), and/or (ii) compare performance of screens with respect to other shading types or between screens with different material and color (Hegazy et al., 2013; Oghazian et.al, 2017; Blanco et.al, 2017), and/or (iii) develop algorithms or tools that could predict the performance of dynamic screen's shade positions to achieve optimized daylighting performance for specific time of the day and year (Grobman et al., 2017; Karamata et al., 2014; Elghazi Y. et al., 2015; Tabadkani et al., 2019).

Some studies used data from field settings to calibrate their computational models. Combining two research methods in this manner improved the accuracy of simulation results. In some cases, the computational results were also validated by comparing them with findings from the actual settings. Mousa, et al. (2015) validated their simulation model of an existing solar screened courtyard house in Cairo, Egypt against the measured data consisting of indoor temperatures, air change rates and window opening schedule; recorded for a period of three weeks; from actual conditions.

The absolute deviance errors between the simulated and measured data on indoor temperatures were found to be within ±0.5° C. Few other studies also used the approach of calibrating computational building models with actual building conditions to test the effectiveness of screen applications and find suitable screen geometric parameters for optimized building and indoor environmental performance (Batool and Elzeyadi, 2014; Lavin and Fiorito, 2017).

2.2.2.2.Experiments using full-scale prototypes.

Experimental methods involving setting up of full-scale testbeds to investigate the performance of dynamic and static screen prototypes is another approach to test performance parameters of screen typologies. In previous investigations on adaptive façade shading systems, studies pointed out that long durations and complexity associated with sensor network and instrumentation for dynamic façade operation control are the major limitations associated with prototype performance experiments (Karlsen et al., 2016; Katsifaraki et al., 2017). To reduce the experimental duration for assessing the energy consumption of buildings with external shading blinds in Denmark, Karlsen et al. (2016) limited the data collection to extreme summer and winter days and used these data to calibrate a simulation model. Subsequently, the calibrated simulation model was used to predict the building energy performance for three cities in Denmark.

2.2.2.3.Field Studies

In field studies, researchers use qualitative and quantitative methods to observe the impact of dynamic screens in actual settings (Attia, 2017). These methods are ideal to investigate the impact of dynamic screens on occupants. Occupant behaviour data collected from field studies has a strong potential to inform mathematical models that predict human-façade interaction (Luna-Navarro et al., 2020). In their case study on dynamic screens of Al Bahr Towers in UAE, Attia and his team (2017) carried out occupant surveys on thermal and visual comfort in the building. They found that most of the occupants, who were approached, were discomforted by the automated opening-closing of the dynamic-screen and their inability to interact with it. Moreover, they asserted that this inability to interact with the external dynamic screens led to their indifferent attitude towards use of the existing operable internal blinds. While these findings are important, they were based on responses from a very low sample size of 22 occupants out of 1000 people who occupied the buildings. This was the case because the researchers met with difficulty in seeking permissions for conducting occupant behaviour surveys in the buildings.

Although field studies are promising methods, there are challenges associated with respect to large sample sizes of occupants involved, researcher's intervention, and building accessibility issues that may affect the study results (Konis, 2011). Large sample sizes of occupants require equivalent number of data recording and monitoring equipment. Besides, while obtaining quantitative and qualitative measurement simultaneously during field studies, inevitable situations like equipment malfunction may arise requiring a researcher's intervention, which may influence occupant behaviour. While it is possible to devise ways to overcome the challenges associated with field studies; they are resource and time intensive research methods.

2.3. Observational field study

Most of the previous studies dealing with solar screens have focused on understanding impacts of screen's geometric parameters on building energy savings and visual comfort whereas their impact on thermal comfort is under-researched. The importance of field studies in in analysing the thermal and visual comfort performance of solar screens was demonstrated by Elzeyadi & Batool (2017). Their results show that the field setting provided more intricate patterns of shade and light distribution that were not adequately conveyed in the simulation environment (Elzeyadi & Batool A., 2017). Realizing this, the thermal comfort performance of massive static screens was investigated through a field study of a naturally ventilated vernacular building with solar screen shading in Ahmedabad, India.

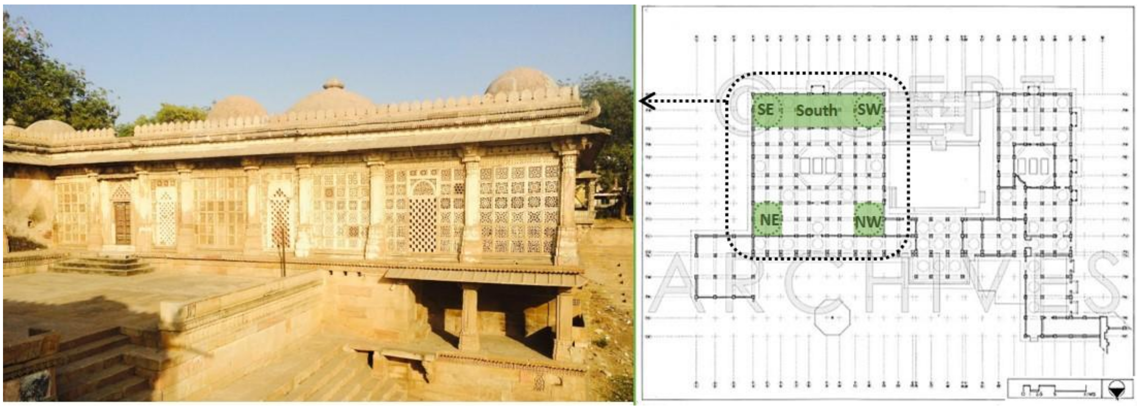


Figure 2.8 West façade of the tomb chamber (left). Building plan with investigated locations highlighted (right) (Architectural documentation; courtesy CEPT University archives, India).

The building under observation is a 500-year-old tomb chamber located in the Sarkhej mosque complex in Ahmedabad, India (Figure 2.9). Tomb chambers in Indian buildings are well daylit, naturally ventilated spaces that are accessible to public. The 40’ (12 m) x 40’ (12 m) x 15’ (4.5 m) (length x width x height) building was selected for the study because it is one of the best surviving examples of solar screen shaded buildings in India. It is entirely shaded by solar screens on its north, south, and west facades. The screen geometric parameters of this building were optimized for thermal comfort performance during extreme hot outdoor conditions. There were a few locations on the south façade of the building where the screens were damaged and replaced by metal grilles. Both, the solar screens with 30 to 50% PR and metal grilles with PR > 90% are shown in Figure 2.10.

2.3.1. Study execution and data collection

As noted earlier, the massive static screen designs are optimized for indoor thermal comfort during worst case conditions (i.e., extreme summers). Their performance during winter conditions (moderate winters in the case of Ahmedabad) is unknown. It is important to determine how these screens, that are optimized for summers, perform during winters. The field study was executed for the duration of two days in late January of 2019. Moderate climatic conditions prevail in Ahmedabad during this time of the year. The exploration consisted of indoor thermal environmental data logging and visitor behaviour observation. Indoor dry bulb temperature (DBT) and relative humidity (RH) were recorded at 15-minute intervals using portable pre-programmed data loggers (HOBO U-12, accuracy: ±0.35°C (±0.63°F) for temperatures ranging from 0° to 50°C (32° to 122°F), resolution: 0.03°C (0.05°F) at 25°C (77°F)). The data loggers were kept at five feet (1.5 m) distance from the screen envelope at south-east (SE), south-west (SW), north-west (NW) and north-east (NE) corners of the building. These data loggers were placed at three levels, that is, at 6” (15 cm), 36” (91 cm), and 72” (1.8 m) from the floor of the naturally ventilated building. Outdoor DBT and RH were also logged at 15-minute intervals. Besides DBT and RH, surface temperatures of the SE, SW, NW, NE corners, south and west facades were recorded during morning (9:00 to 10:30 AM), afternoon (12:00 to 3:00 PM) and evening (5:00 to 6:00 PM) on both the days by using an infra-red thermometer (Raytek RAYMT4U, accuracy: ±2°C (±3.5°F) for temperatures ranging from -1 to 275°C (30 to 525°F), resolution: 0.2°C (0.5ºF)). Furthermore, behavioural observations of visitors, specifically those who spent two-three hours in the space, were recorded using photographs and infrared (IR) images. The infrared images were captured using IR portable camera attachment to a mobile phone (FLIR One Pro camera, accuracy: ±5%, resolution: 0.1°C/0.1°F).

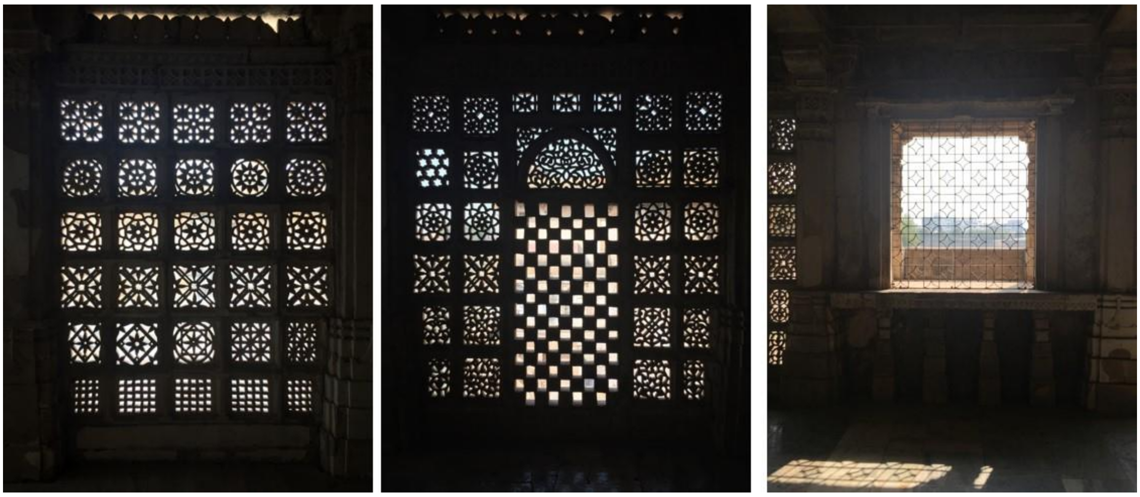


Figure 2.9 Solar screens with 30% PR (left image) and with 50% PR (centre image, middle panel). Metal grilles with PR> 90% were installed at locations where the original screen panels were removed due to damage.

2.3.1.1.Data Analysis

Indoor thermal comfort analysis was conducted (Figure 2.11) based on the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) thermal comfort metrics (ASHRAE Standard-55) which are computed using the measured values of DBT and RH and presumed values of the mean radiant temperature (MRT), airspeed, occupant clothing and metabolic rates. The DBT values were used as MRT values. Based on the researcher's experience in the building space, airspeed of 0.2 m/s (39.3 fpm) was assumed at the three feet height (0.9 m) from the floor, and that of 0.3 m/s (59.05 fpm) was assumed at the six feet height (1.8 m). As per researcher's observations on visitors' clothing and activities, "clo" values of 0.75 and metabolic rate of 1 met were assumed. The R package, "comf" with in-built functions for thermal comfort indices was used to compute the PMV-PPD values at SE, SW, NW, and NW corners of the building (Schweiker M., 2016). The infrared images were run through FLIR's computer-based program "Examin IR" to determine the spread of the pixel data that corresponded surface temperature values. The spread of the surface temperatures in the infrared images was analyzed with reference to the predicted satisfactory floor temperature for local comfort (Figure 2.12).

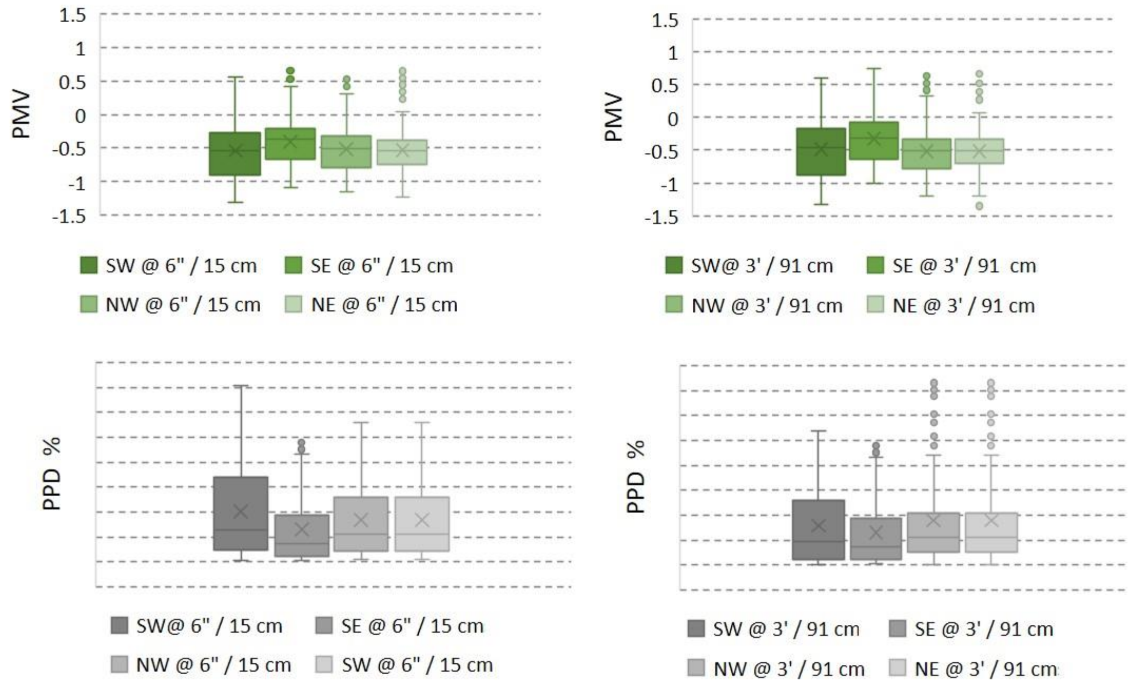


Figure 2.10 Analysis of predicted thermal comfort in SE, SW, NW, and NE corners.

2.3.2. Observation of the thermal environment and human behaviour

The data plotted in Figure 2.11 reveal that the PMV values for the SE, SW, NW, and NE corners were between neutral (0) to slightly cool (-1); with their median being around (-0.5). Based on ASHRAE's thermal comfort Standard-55, the computed PMV values predict the space to be thermally comfortable, however, towards the cooler side. Furthermore, the PPD values were found to be less than 20% for all the corners which addresses the standard's requirement of minimum 80% of people to be satisfied with the thermal environment.

Observation of visitor activities in the space provided a better understanding of their preferred thermally comfortable zones. People began visiting the building from early morning till the end of the day. However, during noon to evening hours the visitors were seen spending more than two-three hours in the locations close to the south façade, towards its central part (Figure 2.12). The closest locations to these central parts (with visitor concentration) from where the data was logged were a minimum 10' away on either side (i.e., the SE and SW corners). Higher variability was found in the PMV values for the southern part of the façade (i.e., the SE and SW corners) than the NE and NW parts (Figure 2.11), which seems to indicate visitors' preference of thermally non-uniform environment for their comfort.

The recorded outdoor diurnal temperatures ranged between 69 °F (20.5 °C) and 82 °F (27.7 °C) suggesting moderate outdoor climatic condition. Visitors beginning to spend more time in the space corelated with the rise in outdoor temperatures starting at 77 °F (25 °C) and reaching up to 82 °F (27.7 °C) which is during afternoon to evening hours. The solar screens were most effective during these six hours as they brought the indoor air temperatures 3 to 6 °F (1.6 to 3.3 °C) lower than outdoors. While the predicted PMV-PPD values and visitors being in the space for longer hours suggested thermal comfort, their choice on occupied spots in the building for lying down or sitting on the floor exhibited their preference of spaces with slight local discomfort. The areas where the visitors chose to spend time were the ones that received direct solar radiation from parts of the south façade where the metal grilles were installed. The maximum floor temperatures in these areas were between 82 °F (27.7 °C) to 92 °F (33.3 °C) (Figure 2.12). As per ASHRAE Standard-55, the acceptable range of floor surface temperatures for local comfort is 19 °C (66.2 °F) to 27.5 °C (81.5 °F) which corresponds to people's dissatisfaction (PD) < 10%. The floor temperatures in the areas with higher visitor concentration was beyond the acceptable range inferring the local discomfort. Despite the local discomfort, visitors were observed sitting on the floor or lying down and exposing their appendages to the patches with the sun for 2-3 hours

(Figure 2.12).

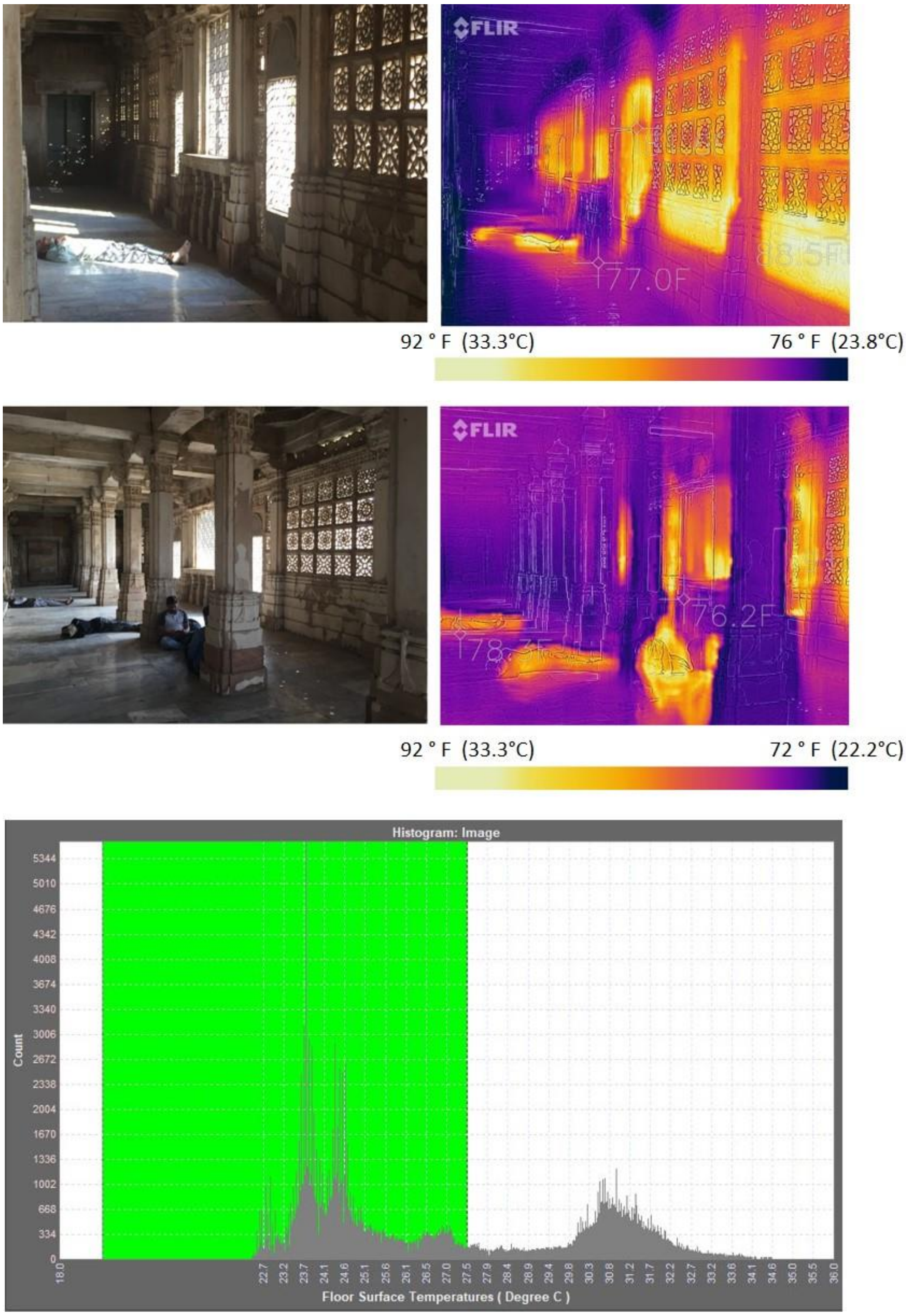


Figure 2.11 Visitor activities near the southern façade. Histogram indicates the floor temperature distribution near the southern façade. Histogram plots showing surface temperature (°C) on X-axis and image pixel counts on Y-axis. The area in green shows floor temperature range (19 °C (66.2 °F) to 27.5 °C (81.5 °F)) that predicts people's dissatisfaction (PD)< 10% (ASHRAE- Standard 55).

2.3.3. Preference for indoor thermal non-uniformity

Based on the analysis of the measured data, the space shaded by the massive static screens was found to be thermally comfortable. However, the visitors' activities were found to be concentrated in areas of local discomfort and larger PMV variability indicting their preference for local thermal nonuniformity. These results seem to advocate a need to revisit the massive static screen geometric designs that are optimized to maintain thermally uniform/neutral conditions in the building perimeter areas. It is suggested that design of solar screens should also consider offering local thermal nonuniformities in the space to enhance occupants' thermal experience. One recommendation is to design movable and dynamic screens with geometric parameters that can transition between values less than and more than their optimized values. Another recommendation, if one is designing a building envelope entirely with optimized solar screen geometry, is to create zones with slight local discomfort.

Lisa Heschong (1979) in her seminal book "Thermal Delight in Architecture" emphasized on the importance of thermal delight in architectural spaces. This idea was further advocated by Brager et.al (2015) and Parkinson & de Dear (2015) who suggested that designing for thermal pleasure/alliesthesia in a building is essential. Perimeter spaces within 10' (3.04 m) to 15' (4.57 m) of a building envelope offer an opportunity to achieve thermal variability through appropriate designs of solar screens. The design of screens can be further explored to create a sensation of thermal pleasure/alliestheia in occupants.

2.4. Discussion: Application gaps in existing studies on dynamic screens and proposal for future work

Not only do the dynamic screens impact building energy savings and indoor physical environment but also aesthetics; filling up the interior spaces with sunlight patterns; and degree of privacy inside a space. It is the occupant, who is primarily exposed to the indoor objective and subjective effects of dynamic screens (Figure 2.13). However, the influence of dynamic screens on occupant's comfort and perception remains under-studied. The knowledge gap about the impact of dynamic screens on occupants' thermal and visual comfort continues due to increasing reliance, on computational research methods solely. Studies in human interaction with smart building technologies is gaining momentum (Luna-Navarro, et al., 2020). Artificial Intelligence based logic and data generated from occupant interaction with automated dynamic screens can promise a system that can be controlled to the occupant's preferred indoor environmental quality.

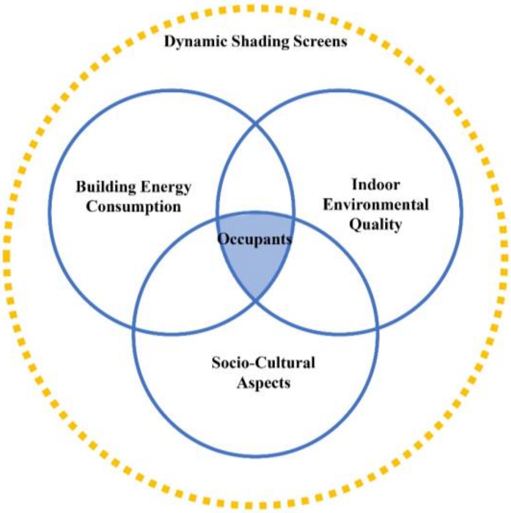


Figure 2.12 Conceptual diagram summarizing the ability of dynamic screens to impact occupants and influence their interaction with the facade to optimize building energy consumption.

Diverging from the trend of using only computational methods, Chamilotori (2019) investigated human perception of indoor environments created by patterned-solar screened facades employing virtual reality (VR) based experimental method. It was found that scenes of indoor environments shaded by patterned solar screened facades were rated to be significantly higher than those having facades with horizontally striped blinds. The higher rating was with respect to how interesting, pleasurable, and exciting was the scene with facade perceived. Further, it was found that the combined impact of patterned solar screened façade and sunlight patterns affected the participants' heart rate responses, which decelerated when they got immersed in the scene. Analysis of these physiological responses suggested that immersive scenes with pattered solar screened façades restored participants' attention. This study focused on investigating façade design for human visual perception and wellness and thus the indoor thermal parameters were maintained as constants in the experiments involved. Moreover, the immersive views of patterned facades in VR headsets, comprised of static screens with optimized geometric parameters.

The common aspect about all dynamic screen shading types is their ability to accommodate change. With this ability, change in indoor aesthetics and exposure to outdoor view can be controlled. Moreover, it should be noted that this change influences the visual and the thermal environment. Thus, accounting for both, the physical and non-physical parameters of the indoor environment can offer deeper insights while assessing the impacts of dynamic screens on human-occupant perception.

2.4.1. Assessment of the impact of dynamic screen designs on occupants

Due to their efficiency with respect to the time and resources involved, computational simulations are the most preferred methods in the study of dynamic screens. Field studies, however, are the best approaches to measure their impacts on occupants' comfort and perception. But, as the buildings with dynamic screens applications are scarce and scattered in different climates, and have accessibility challenges, it is difficult to employ field studies in their analysis or compare their performance effectively (Attia, 2017). Thus, in case of feasibility issues related to field studies a combination of two methods; mixed method approach; like computational simulations and human factors based experimental research in full-scale prototypical set-ups could prove to be the most suitable to inform occupant centric dynamic screen designs.

2.4.2. Future studies on dynamic screen designs for occupant well-being

Occupant well-being is defined by over-all health and comfort in the built environment (Bluyssen et al., 2011; Veitch et al., 2008; Ortiz et.al, 2017). Occupant comfort is considered synonymous to a preferred, stress-free, and relieving uniform indoor environment. However, comfortable living and working environments are not necessarily responsible for occupant satisfaction and good health (Brager et al., 2015; van Marken Lichtenbelt et al., 2017; Brager, 2019). Similar concern was raised by Reinhart (2015) related to daylighting and visual comfort metrics and their stringent requirements to prevent penetration of direct sunlight to avoid discomfort. It was asserted that though solar penetration could be the source of glare, occupants generally welcome it and preventing it would promote "dull spaces" (Reinhart, 2015; Boubekri et al., 1991). Studies within the field of indoor environmental quality have hypothesized that ambient environmental transitions or variability from discomfort (stress) to comfort (no stress) are associated with the attainment of occupant well-being (Elzeyadi, 2002; Bluyssen et al., 2011; Ortiz et al., 2017).

Within thermal comfort research, studies have provided evidence that transient environments shifting between discomfort and comfort induce a sensation of thermal pleasure (Brager et al., 2015; de Dear, 2013). Moving beyond merely designing for thermal comfort, provision for thermal pleasure and biophilia is a step forward towards design for occupant well-being (Brager, 2019). Thermal discomfort disturbs a human body's heat exchange balancing, termed as *homeostasis*. Bringing back the body in thermally comforting condition restores *homeostasis*. Thermal environments that keep varying between comforting and slightly discomforting conditions potentially impact occupant resilience and adaptability to their surrounding; thus, positively influencing long term health (van Marken Lichenbelt et al., 2017; Kingma et al., 2017).

The ability of the dynamic screens to accommodate change can be utilized to create variability in the indoor physical and non-physical environment. The authors hypothesize that this variability can be carefully designed to create controlled transitions between comfort and discomfort to influence occupant pleasure and well-being.

2.4.3. Occupant well-being indicators

The occupant related physiological, psychological, and behavioral parameters; listed in Table 2.4; were measured and quantified in previous work in human factors research to investigate occupant well-being. They have been briefly discussed here in relation to the proposed hypothesis. Thermal variation in the indoor environment drives the thermoregulatory and thermal sensation responses that facilitate heat transfer between the occupant's body and its surrounding environment (Arens and Zhang, 2006b; Kingma et.al, 2017). Thermoregulation and subjective thermal sensation responses determine occupant adaptability to remain comfortable in a wide range of indoor thermal conditions. Thermoregulation is usually investigated using body core and distal skin temperatures.

Variation in daylighting levels influences human eye's melatonin levels that regulate an occupant's sleep-wake cycles. Daylight suppresses melatonin levels and darkness elevates them (WELL Building Standard, 2016). Increase or decrease in the melatonin suppression can impact an occupant's alertness. The variation in the daylighting and thermal conditions may expose an occupant to moments of stress, which is experienced through the sensations from eyes and skin (Bluyssen et. al, 2011). These sensations are perceived individually but their interpretation occurs together. When stress is short termed, occupant will voluntarily; through behaviour; or involuntarily; through physiological or parasympathetic activation; attempt to get destressed. Occupant heart rate variability (HRV), which indicates the sympathetic to parasympathetic ratio is used as an indicator to stress occurrence in many previous studies (Zhang et al., 2017; De Kort et al., 2006; Liu et al., 2008). The sympathetic dominance suggests stress. A recent study by Harvard medical school suggests that the ability of a person to switch faster from high to low HRV determines his/her healthy state (Campos, 2017). Stress also leads to emotional sweating which occurs due to adrenalin secretion and its circulation in blood stimulating sweat glands on palms and soles (Arens and Zhang, 2006). This kind of sweating is short-termed. It changes the skin's electrical resistance or galvanic skin response, which is also been used as an indicator to determine stress (De Kort et al., 2006).

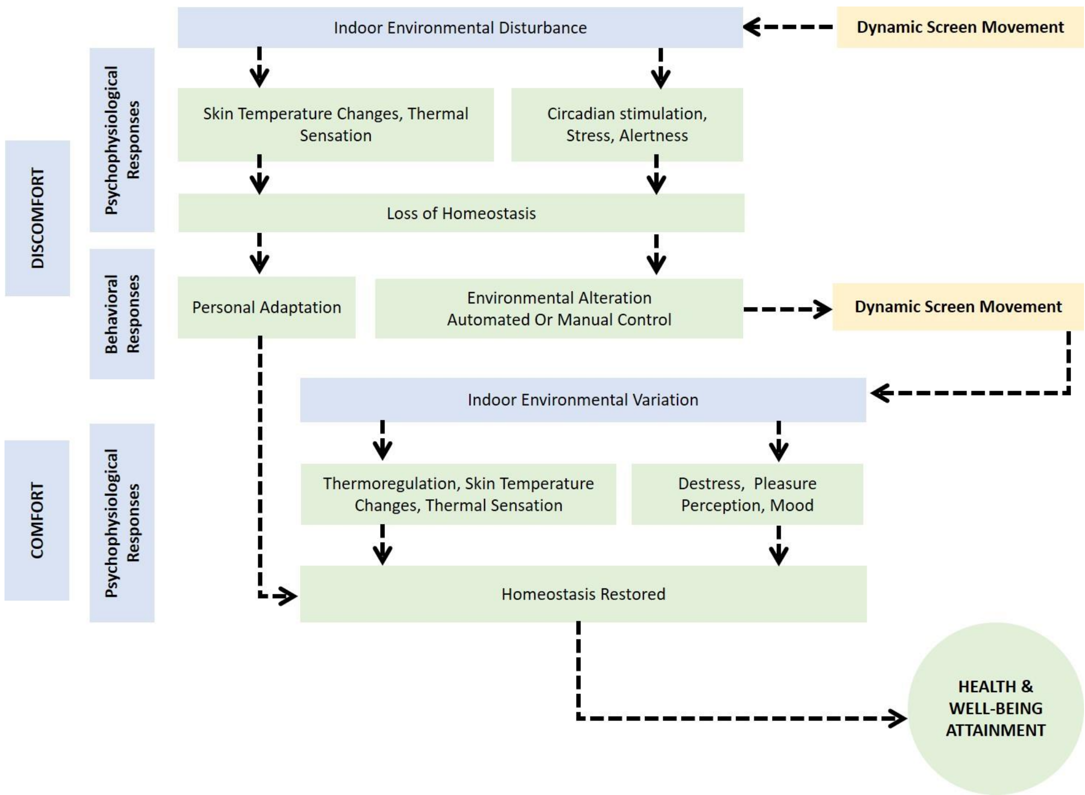


Figure 2.13 Dynamic screens and their potential impact on occupant well-being. A hypothesis based on the proposition by (Ortiz et al., 2017)

Table 2.4 Variables and indicators that determine occupant well-being.

	Variables	Indicators
PHYSIOLOGICAL	Thermoregulation & Thermal Sensation	*Objective*: Mean skin temperature, local skin temperature, core body temperature, *Subjective*: Thermal Sensation Likert Scale, Thermal Preference Likert Scale, Thermal Pleasure Likert Scale
	Circadian Physiology	*Objective*: Circadian Stimulus (CS) *Subjective*: Alertness - Karolinska Sleepiness Scale (Akerstedt & Gillberg, 1990), Activation-Deactivation questionnaire, Cognitive Tasks: Letter Digit Substitution Test (LDST) (Smolders et.al, 2012)
PSYCHOLOGICAL	Stress	*Objective*: Heart Rate Variability (HRV), Galvanic skin responses Subjective: Affect questionnaire
	Mood and Pleasure	*Subjective*: Affect questionnaire for pleasure, Lighting and Workplace appraisal (Veitch, et.al, 2008; Smolders et.al, 2012)
BEHAVIORAL	Indoor Environmental Alteration	*Observational*: Shade control open/close, Switching Lights on/off, Using thermostat
	Personal Adaptation	*Observational*: Wearing/removing clothing, drinking hot/cold beverage, Increased blinking, straining eyes, changing seating position, increasing/decreasing movement

Thus, when investigating the impact of dynamic screens on occupant well-being, the physiological, psychological, and behavioural parameters can be recorded and examined. The hypothesis, that is the operability of dynamic screens if designed to manage indoor environmental change that takes a person from feeling uncomfortable-stressed to comfortable-destressed influences human pleasure perception and impacts occupant well-being (Figure 2.10), can be investigated using experimental methods that involve human participants.

2.5. Summary and application

Massive static and deep dynamic screens can potentially increase 10-15% energy savings on building cooling and reduce solar heat gain by 20-25% compared to the light-weight static and 3-D geometric screens. Thus, massive static and dense dynamic screens are the suitable shading typologies for indoor thermal environmental control. For a balanced, thermal, daylighting, and visual comfort performance, it was found that the dense dynamic screens, because of their ability to change in response to climate and occupant demand, could potentially perform better than the massive static screens.

The observations from the field study indicated that there is a need to revisit the massive static screen geometric designs that are optimized to maintain thermally uniform conditions in the building perimeter areas. It is suggested that solar screen designs should also account for offering thermal non-uniformities in the space to enhance occupants' thermal experience. Thus, dense dynamic screens are recommended for achieving thermally non-uniform indoor conditions.

Dynamic screens with geometric patterns have a strong cultural and aesthetic significance over other adaptive façade shading types. Their application to office buildings is apt because of their thermal performance and the ability to offer outdoor view, and privacy simultaneously. Office buildings with large glazing areas require adequate façade shading strategies, even in cold climates (Grynning et al., 2014). Thus, besides tropical, and warm climates, the application of dense dynamic screens may also prove suitable to office buildings facades in moderate and cold climates.

The purpose of designing dynamic screen applications beyond facade aesthetics, daylighting sufficiency, and energy efficiency has not been explored. Impact of dynamic screens on occupant's thermal perception is not studied presumably because of the challenges associated with conducting field studies. Use of mixed-method approach by combining experiments in computational environments and real-world settings involving full-scale prototypes and human factors; could allow for an in-depth assessment of dynamic screen impacts. Using the mixed-methods approach, the authors propose to investigate the potential of dynamic screens in creating controlled change in the indoor environment and its impact on human perception. Given the scholarly discourses on controlled thermally non-uniform indoor environments as agents for occupant pleasure and well-being, the authors propose to test the hypothesis that dynamic screens can be used as media to generate occupant thermal pleasure in building perimeter spaces. Such human centric designs of dynamic screens can impact occupant well-being.

CHAPTER III: SENSITIVITY ANALYSIS AND PILOT STUDY

This chapter is a compilation of published articles, which have been co-authored by Prof. Ihab Elzeyadi. They were peer-reviewed and published in the proceedings of Association of Collegiate Schools of Architecture (ACSA)- 108th Annual Meeting-2020 and Passive and Low Energy Architecture (PLEA-2020) conferences.

Through the literature review and an observational field study reported in Chapter 2, it was clear that massive static and dense dynamic screens can effectively control indoor thermal conditions. Following that, the next step was to address the question that is, how to design massive static (= static) and dense dynamic screens (= dynamic) for thermal pleasure? This chapter is a compilation of two papers, one of which reports on findings from a computational study that was used to inform the design and fabrication of static and dynamic screen prototypes for thermal pleasure. The other paper reports on findings from a pilot study, which was used to design the thermal environment using static and dynamic screens for human exposure to the experimental office set-ups.

The computational study focused on investigating the sensitivity of thermal comfort to various combinations of solar screen geometric parameters using simulations in the computer program IESVE. The predicted thermal comfort metric (PMV) was used to predict design for thermal pleasure. In designing for thermal pleasure, the aim was to create a thermal environment that transited between the upper (slightly warm) and lower (slightly cool) limits of the thermal comfort zone ($-0.5 \leq PMV \leq +0.5$). The sensitivity analysis informed the design decision on geometric parameters of the static (stationary) and dynamic (movable) screen prototypes. Moreover, it informed that for an east facing perimeter office during the summer of ASHRAE Climate Zone (CZ)-4C, the best time to provide pleasurable thermal environment using solar screens would be between early morning to noon hours.

In the pilot study, the indoor thermal environmental performance of the static and dynamic screened experimental offices was monitored between early morning to noon hours during summer months under sunny sky conditions of ASHRAE-CZ-4C. Three types of movement frequencies of the dynamic screens were tested. This study informed that 8:00 to 11:00 AM was the time when the intended thermal conditions for human exposure were achieved in the static and dynamic screened offices. The dynamic screen's movement was finalized to change between OPEN and CLOSED positions in 10-20-10 minute intervals during human exposure. With this frequency, it was possible to keep the indoor thermal environment comfortable for most of the time besides creating short instances (10 minutes) of a slightly warm environment when in an OPEN position.

3.1. Advances in thermal comfort research and opportunity for contribution

Building envelopes and mechanical systems are designed to maintain thermally uniform indoor conditions as required by the thermal comfort standards (ASHRAE 55, EN-15251, ISO7730). These standards prescribe narrow limits of thermal conditions as 'comfortable'. Predicted mean vote (PMV) is a widely used metric for thermal comfort assessment (ASHRAE-55). PMV values are computed using a steady state mathematical model, which comprises of dry bulb temperature (DBT), relative humidity (RH), mean radiant temperature (MRT), air speed (m/s), occupant metabolic rate (met), and clothing insulation (clo), as its independent variables. PMV values in the range of (-0.5) to (+0.5) determines the thermal comfort zone. It is predicted that this limitation keeps a minimum of 80% of occupants satisfied (ASHRAE-55, EN-15251).

Over the past twenty years, there has been a paradigm shift in the conception of provision for thermal comfort (de Dear, 2011). The notion of a uniform thermal environment continues to be challenged. Investigations of different types of thermally non-uniform indoor conditions involving parameters such as air movement and body localized heating/cooling on occupant thermal perception and satisfaction is one of the currently sought out directions in thermal comfort studies (Brager et al., 2015; Parkinson & de Dear, 2015; Parkinson et al., 2012; Parkinson et al., 2016; Naik & Elzeyadi, 2020a).

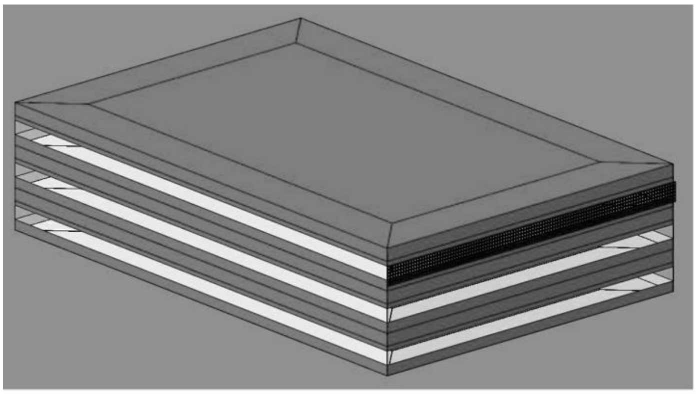
Recent studies suggest that thermally non-uniform environments within a broader comfort range of +1 to -1 PMV can lead to occupant's well-being (Brager et al., 2015; van Marken Lichtenbelt et al., 2012; Kingma et al., 2017). They can evoke perception of thermal pleasure among occupants (Parkinson et al., 2016). Occurrence of thermal pleasure is explained by changes in physiological state of occupants within the boundaries of thermal comfort range, termed as alliesthesia. In addition to their potential to evoke thermal pleasure, the thermally non-uniform environments are also considered to be energizing for the occupants (Brager et al., 2015). These environments can potentially affect occupants' resilience and adaptability to their surroundings, thereby positively influencing long-term well-being (van Marken Lichtenbelt et al., 2017, Kingma et al., 2017). These studies provide a motivation for deeper investigations to uncover occupant's thermal perception and satisfaction in a wide variety of non-uniform environments.

Design of dense dynamic screens provide a unique opportunity to create thermally non-uniform indoor environments within a broader comfort range that can potentially induce thermal pleasure among occupants. The sensitivity analysis and the pilot study aim to explore this opportunity.

3.2. Sensitivity analysis using computational simulations

This study is a part of a research project that seeks to quantify the impact of dynamic screens on occupant thermal comfort and alliesthesia. Experiments involving human subjects in full scale office-like set-ups shaded by screen prototypes are the main research method. To inform the design of screen prototypes and related experimental design, screen geometric parameters were researched in Integrated Environmental Simulations Virtual Environment (IESVE) software. Sensitivity of predicted thermal comfort to screen geometric parameters such as PR (perforation ratio) and DR (depth ratio) were tested. This paper reports on the findings from the sensitivity analysis and describes the process followed in developing the actual prototypes.

This study provided guidelines to build dynamic and static screen prototypes for intended indoor thermal environment in full-scale experimental tests. This study also indicated a suitable timeframe of a day to execute future experiments involving human subjects in dynamic and static screen shaded full-scale set-ups.



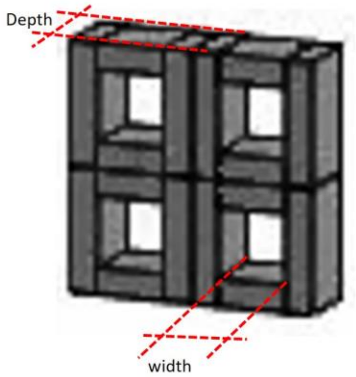


Figure 3.1 Mid-sized office building with screen modelled on its east facade. Screens typical modelled geometry (PR = % of open, DR = depth/width).

3.2.1. Description of the model

A mid-sized, typical office building, based on ASHRAE (2013) model shown in Figure 3.1., was used for the simulations (gross area = 53,658 ft²) w with optimized systems design. It was assumed that the building would accommodate medium density occupancy. Fifteen screen panel alternatives with combination of one value from 5 different PR values (PR = 10%, 30%, 50%, 70%, 90%) and another from 3 different DR values (DR = 0.1, 0.5 and 1) were modelled on east facing perimeter space of the top floor of the building. Modelled screens were of simplest geometry (as illustrated in Figure 3.1.) because it reduced the computation time. The number of perforations is same for all fifteen panels. Hence, the different perforation ratios are obtained by changing the perforation width. For a given value of PR, different values of DR are obtained by changing the perforation depth while keeping the width constant.

Predicted thermal comfort performance of each of the screen alternatives was evaluated using yearly dynamic simulations for design days (15th of every month) of the summer months from June to September for the moderate climate of Eugene (44°03′07″N 123°05′12″W), Oregon (ASHRAE, Climate Zone 4C).

It was important to investigate the screen performance on west and south oriented perimeter spaces, however, the main purpose of this computational study was to inform the design of next phase experiments with human subjects; execution of which is possible in an east facing full-scale, one-person office set-up in Eugene, Oregon. To reduce the computational time and focus on evaluating the impact of screens on indoor thermal performance of the east facing perimeter space, it was simulated for east façade in isolation.

For the predicted thermal simulations, airspeed of 0.2 m/s (in indoor environment), occupant clothing of 0.6 clo (summer clothing) and metabolic rate of 1.2 (for typing tasks) were used as constant inputs. The visible transmittance (Tvis = 80%) and solar heat gain coefficient (SHGC = 0.8) were assigned to the glazing of the building based on the actual window properties of the full-scale set-up. The heating and cooling profile of the HVAC system was switched off.

3.2.2. The study variable: predicted thermal comfort

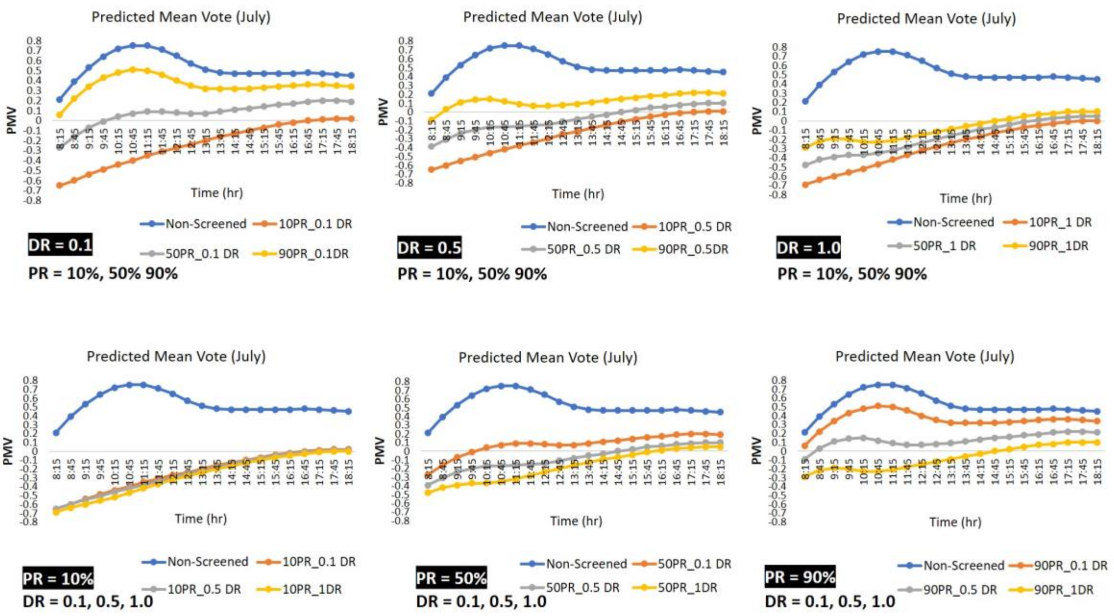


Figure 3.2 Sensitivity analysis of indoor predicted thermal comfort due to screens with different combinations of PR and DR for the design day in month of July. PMV values plotted at every thirty minutes. (Top Row) Impact of PR on variability in PMV can be observed at lower DR value. (Bottom Row) Impact of DR on variability in PMV values can be observed at a higher PR value.

The Predicted Mean Vote (PMV) (ASHRAE-55, 2017) metric was used to predict occupant thermal sensation and thermal comfort in the east facing perimeter space. Six parameters, namely, dry bulb temperature (DBT), mean radiant temperature (MRT), relative humidity (RH), air speed, occupant clothing and metabolic rate determine the PMV values that range between -3 (cold) and +3 (hot). The PMV values in the range of (-0.5) to (+0.5) indicate the thermoneutral comfort zone, with (0) predicting thermal uniformity/neutrality and (+0.5) indicating as slightly warm and (-0.5) as slightly cool thermal sensations. Parkinson and de Dear, who conducted numerous studies in thermal comfort research found that thermal environments which transitioned between neutral (PMV = 0) and upper (PMV = + 0.5) and/or lower fringes (PMV= -0.5) of the thermal comfort zone created thermal pleasure or alliesthesia (Parkinson et al., 2016).

The Adaptive Model confirms to occupant expectations on thermal comfort for non-uniform thermal conditions (ASHRAE 55, 2010) and could also be used for thermal comfort assessment. However, the PMV is a widely used model for thermal comfort which caters to the goal of the study; that is to understand the variability in people's thermal sensation due to different screen applications.

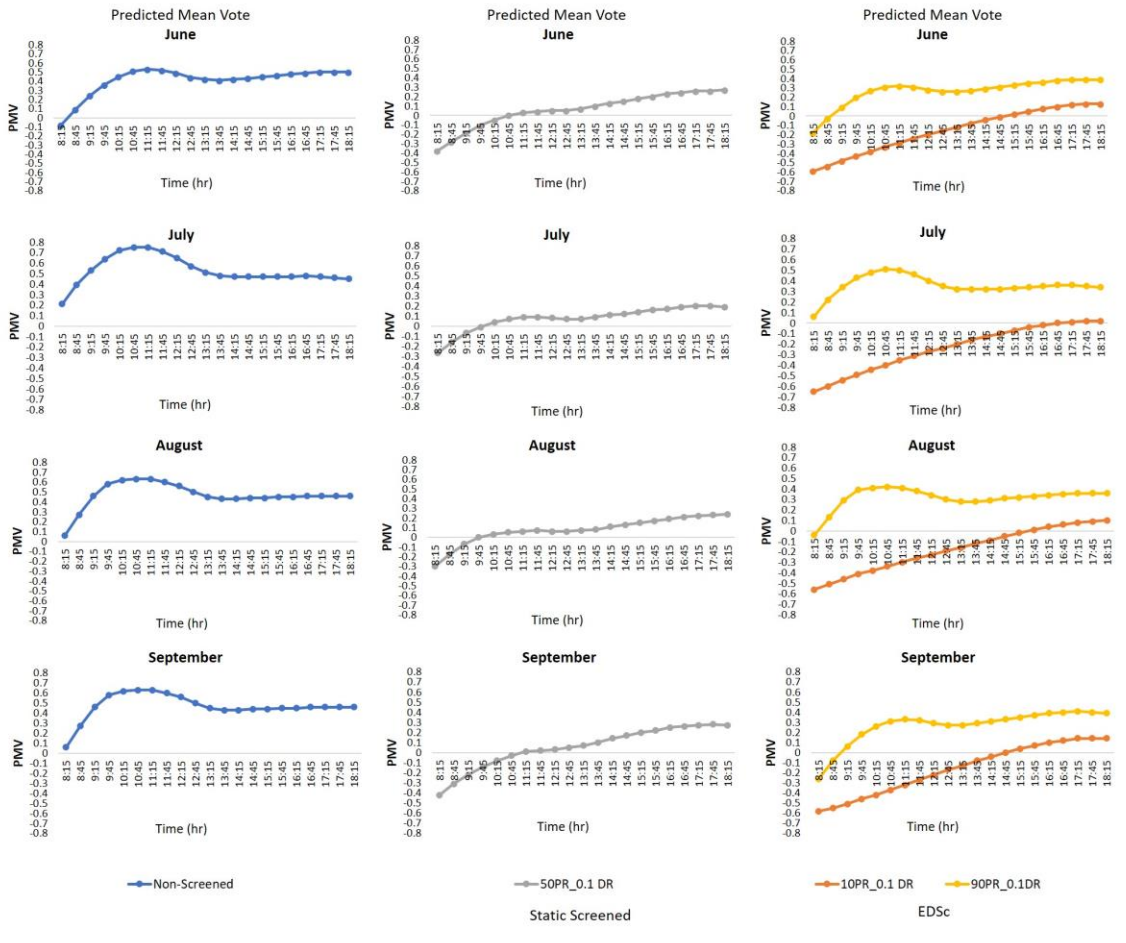


Figure 3.3 Predicted thermal comfort in non-screened (left), static (centre) and dynamic screen (right) shaded east facing perimeter space during summer months in Eugene, Oregon.

3.2.3. Analysis of results

In Figure 3.2, PMV values are plotted every thirty minutes for fixed value of one parameter (PR or DR) and different values of the other parameter. These results show the PMV trend from 8:15 AM to 6:15 PM for the month of July. PMV trends for non-screened condition and screens with highest, middle, and lowest values of PR (10%, 50% and 90%) and three DR values (0.1, 0.5 and 1) are plotted. These results reveal that variability in the PMV values between trend lines of each plot is higher for time between 8:45 AM and 12:15 PM and it reduces during later hours of the day. This high PMV variability in the morning hours can be attributed to radiative heat transfer in the east facing perimeter space.

For a constant value of DR, the variability in the PMV values with the change in PR value is highest for the lowest value of DR (= 0.1). This variability reduces as DR value increases. For DR = 0.1, PMV value transits from minimum (-0.6) to maximum (+0.5) when PR changes from 10% to 90%. DR = 0.1 corresponded to thin screen panels that led to max. radiative heat transfer. As the DR value increases, the depth/thickness of screen panel increases, causing lesser radiative heat transfer. For DR = 1, PMV values vary in a narrow range from minimum (-0.7) to maximum (- 0.2) with the increase in PR from 10% to 90%.

For a constant value of PR, the variability in the PMV values with the change in DR value is highest for the highest value of PR (= 90%). This variability reduces as PR value reduces. For PR = 90%, the change in DR value from 1 to 0.1 (i.e., deeper to thinner screens) controls the radiative heat transfer yielding the variation in PMV value from minimum (-0.3) to maximum (+0.4). For PR = 10%, the radiative heat transfer is obstructed due to small perforation opening. Hence, the change in DR value (i.e., the screen thickness) does not have noticeable impact on variability in PMV value.

3.2.4. Findings and application

Results on predicted thermal comfort during morning to noon hours, plotted in Figure 3.3, illustrate that having no screens (non-screened) keeps the indoors warm; indicated by PMV values in the range of (+0.3) to (+0.8). Static screened condition with PR = 50% and DR = 0.1 maintains thermal neutrality by keeping the predicted thermal sensation between neutral (PMV =0) and slightly cool (PMV = -0.3). These results align with previous studies on static screens (Elzeyadi et al., 2016). The dynamic screen shaded condition, if designed using sliding and overlapping screen panels with (PR, DR) = (10%, 0.1) and (90%, 0.1), can create an indoor thermal environment that can change between slightly warm and slightly cool, at a time due to its potential to transit between PMV = +0.5 and PMV = -0.5.

In creating a dynamic screen shaded set-up, the intent was to design a thermal environment that transits between the upper and lower limits of the thermoneutral comfort zone and induce a feeling of thermal alliesthesia and thermal delight in occupants. A dynamic screen prototype, designed with the capability to change between screen panels with (PR, DR) = (10%, 0.1) and (90%, 0.1) for an east facing set-up in Eugene, Oregon, offers an opportunity to attain the intended transient indoor environment during 9:45 AM to 12:45 PM on a summer day in a non-HVAC set-up.

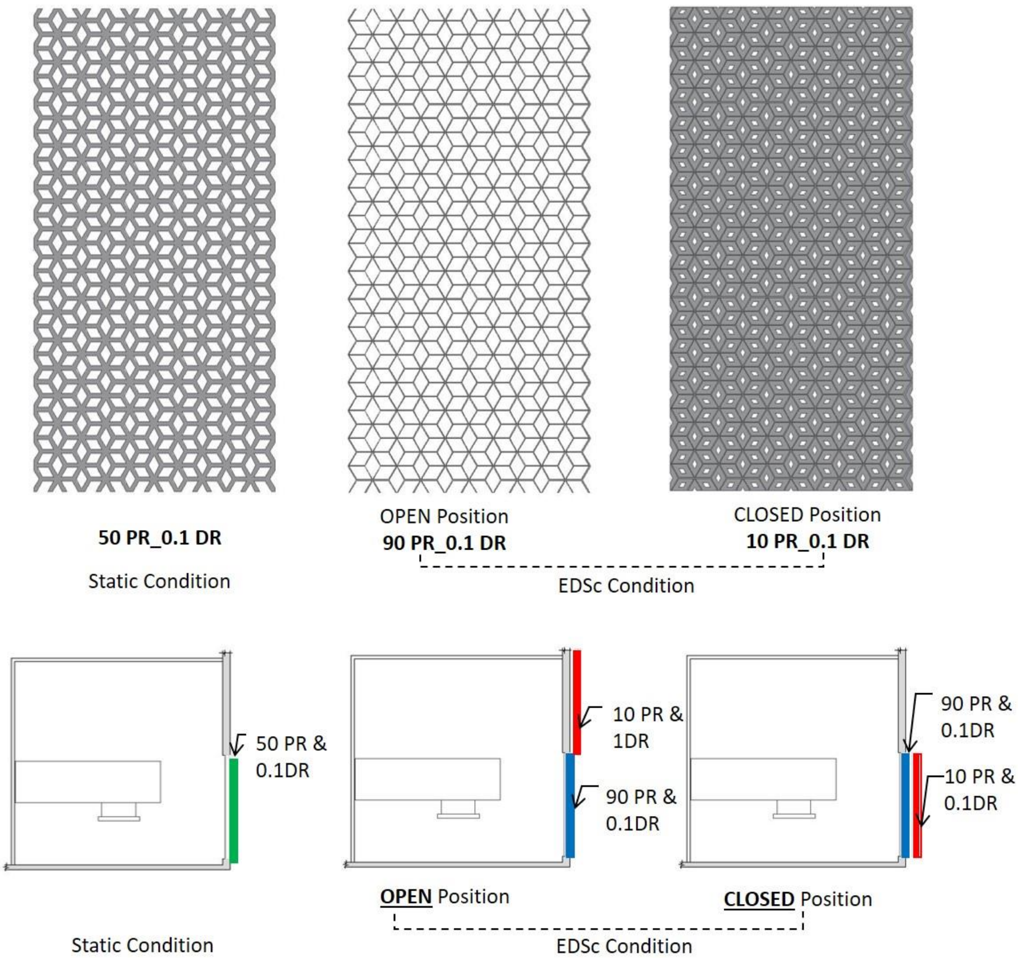


Figure 3.4 Static and dynamic shaded conditions as arranged for one-person office set-ups.

In creating a static screened set-up, the intent was to attain a thermally neutral environment. A static screened prototype with PR = 50% and DR = 0.1 offers an opportunity to attain the desired thermal conditions between 9:45 AM and 12:45 PM in a non-HVAC east facing set-up in Eugene, Oregon. Learnings from this simulation study were used to produce the dynamic and static screen prototypes, which are illustrated in Figure 3.4. Further, based on recommendations from a recent study, geometric patterns formed by rhombus-based shapes were created as perforations in the actual prototypes (Oghazian et al., 2017).

Both, the static and dynamic screen shaded set-ups were arranged in east facing studios at Lawrence Hall, University of Oregon. A pilot study measuring the actual impact of static vs. dynamic on indoor thermal and visual comfort performance was carried out in July 2019 followed by the experiments involving human subjects during August-September of 2019.

3.3. Pilot study

This study attempts to address the following question: how can dynamic screens be designed to create thermally non-uniform indoors for occupant's thermal comfort and thermal pleasure within an accepted yet broader comfort range? It also provides a comparative assessment of the impacts of dynamic and static screens on predicted thermal comfort and indoor thermal environment. Full-scale prototypes of static and dynamic screens were developed and installed on east facing, single-occupancy office set-up in the moderate climate of Eugene, Oregon (ASHRAE, Climate Zone 4C). The impact of five different conditions including non-screened, static, and dynamic screens (with three different movement frequencies) on the indoor thermal environment was recorded for sunny-sky, hot days during typical summer months in July and August.

3.3.1. Static and dynamic screen prototypes

The static screen prototype was intended to create a uniform thermal environment within the ASHRAE-55 comfort range, whereas the dynamic screen prototype was intended to create non-uniform indoor thermal conditions within the expanded boundaries of the ASHRAE-55 comfort range. To inform design of the prototypes, a sensitivity analysis delineating effects of screen geometric parameters such as PR and DR on predicted indoor thermal comfort was simulated in computational environment for summer months (June-September) for ASHRAE

Climate Zone 4C using computational modelling and simulations in the IESVE software (Naik & Elzeyadi, 2020b). The results were used to decide the geometric parameters for static and dynamic prototypes. Details on the sensitivity investigation have been reported in a previous study (Naik & Elzeyadi, 2020b).

The screen prototypes were designed to be two-dimensional, thick planar surfaces, which were non-movable/fixed and moveable/operable in static and dynamic conditions respectively (Figure 3.5). Based on results of the simulations (Naik & Elzeyadi, 2020b), the optimized static screen prototype was designed to have (PR, DR) = (50%, 0.1) (Figure 3.5b) which were predicted to produce uniform thermal condition close to the neutral line (PMV = 0) within the thermal comfort zone (ASHRAE-55). The results of simulations also suggested that a dynamic screen with the geometric parameters altering between (PR, DR) = (10%, 0.1) and (PR, DR) = (90%, 0.1) can produce desired nonuniform thermal conditions that transition between the upper and the lower limits (-0.5 < PMV < +0.5) of the thermal comfort zone. Hence, a dynamic screen prototype was built comprising of two sliding panels (one with (PR, DR) = (10%, 0.1) and the other with (PR, DR) = (90%, 0.1) which could overlap sequentially (Figure 3.5, c-d).

3.3.2. Experimental set-up

The current study was carried out in a 10’ x 10’ (3 x 3 m) experimental, single occupancy office set-up arranged in the perimeter space of an open-plan, east-facing studio in an educational building. The set-up was physically isolated by 7’ high partitions and had a single-glazed 5’ (wide) x 8’ (high) fixed window (Tvis = 0.80, SHGC= 0.80) on its east facing wall. The dynamic and static screen prototypes shaded the outer surface of the window. Inside the set-up the work-desk arrangement faced south. Equipment required to measure thermal and visual environment was placed inside the set-up in the occupant’s seating position plane. Figure 3.6 shows the details of the set-up.

Pre-programmed data-loggers (Onset HOBO U-12, accuracy: ±0.35°C (±0.63°F)) were placed at three locations horizontally and at three stratified levels vertically at 0.1 m (3.93”), 0.6 m (23.6”), and 1.1 m (43.3”) to measure dry-bulb temperatures, relative humidity and globe temperatures. Globe temperature sensors fabricated and used for the study [25] were connected to HOBO-U-12's extra-channel. Hot wire-anemometer (Testo 405i, accuracy: ± (0.1 m/s + 5 % of mv), measurement range: 0 to 2 m/s) was mounted at a seated-human's head-height on a tripod placed in the center of the set-up. The pre-programmed data logging unit to measure solar radiation (W/m^2) consisted of a calibrated pyranometer sensor (LI-COR LI-200R) connected to a calibrated transconductance amplifier (UTA for L-COR™ sensors) and a data logger (Onset-HOBO U-12). Of the two solar radiation logging units, one was placed on the window surface behind the screen and the other in the outdoor environment.

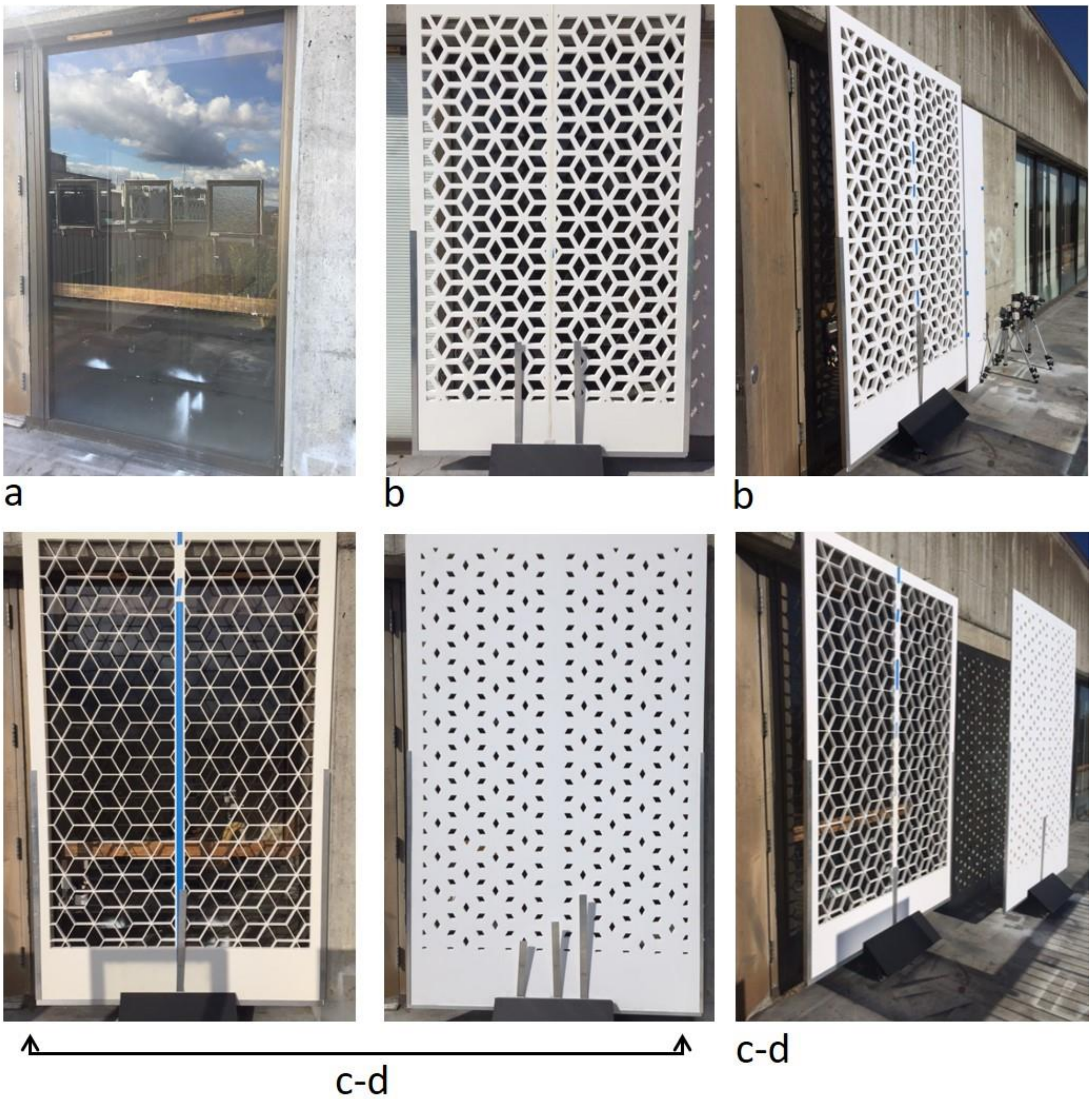


Figure 3.5 (a) non-screened window, (b) window with static screens having (PR, DR) = (50, 0.1), (c-d) dynamic screened window with overlapping panels having (PR, DR) = (90, 0.1) and (PR, DR) = (10, 0.1).

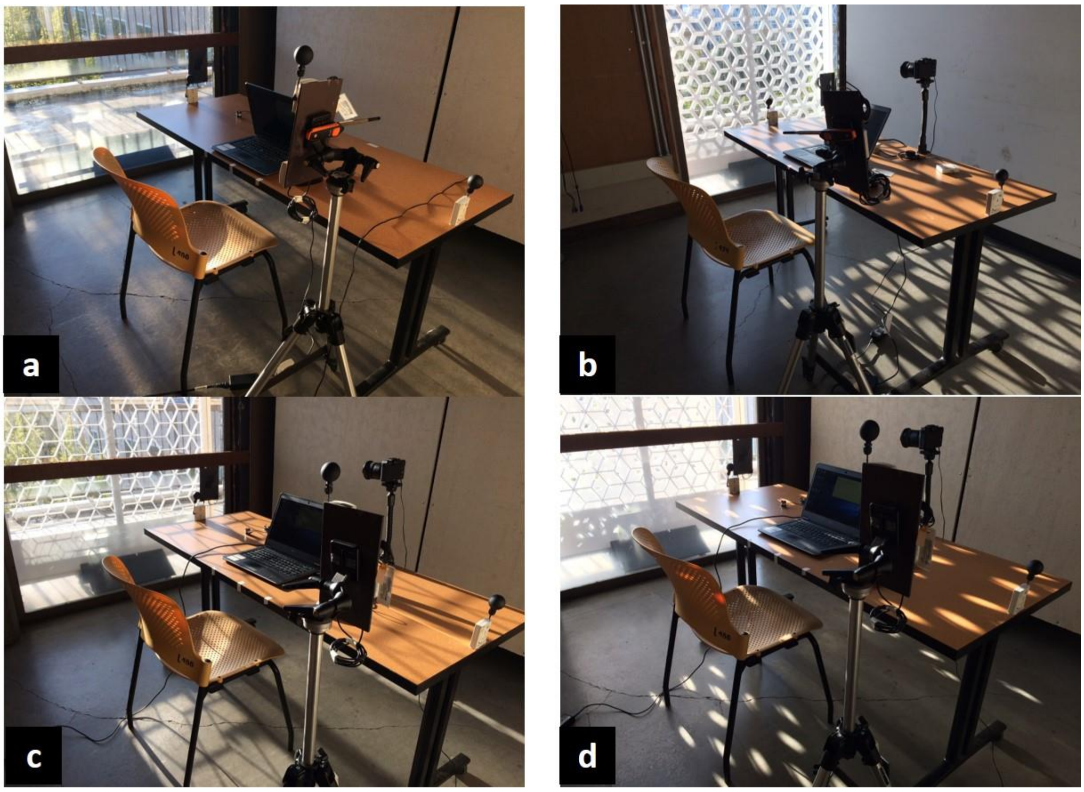


Figure 3.6 (a) non-screened condition, (b) static screened condition, (c-d) dynamic screened condition with screen in open position ‘O’ in (**c**) and closed position ‘C’ in (d).

3.3.3. Study design

The non-screened, static, and dynamic screened conditions were tested during morning hours (8:30 AM - Noon) for the east-facing set-up. The dynamic condition transitioned between open ‘O’ position (screen panel with (PR, DR) = (90%, 0.1)) and closed ‘C’ positions (when screen panel with (PR, DR) = (10%, 0.1) overlaps the ‘O’ position). With the dynamic condition, it was intended to create variable thermal environment that could transition between the upper and lower fringes of the ASHARE-55 thermal comfort zone. Beginning with ‘O’ at 8:45 AM the position was changed to ‘C’ after 30 thirty minutes continuing the cycle until 12:15 PM. This movement, however, did not produce the desired indoor thermal variability. Hence, it was decided to test the dynamic condition with increased movement frequencies. As shown in Figure 3.7, the following three dynamic movement frequencies were tested during a typical morning hour, beginning from 8:45 AM: (i) every 15 min (O-C-O-C), (ii) every 20 min (O-C-O), and (iii) every alternate 10 min (O) and 20 min (C) (O-C-O-C).

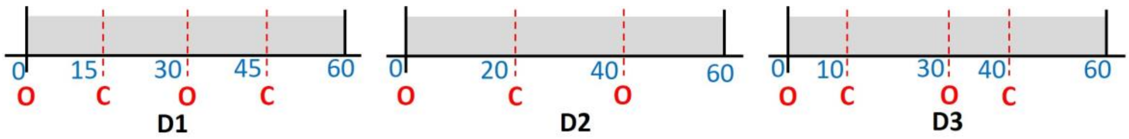


Figure 3.7 D1, D2, D3 are three different movement frequencies of dynamic screened condition tested during a typical morning hour. ‘O’ and ‘C’ denote open and closed positions of the dynamic condition.

3.3.4. *Data collection and analysis*

Outdoor and indoor environmental data consisting of solar radiation (W/m^2), dry-bulb temperature (°F), globe temperatures (°F), relative humidity (%), and airspeed (m/s) were recorded every minute during the study runs. The metabolic rate (met = 1.2) and clothing insulation (clo = 0.5) were kept constant during the experiment. The globe temperatures were used to calculate the mean radiant temperatures using Equation (2). Infrared images (IR) were captured at regular intervals using IR portable camera attachment to a mobile phone (FLIR One Pro LT iOS camera, accuracy: ±5%, resolution: 0.1° C/ 0.1° F).

The measured indoor environmental thermal data comprising of DBT, RH, MRT, and airspeed was used to predict occupant thermal comfort by computing PMV values [13]. Occupant metabolic rate and clothing value were assumed as 1.2 met and 0.5 ‘clo’ for PMV calculation. Metabolic rate of 1.2 was assumed for an occupant in the one-person office where he/she could be involved in light office work. Occupant clothing value of 0.5 ‘clo’ was used for a person occupying the set-up during moderate summers in ASHRAE Climate Zone, 4C. The R package, “comf” with in-built functions for thermal comfort indices was used to compute the PMV values (Schweiker, 2016). The computed PMV values were used to predict indoor thermal conditions inside the screened set-ups. PMV values between (i) (+ 0.5) and (-0.5) indicate the thermal comfort zone, (ii) (+1) and (-1) indicate the thermal neutrality limit, and (iii) (+1) and (+2) indicate a slightly warm thermal environment which could produce slight discomfort and heat stress.

Difference between outdoor and behind-the-shade solar radiation data was used to determine the reduction in solar radiation due to static and dynamic screen shading. The infrared images were analyzed in FLIR’s computer-based program ‘ResearchIR’ to understand distribution of surface temperatures in the screened conditions.

3.3.5. Findings

As hypothesized the reduction in solar gain due to the static screen panel with (PR, DR) = (50, 0.1) was 45-70%. In comparison, the dynamic screen in positions 'O' (i.e., (PR, DR) = (90, 0.1)) and 'C' (i.e., (PR, DR) = (10, 0.1)) reduced 80-90% of the solar gain. This suggests that dynamic screen with carefully designed movement frequency can achieve higher reduction in solar gain compared to the static screen. It is evident that the static and dynamic screens can effectively reduce surface temperatures compared to non-screened conditions (Figure 3.8). In the case of dynamic screened condition, transition from 'O' to 'C' reduces indoor surface temperature further by an additional 6° F (Figure 3.8 c-d).

Both static and dynamic screened conditions created an indoor environment consisting of patterned solar patches (Figure 3.8) with higher surface temperatures on the floor and work plane. Moreover, they also created conditions wherein the radiant temperatures varied between the two boundaries of the space left and right to the occupant; a condition termed as 'radiant temperature asymmetry'. The surface temperatures in the static and dynamic set-ups remained within the range of 75° F - 80° F. However, the solar patches had temperatures between 85° F and 90° F, which could potentially be the sources of local thermal discomfort. Difference between mean radiant temperatures (i.e., ΔMRT) at two points in the set-up showed that the approximate radiant asymmetry between the warm-window and the cool wall was less than 15° C (Figure 3.9). This suggested that radiant asymmetry in the set-up did not exceed the limits of predicted local thermal comfort (i.e., predicted dissatisfaction, PD < 10) which requires ΔMRT < 30° C (ASHRAE-55, 2017).

Analysis of the distribution of PMV values of the set-up under different conditions suggest that the non-screened condition was slightly warm as indicated by PMV values within 1.0 to 1.5. Results plotted in Figure 3.10 indicate that the static screen and dynamic screens with movement type D3 were effective in keeping the indoor conditions within thermal neutrality limit (PMV < 1). The quartile range of PMV values in the set-ups with static screen and dynamic screens indicated that the later caused higher variability in the indoor thermal environment by creating transitions between ‘neutral’ and ‘slightly warm’ conditions. Dynamic screens with movement type D3 kept the indoor environment ‘neutral’ for most of the time besides creating instances of slightly warm/ discomforting conditions when PMV values exceeded one (PMV=1).

As depicted in Figure 3.11, a further analysis of indoor thermal environment for the dynamic screen set-up with movement type D3 revealed that the transition from ‘O’ to ‘C’ position and vice-versa decreases or increases the indoor air-temperature by 4-6° F. This can be attributed to the control of solar radiation with the screen’s movement. The drop or rise in the temperature occurred during the early morning hours, with-in five minutes after the screen’s position change.

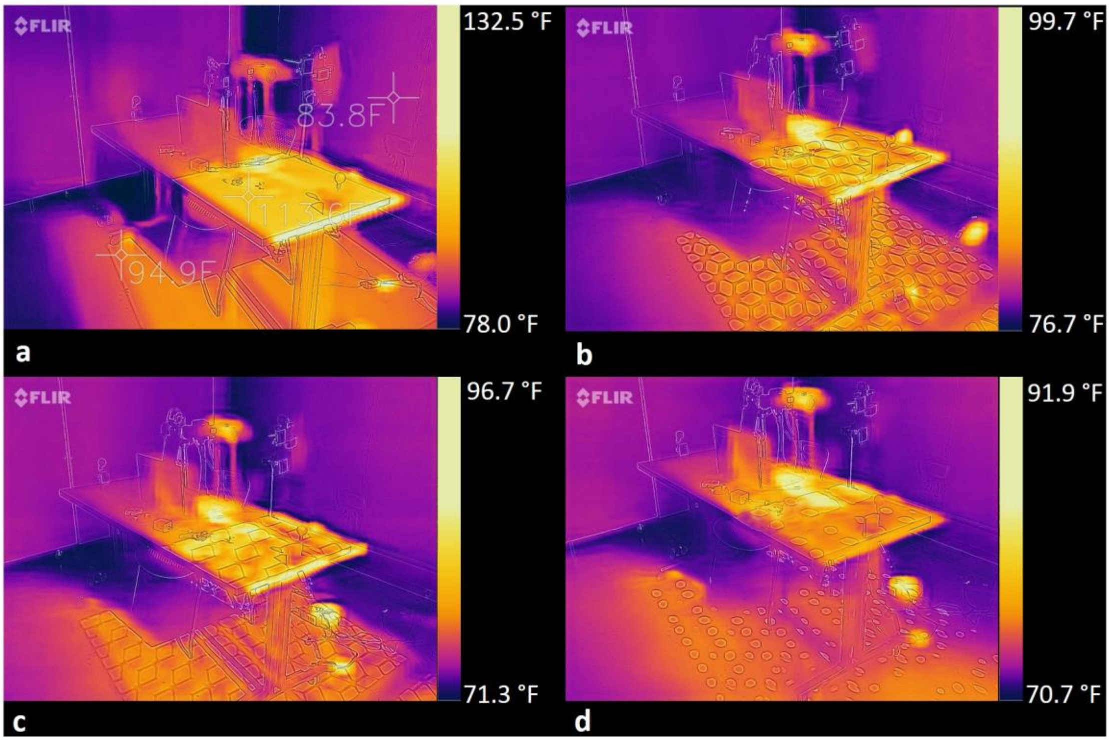


Figure 3.8 Infrared images of (a) Non-screened condition, (b) Static screened condition, (c-d) Dynamic screened condition with screen in open position ‘O’ in (c) and closed position ‘C’ in (d) at 9:30 AM.

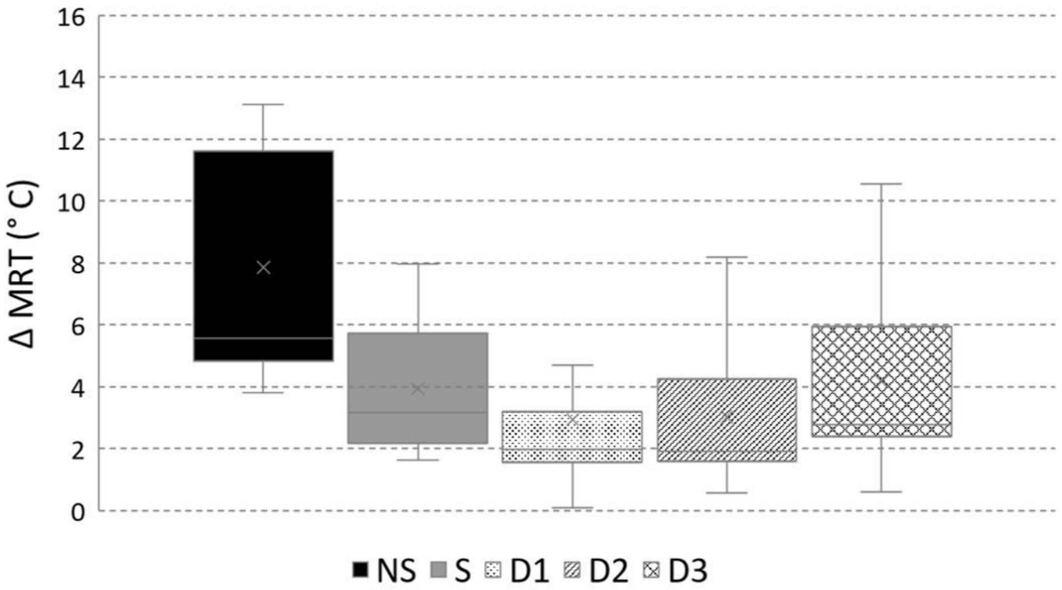


Figure 3.9 Difference in Mean Radiant Temperature (MRT) between warm and cool wall inside non-screened (NS), static screened (S) and dynamic screened conditions with movement frequencies (D1, D2, D3).

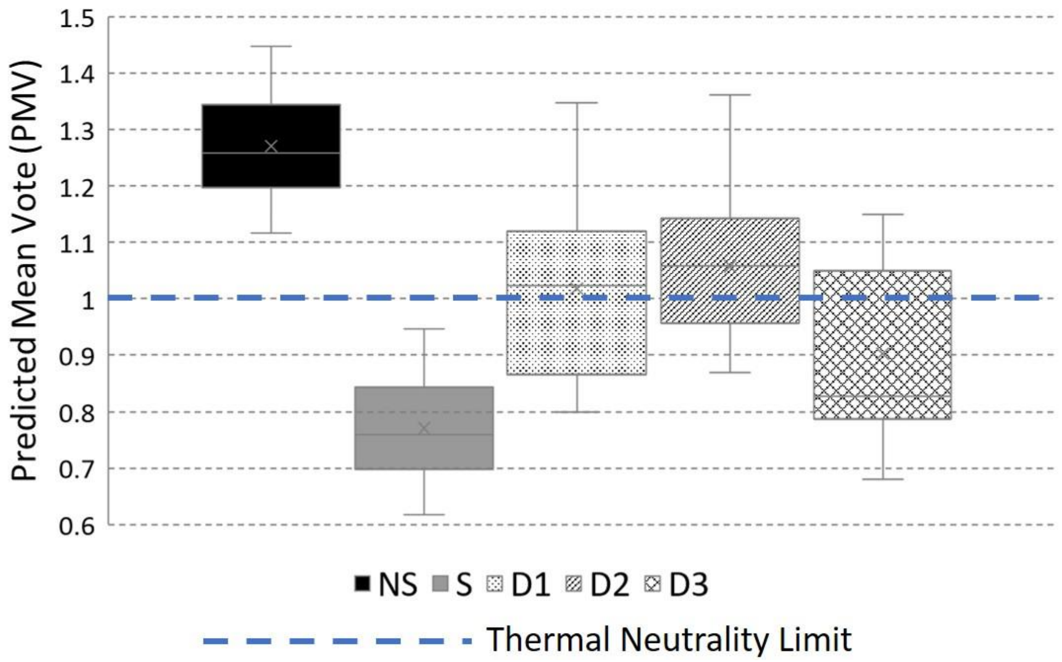


Figure 3.10 Distribution of Predicted Thermal Comfort inside non-screened (NS), static screened (S) and dynamic screened conditions with movement frequencies (D1, D2, D3).

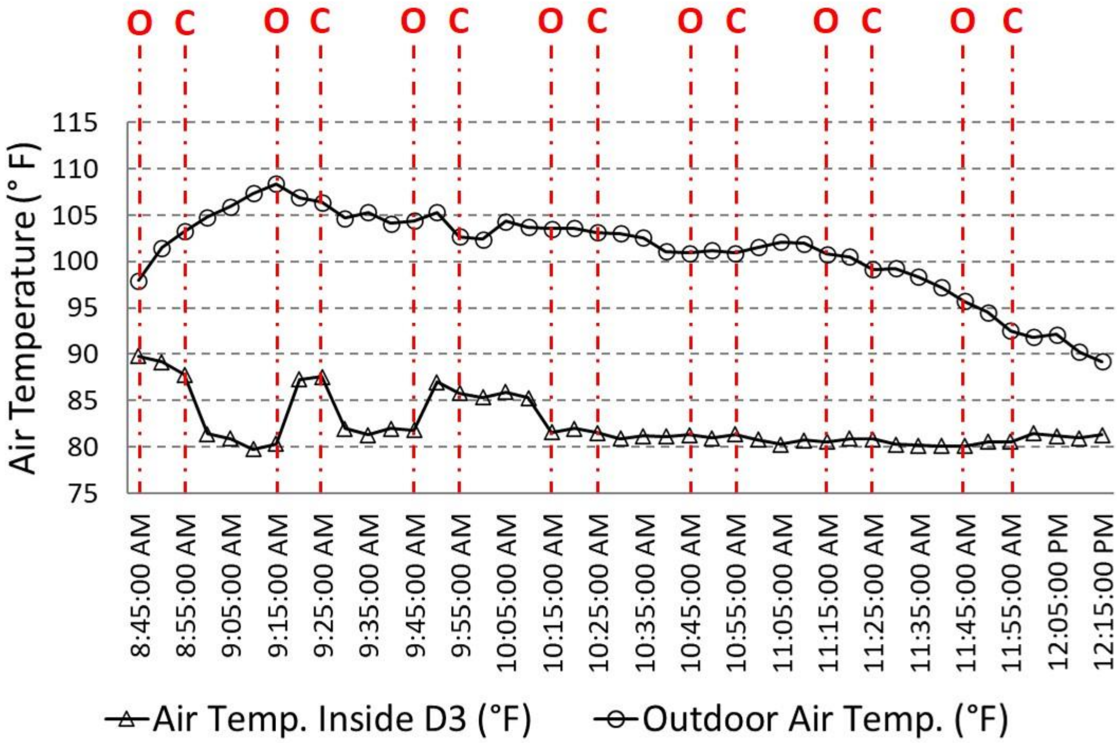


Figure 3.11 Air Temperature trend inside the set-up shaded by dynamic screens with movement type D3. 4-6° F drop/rise is observed after change in the screen position from 'O' to 'C' or vice-versa during early morning hours.

3.4. Summary and application

Through the computational study, the impact of screen geometric parameters on predicted thermal comfort inside the east facing perimeter space of a mid-size office building in Eugene during summer months was analysed using simulations in IESVE program. Results demonstrated that dynamic screens can be designed to create thermally non-uniform environment in perimeter spaces of buildings. One way to design dynamic screen is by using two sliding screen panels with (PR, DR) = (10%, 0.1) and (90%, 0.1) that can overlap. Alternatively, sliding panels with (PR, DR) = (90%, 0.1) and (90%, 1) can also produce similar thermal conditions. The resulting thermal environment can potentially induce "thermal alliesthesia" in occupants.

Pilot study of the thermal conditions inside the static and dynamic screened, single-occupancy, experimental offices informed that 8:00 to 11:00 AM was the time when the intended thermal conditions were achieved. Changes in the dynamic screen led to a drop or rise in the indoor air temperature by 4 - 6°F (1.7-2.8 °C) within five minutes of the screen's position change. The dynamic screen's movement was finalized to change between OPEN and CLOSED positions in 10-20-10 minutes intervals during human exposure. With this movement frequency, it was possible to keep the indoor environment comfortable for most of the time besides creating short instances (10 minutes) of a slightly warm environment when in an OPEN position.

Equations

The globe temperature, GT, is computed using Eq. (1):

$$GT = \frac{1.8}{A + A_1 + A_2} - 459.67 \quad (°C) \qquad (1)$$

where

$A = 1.12886430756012 \times 10^{-3}$,

$A_1 = B \times LN\left(10000(2.5/V - 1)\right)$,

$A_2 = C\left[LN\left(10000(2.5/V - 1)\right)\right]^3$,

$B = 2.34149078860173 \times 10^{-4}$,

$C = 8.77065543744161 \times 10^{-8}$, and

V = voltage equivalent to the resistance measured through US sensor 10,000 Ω curve "J" thermistor. The symbol 'x' in the equation denotes the multiplication.

The mean radiant temperature, MRT, is computed using Eq. (2) (ISO-7726, 1998):

$$MRT = \left[(GT + 273)^4 + \frac{1.1 \times 10^8 v_a^{0.6}}{\varepsilon D^{0.4}}(GT - T_a)\right]^{1/4} - 273 \qquad (2)$$

where

MRT is the mean radiant temperature (°C), GT the globe temperature (°C) computed using Eq. (1), v_a the air velocity at the level of the globe (m/s), ε = 0.95 is the emissivity of the globe, D = 0.15 is the diameter of the globe, and T_a is the air Temperature (°C).

CHAPTER IV: EXPERIMENT INVOLVING HUMAN PARTICIPANTS

This entire chapter has been submitted as a research paper to the journal, Building Research and Information (BRI) and is under final review. It has been co-authored by Prof. Ihab Elzeyadi, Prof. Christopher Minson, and Dr. Jun-Hak Lee.

After the design and development of the experimental offices shaded by the static and dynamic screens informed by the computational and pilot studies reported in Chapter 3, it was the time to expose human participants to the screened offices. This chapter reports on the results from experiment that involved human participants (N=27) inside the static and dynamic screened experimental offices. It addresses the question on the relationship of subjective reporting of thermal pleasure with indoor thermal environmental parameters and human physiological variables inside dynamic and static screened experimental offices. It elaborates on thermal alliesthesia, its relevance inside buildings and discusses findings from the experiment. Co-relations of subjective data with physical environmental variables and objective human related parameters have been quantified and compared with findings from previous work focusing on thermal pleasure inside buildings.

Controlled non-uniform indoor thermal environments have the potential to evoke thermal pleasure in occupants as explained by the psychophysiological framework of alliesthesia. In this study, the authors aimed to explore thermal pleasure inside solar screen shaded, single-occupancy, experimental, perimeter offices that are within 4.5 m distance from a building facade. Two solar screens, static (stationary) and dynamic (movable), were designed to differently control the thermal environments inside these single-occupancy offices. A within-subject experiment was designed in which 27 human participants were exposed to both the screened offices. Subjective responses on thermal pleasure as well as objective data including the participants' physiological responses and indoor environmental data were collected during those exposures. Correlations between the subjective responses and objective data were analysed. Ramps in operative temperatures and skin temperature contrasts were found to have significant influence ($p<0.05$) on evoking thermal pleasure in ambient thermal environments of the solar-screened, perimeter offices that remained in the upper fringes of the thermoneutrality limits. The findings provide experimental evidence that expands the application of thermal alliesthesia framework to building perimeter offices.

4.1. Introduction

Thermal pleasure is the affective component of human thermal perception (Cabanac, 1979). Bioclimatic buildings that employ passive design strategies have been touted as the architectural precedents for thermal pleasure in thermal comfort literature (Heschong, 1979; Reynolds, 2002; de Dear, 2014; Passe & Battaglia, 2015; Naik & Elzeyadi, 2020a). The passive design strategy of exterior façade shading is frequently employed to control solar gain and building overheating in LEED™ certified buildings. However, its impact on occupant’s thermal perception remains under-researched (Attia, 2018; Kunwar et al., 2018). While the ongoing exploration on thermal pleasure based on space’s programmatic use and through non-architectural interventions in thermal environments are positive steps towards designing occupant-centric buildings, the potential of passive design strategy of exterior façade shading to impact thermal pleasure remains un-explored. In the present work, the researchers explored thermal pleasure in the building perimeter offices within a 4.5 m distance from the façade that was shaded by solar screens.

The psychophysiological framework of thermal alliesthesia gives the basis for understanding thermal pleasure. It is essential to understand the difference between the concepts of thermal comfort and thermal alliesthesia while exploring thermal pleasure in building indoor environments. Standardized thermal comfort requirements establish limits to control ambient thermal conditions for an occupant to perceive thermal neutrality (Brager et al., 2015). Thermally uniform indoor environments are required to maintain comfort. Thermally non-uniform environments, on the other hand may lead to thermal pleasure as explained by the psychophysiological framework of thermal alliesthesia, which describes the relationship between the internal state of an occupant and the perceived pleasure from the ambient thermal environment. (Brager et al., 2015, Parkinson & de Dear, 2015). For example, ambient thermal conditions will be felt pleasurable if a human body that is in discomfort senses a transition towards comfort. Thus, thermally non-uniform conditions that cause slight transitions within and between the upper and lower limits of the thermal comfort zone can influence occupant thermal pleasure perception inside buildings.

4.1.1. Thermal alliesthesia and its applicability to indoor environments

Thermoregulation balances heat loss and heat gain between the body and the ambient environment to maintain stable body core temperatures. The “thermoneutral zone” defines a range of ambient temperatures within which humans can maintain body core temperature without changing metabolic heat production (Kingma et al., 2017; van Marken Lichtenbelt et al., 2017). A human body gains heat from metabolic heat production and the ambient environment through processes such as conduction, convection, and radiation. Metabolic heat is lost to the environment through radiation, which is the major factor during the resting state. Conduction, convection, and evaporation influence heat loss during exercise or in very hot-dry ambient conditions during the resting state. A high amount of the human body’s heat gain or loss disturbs core temperature creating a thermoregulatory load error. As a primary response, the human body activates mechanisms such as shivering, vasoconstriction, vasodilation, and sweating to manage heat-balance. In this situation, if a peripheral thermal stimulus; through skin; is applied to counter the thermoregulatory load error, it is pleasantly perceived. “Cold thermal stimuli will be perceived as pleasant if the core temperature has increased above normal temperatures, whereas a warm thermal stimulus will be experienced as pleasant if the core temperature has decreased below normal temperatures.” (Parkinson & de Dear, 2015). Thermal alliesthesia is the phenomenon that explains this feeling of pleasure. The heat transfer process occurring in a human body in different thermoregulatory zones is diagrammed in Figure 4.1A. The potential of these thermoregulatory zones to elicit thermal pleasure as explained by temporal and spatial alliesthesia is diagrammed in Figure 4.1B.

According to the original concept of “whole-body thermal alliesthesia”, “thermal pleasure is driven by contrasts between core and skin temperatures of a human body” (Cabanac, 1971; de Dear, 2011). A human body needs to be in a slightly less comfortable (warm/cool) state to be able to experience pleasure due to a thermal stimulus that brings it towards comfort (Brager et al., 2015). “Temporal alliesthesia” is the term that is used to describe thermal pleasure experienced this way. It was recently explored through case studies of institutional and commercial buildings in China, Singapore, and the UK. In these studies, it was found that people's short-term transitions between slightly less and more comfortable thermal environments of indoor transition spaces such as atriums and lobbies significantly impacted their perception of thermal pleasure (Vargas et al., 2017; Zhang & Lau, 2017). Temperature differences in the range of 1-9 °C when people moved from either cold to hot with base case temperature range of 6-13 °C or hot to cold areas with base case temperature above 24 °C immediately satisfied their thermal preferences (Vargas et al., 2017). In another study, it was found that modulation of indoor set-point temperatures by ± 1.1 - 2.2 °C in three to five minutes within the base case range of 22-26 °C increased chances for a seated occupant's thermal pleasure in indoor environments (Traylor et al., 2019).

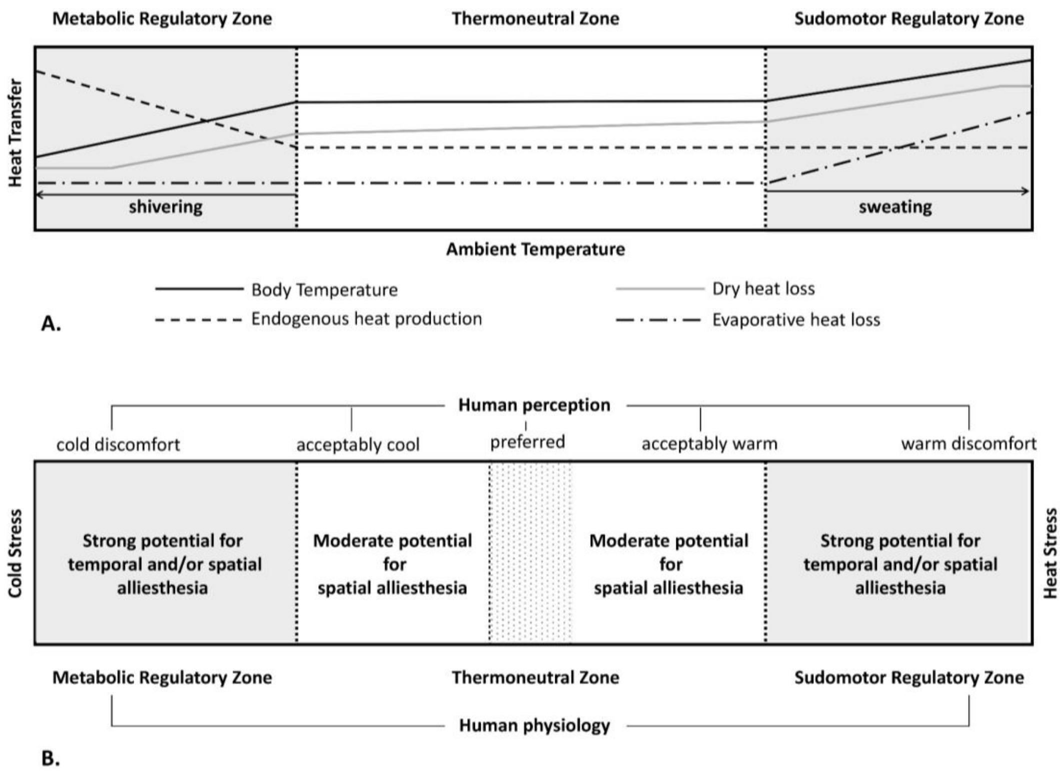


Figure 4.1 (A) Conceptual illustration of thermoregulatory heat transfer occurring in the human body at different ambient temperatures (B) conceptual understanding of human thermal perception corresponding to its respective thermoregulatory zone. Source: Modified after Parkinson and de Dear (2015) and Parkinson and de Dear (2016).

Thermal pleasure that is confined to a body-part and not for the whole-body is referred to as "spatial alliesthesia". The peripheral thermal sensation that is driven by cutaneous thermoreceptors in the skin (different from thermoregulatory load error in the temporal model) impacts the perception of thermal pleasure in this case. Spatial alliesthesia conceptualizes that the pleasure, seemingly experienced by the human body, is derived due to “rapid changes in local skin temperatures, contrapuntal to global skin temperature.” (Parkinson & de Dear, 2015). As per spatial alliesthesia, it is possible to make a human body experience thermal pleasure through distal skin temperature changes within the thermoneutral zone (Parkinson et al., 2016). Personal comfort systems employing strategies like contact heating-cooling, radiant heating, and fan-forced ventilation were identified as generators of thermal pleasure in controlled ambient thermal conditions inside laboratory settings (Parkinson et al., 2016; Parkinson & de Dear,2016; Parkinson & de Dear, 2017).

The hypothesis of temporal alliesthesia is appropriate for understanding occupant thermal pleasure in transition spaces such as lobbies, atriums, and vestibules (Parkinson & de Dear, 2015; Brager et al., 2015) where both the occupant and the ambient environment are in non-steady states, such as, the occupant is in motion with respect to free-flowing thermal conditions. The hypothesis of spatial alliesthesia applies to understanding and designing for thermal pleasure in situations where occupants are in sedentary positions. Targeting spatial alliesthesia by creating contrasts between distal and mean-skin temperatures is a feasible method to design for occupant thermal pleasure in everyday work environments. As a result, personal comfort systems (PCS) such as foot warmers, heated and cooled chairs have been extensively researched for their potential to evoke thermal pleasure (Pasut et al., 2015; Zhang et al., 2010 a; Zhang et al., 2010 b). However, such systems are more suitable for building core zones within which the indoor thermal environments are tightly controlled compared to perimeter zones that are typically within a 4.5 m distance from the building facades.

In optimizing building façade designs to maintain adequate daylighting, visual comfort, and outdoor views in the perimeter zones, the thermal conditions within them remain non-uniform (Zelenay et al., 2011; Attia et al., 2018; Elzeyadi & Gatland, 2019). Buildings with perimeter offices, comprising of occupants who are in steady state within non-uniform ambient thermal conditions, offer unique design opportunities to explore spatial alliesthesia. Different types of existing thermal non-uniformities in building perimeter spaces can be controlled to provide for thermal pleasure.

4.1.2. Regulated thermal conditions in buildings

ASHRAE Standard-55 (2017) defines indoor thermal conditions to provide for occupant's thermal comfort and satisfaction in air-conditioned and mixed-mode buildings. As per the standard, thermal comfort is affected by two human-related and four physical parameters including metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity, and relative humidity (RH). Thermal comfort in air-conditioned buildings requires "cool, dry, and still air", the parameters of which are regulated by the Predicted Mean Vote (PMV) model (Fanger, 1970; ASHRAE-55). The PMV index predicts an occupant's thermal sensation on a seven-point scale ranging from -3 (cold) to +3 (hot). A PMV value of zero represents thermal neutrality with (-0.5) to (+0.5) as recommended limits of the thermal comfort zone. Thermal conditions in mixed-mode buildings are regulated by the adaptive comfort model, which establishes a range of indoor operative temperatures as 'comfort zone' based on the outdoor thermal conditions (de Dear & Brager, 2002; ASHRAE-55). The boundaries of the adaptive comfort zone are in between physiological neutrality and hyperthermia (hypothermia) on the warm (cool) side, resulting in a relatively non-uniform thermal environment.

ASHRAE-55 also provides models to manage local discomfort due to thermal non-uniformities. Thermal non-uniformities in building perimeter spaces are characterized by "temperature ramps and cycles" and temperature asymmetries (Parkinson & de Dear, 2015). The regulations established by ASHRAE-55 predict that occupants in nearly steady-state would experience discomfort if the indoor operative temperatures remained outside the comfort zone for more than an hour. Moreover, it restricts the cyclical variations of operative temperatures to 2.2 °C/h to prevent discomfort. It is observed that if the ambient temperatures modulate within ± 2.2 °C/h around an occupant's perceived neutral temperature, it is likely that this change will not affect an occupant's "general thermal state" to generate a "spatial alliesthesia load error" (Parkinson & de Dear, 2015). The "dynamic sensitivity" of the human skin's thermoreceptors remains dormant at operative temperatures changing at such a slow rate. This may lead to an occupant's inability to distinguish any drastic changes in the skin temperatures that prompt their perception of thermal pleasure.

It would be useful to explore the impact of temperature asymmetries and “temperature ramps and cycles” in building perimeter spaces mediated by passive architectural external façade shading on occupant’s thermal pleasure. Outdoor environmental changes from events like solar transit can be be tapped through the shaded façade to create subtle and acceptable temperature asymmetries to provide for thermal pleasure. With technological advancement in the research and application of dynamic or movable façade shading (Luna-Navarro et al., 2020), the kinetic nature of the shade itself can be explored to create allowable temperature asymmetries and temperature ramps to target occupant pleasure and satisfaction.

Temperature asymmetries arise due to warm external walls/windows and cool internal walls or vertical and horizontal air temperature differences (ASHRAE-55). These asymmetries are caused due to the heat of direct solar radiation entering the building perimeter spaces. The following non-uniformities are predicted to cause occupant dissatisfaction and local discomfort in building perimeter spaces: (i) radiant temperature difference beyond 30 °C between a warm window and opposite cool wall (ii) air temperature difference more than 4 °C between head and feet, and (iii) floor temperatures outside the range of 18 - 28 °C. Parkinson and de Dear (2015) have discussed few examples of local discomfort management to evoke thermal pleasure and increase occupant satisfaction with the indoor environment. The skin temperature asymmetries leading to a cooler head and warmer feet could generate thermal pleasure. Occupants who are within the lower fringe of the thermoneutral zone may feel higher-discomforting floor temperatures to be pleasurable and vice-versa.

It would be useful to explore the impact of temperature asymmetries and “temperature ramps and cycles” in building perimeter spaces mediated by passive architectural external façade shading on occupant’s thermal pleasure. Outdoor environmental changes from events like solar transit can be be tapped through the shaded façade to create subtle and acceptable temperature asymmetries to provide for thermal pleasure. With technological advancement in the research and application of dynamic or movable façade shading (Luna-Navarro et al., 2020), the kinetic nature of the shade itself can be explored to create allowable temperature asymmetries and temperature ramps to target occupant pleasure and satisfaction.

4.1.3. Research aim

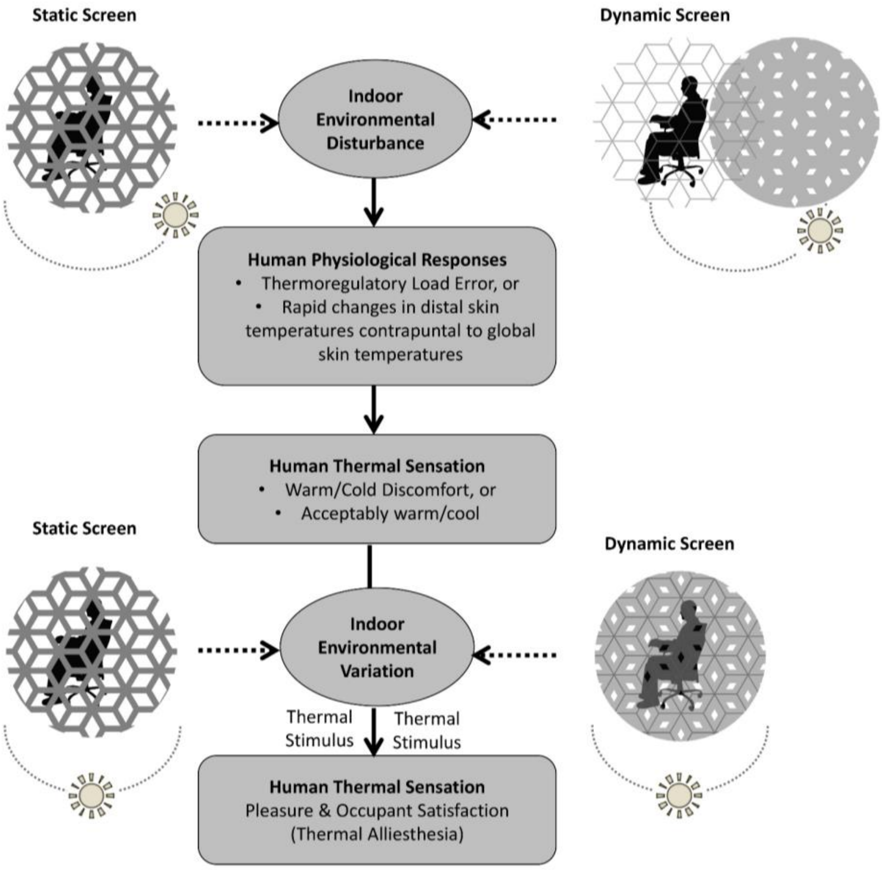


Figure 4.2 Conceptual framework explaining the functioning of static and dynamic screens that were designed to influence thermal pleasure.

Using exterior façade solar screen shading as a medium to control the indoor environment, the researchers of the present work aimed to explore thermal pleasure inside single-occupancy, perimeter office set-ups during warm summers of ASHRAE Climate Zone (CZ)-4C through an experimental study involving human participants. Passive solar shading is widely used on building facades in this climate zone. Through a climatic analysis that was performed to understand the impact of shading for different ASHRAE climate zones it was found that buildings in this climate zone had substantial cooling loads during summer and the average impact of solar shading on predicted thermal comfort was 13.75 % (Elzeyadi et al., 2016).

Solar screens with static and dynamic operations as illustrated in Figure 4.2, were used to achieve different thermal environments in the two, single-occupancy, perimeter office set-ups. The design intention behind the static solar screen was to optimize its geometric parameters to maintain thermal uniformity in the set-up for the summer months. For the static screened set-up, it was hypothesized that the non-uniformity created by naturally occurring outdoor environmental changes like; solar transit would mildly influence the perception of thermal pleasure. The design intention behind the dynamic solar screen was to use its movement and changes in its geometric parameters to create controlled thermal non-uniformity in the set-up. For the dynamic screened set-up, it was hypothesized that the indoor thermal non-uniformity created by the screen would substantially influence the perception of thermal pleasure.

The objectives of this work included the following: (i) to investigate the impact of passive architectural elements such as static and dynamic screens on the indoor thermal environment and human physiological variables inside the respective set-ups (ii) to understand and quantify the relationships of subjective thermal pleasure with human physiological variables and the thermal environment inside the static and dynamic screened set-ups.

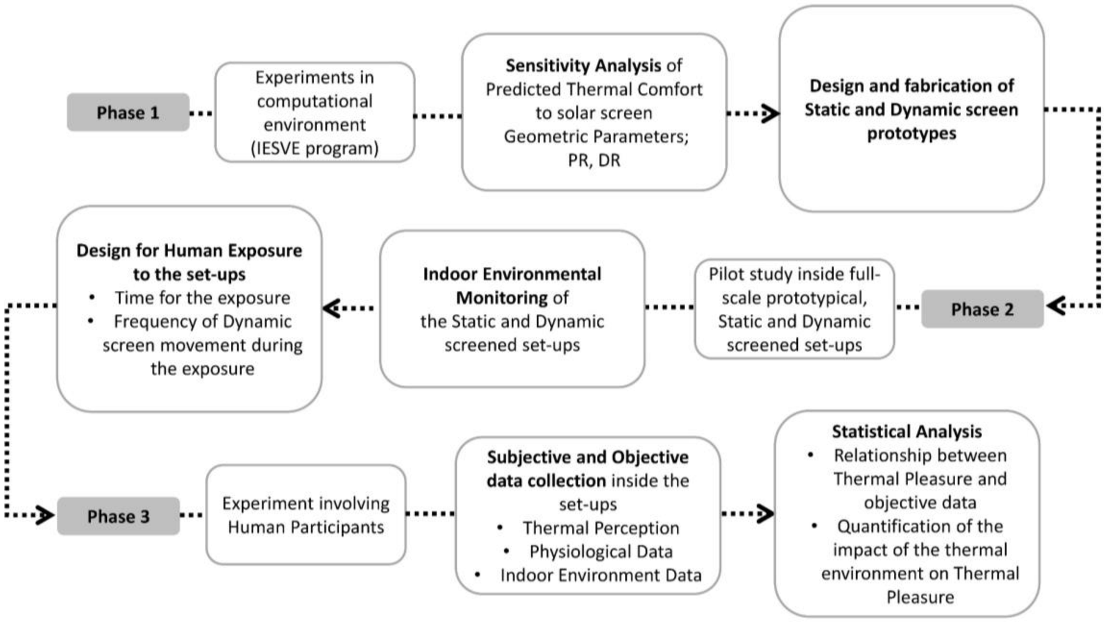


Figure 4.3 Overarching workflow of the research method.

4.2. Methods

A three-phased investigation, illustrated in Figure 4.3, was used to explore thermal pleasure inside solar screen shaded, single-occupancy office set-ups. Results from each phase were used to inform the design of its successive phase. Phase 1 involved the design and fabrication of static and dynamic screen prototypes. Subsequently, the indoor environments of the static and dynamic screened set-ups were monitored in phase 2 to inform the design of experiments involving human participants in phase 3.

4.2.1. Phase 1: Design and fabrication of screen prototypes

First, a sensitivity analysis of predicted thermal comfort to solar screen geometric parameters including perforation ratio (PR=% of perforation) and depth ratio (DR = perforation depth/perforation width) was performed in the IESVE computation environment (Naik & Elzeyadi, 2020b) to inform the design of static and dynamic screen prototypes. Screens with different combinations of PR and DR were simulated to assess their predicted thermal comfort performance during mid-summer mornings inside an east-facing perimeter space of a typical mid-sized office building in Eugene, OR (ASHRAE CZ-4C). For the static screen prototype, the intent was to optimize its design for thermal comfort during the summer months. The solar screen with (PR, DR) = (50%, 0.1), was predicted to attain PMV values close to “0” throughout a typical summer day in Eugene. Using a static screen prototype with (PR, DR) = (50%, 0.1), it was conceptualized that while it would provide a sensation of thermal neutrality (PMV close to 0), the indoor temperature variations and temperature asymmetry created by solar transit would evoke subjective thermal pleasure (Figure 4.2).

Using the dynamic screen prototype, the intent was to create thermal conditions that would transit within and between the upper and lower fringes of the thermal comfort zone. During early morning to noon hours, screens with (PR, DR) = (90%, 0.1) were predicted to provide a slightly warm thermal sensation with PMV as high as 0.6 whereas screens with (PR, DR) = (10%, 0.1) were predicted to provide slightly cool sensation with PMV as low as -0.4. Thus, the design of a dynamic screen required interchangeability between screen geometric parameters in creating an indoor thermal environment that transited between slightly warm and slightly cool conditions. Using a dynamic screen prototype that was designed to swap between geometric parameters, (PR, DR) = (90%, 0.1) and (PR, DR) = (10%, 0.1), it was conceptualized that while the indoor condition would be within thermal neutrality limits ($-1 \leq PMV \leq 1$), the screen movement would create controlled temperature asymmetry and cyclical variations to evoke subjective thermal pleasure (Figure 4.2).

4.2.1.1. Fabrication of static and dynamic screen prototypes

The static and dynamic screen prototypes were two-dimensional (X-Y) planar elements fabricated from a 50.8 mm thick composite foam core board (Figure 4.4). This material was selected because of its high strength and light weight, which would prevent buckling when used as a stand-alone 1.52 m (wide) x 2.43 m (high) solar-screen panel. The selection of screen patterns was based on recommendations from a previous study that found that rhombus-shaped perforations were more successful in maintaining optimum daylighting for office tasks compared to other typical perforation geometries tested (Oghazian et al., 2017). The static screen prototype (Figure 4.4 A-a) was a fixed screen panel with perforation ratio and depth ratio set as (PR, DR) = (50%, 0.1). The dynamic screen prototype (Figure 4.4 A-b, Figure 4.4 A-c) was composed of two sliding panels that could alternatively overlap. The position in which the panels were not overlapping was named OPEN that is when the screen with (PR, DR) = (90%, 0.1) shaded the window. The CLOSED position was when the screen with (PR, DR) = (10%, 0.1) overlapped the screen with (PR, DR) = (90%, 0.1) through the sliding mechanism.

4.2.2. Phase 2: Pilot study

Indoor thermal environmental monitoring of the east-facing static and dynamic screened experimental set-ups was conducted during the early morning to noon hours under sunny sky conditions to inform time-interval and design of the final experiment involving human participation. Another objective of the pilot study was to decide on the movement frequency of the dynamic screen that was designed as sliding panels for the human subject exposure to elicit desired thermal non-uniformity within the set-up. Three types of dynamic screen movement frequencies were tested; the details of which are reported in a previous article (Naik & Elzeyadi, 2020c). The solar screen prototypes and experimental set-ups used for phases 2 and 3 were the same (Figure 4.4).

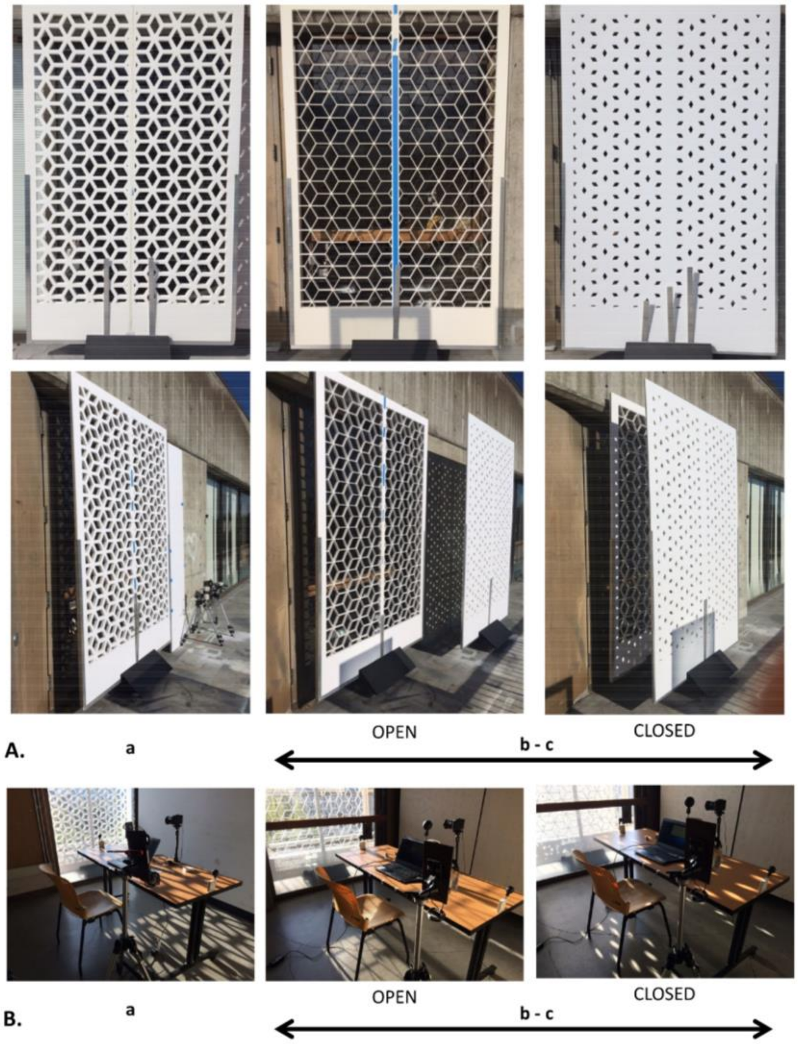


Figure 4.4 (A) External view of static and dynamic shading prototypes. Condition (a) represents the static screen with (PR, DR) = (50 %, 0.1) and condition (b-c) represents the dynamic screen prototype that transitions between OPEN and CLOSED positions created by panels with (PR, DR) = (90%, 0.1) and (PR, DR) = (10 %, 0.1). (B) Interior view of the static and dynamic screened set-ups.

4.2.3. Static and dynamic screened experimental set-ups

The 3 m x 3 m experimental set-ups were arranged as single-occupancy office spaces in an east-facing open-plan building (Figure 4.4 B). The set-ups were isolated by 2.13 m high room dividers. Each one had a 1.52 m x 2.43 m, clear-glass, single-pane, fixed window (Tvis = 0.80, SHGC= 0.80) on its east-facing wall. The static and dynamic screen prototypes were installed at a distance closest to the external surface of the window. Each set-up had a south-facing work-desk, personal computer arrangement, and equipment to measure the thermal and visual physical environmental parameters (Figure 4.4B, Figure 4.5). Pre-programmed data-loggers (HOBO U-12, accuracy:

Temperature ±0.2 °C for range 0 to 50 °C, RH ±2.5% for range 10 to 90%) were placed at three stratified levels, horizontally and vertically to measure dry-bulb temperatures, RH, and globe temperatures. The vertical placement of data loggers at three levels (that is at 0.1, 0.6, and 1.1 m) of vertical distance was based on ASHRAE-55 recommendations for the determination of thermal comfort for seated occupants. Globe temperature sensors were placed at six locations between 0.6 – 1.1 m levels, as shown in Figure 4.5. They were fabricated and approved previously by a scientific committee for use in similar studies (Abboushi, 2018). Hot wire-anemometer (Testo 405i, accuracy: ±0.05 m/s for range 0 to 2 m/s) was mounted at a seated subject's head-height on a tripod placed in the center of the set-up. Data loggers to measure horizontal and vertical illuminance were placed in the center of the work-plane and on a tripod at 1.1 m height, facing the window, respectively.

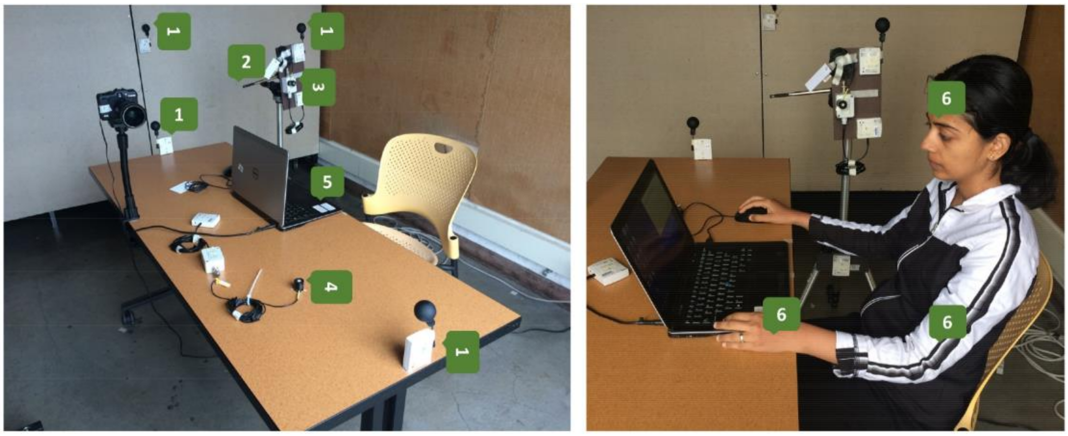


Figure 4.5 Data loggers for recording (1) air temperature, relative humidity, and globe temperature, (2) airspeed, (3) vertical illuminance, (4) horizontal illuminance, (5) subjective responses, (6) participant's skin temperatures.

4.2.4. Design of the indoor thermal environment for human exposure to the experimental set-ups

Pilot monitoring suggested that 8:00 to 11:00 AM was the time when thermal conditions, close to those intended, were achieved in both the set-ups. The changes in dynamic screen positions led to a drop or rise in the indoor operative temperature by 1.7-2.8 °C within five minutes of the screen's position change. Hence, the dynamic screen's movement was finalized to change between OPEN and CLOSED positions in 10-20-10 minutes intervals (Figure 4.6) for the phase 3 of the study. With this frequency, it was possible to keep the indoor environment comfortable for most of the time besides creating short instances (10 minutes) of a slightly warm environment when in an OPEN position. Next, radiant temperature asymmetry was observed in both the static and dynamic set-ups. However, the mean radiant temperature differences between the warm and cool walls remained below 8.3 °C, which was lower than the limit that predicts dissatisfaction due to local thermal discomfort.

4.2.5. Phase 3: Experiment involving human participants

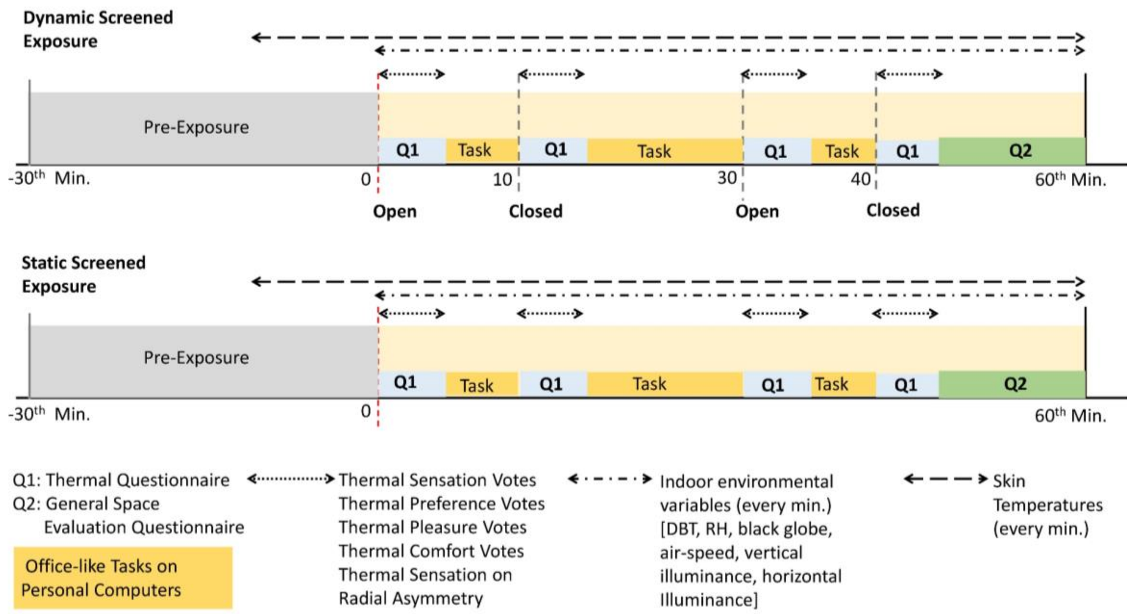


Figure 4.6 Diagram of a participant's involvement and indoor environmental data collection during the exposure to static and dynamic screened conditions.

A 2x2 factorial, within-subject, experimental design was used to investigate the impact of static and dynamic screens on subjective thermal perception. The period between 8:00 AM and 10.30 AM during the months of August and September in Eugene, Oregon was chosen for the experiment. There were 27 human participants including 15 females and 12 males within the age group of 22-50. Healthy research participants without any background of cardiovascular, eye, or skin disease were recruited on the following conditions: (i) they had full or part-time involvement in doing clerical jobs in air-conditioned office environments; (ii) they were confident of responding to questionnaires in English, and (iii) they could work through computer-based tasks. Participation was voluntary and was compensated for after completion of the study runs. Moreover, they were made aware of their liberty to stop participation if they had any major discomfort or for any other reasons.

The within-subjects experimental design ensured that each of the 27 research participants was exposed to both static and dynamic screened set-ups for one-hour inside each. The total participation time for each set-up was 1.5 hours (Figure 4.6), which required every person to arrive thirty minutes before the one-hour screened exposure. In the initial thirty minutes of pre-exposure, they were required to occupy a thermally uniform air-conditioned space. Next, skin temperature sensors were given, which they were required to tape at locations highlighted in a provided instructional diagram. Further, they were familiarized with the type of subjective questionnaires and tasks that they were to respond to during their screened exposure.

During the static screened exposure, the participants occupied the set-up, which was shaded by the fixed solar screen with (PR, DR) = (50%, 0.1) (Figure 4A-a, Figure 4.6). While, during the dynamic screened exposure, the participants were exposed to an environment shaded by movable solar screens, that transitioned between the OPEN and CLOSED positions in 10-20-10 minutes intervals (Figure 4A-b, Figure 4A-c, Figure 4.6). The OPEN position was when the window was shaded with a light screen having (PR, DR) = (90%, 0.1) and CLOSED position was when the denser screen panel with (PR, DR) = (10%, 0.1) overlapped the OPEN position. The single-occupancy seating was oriented in such a manner that the participant’s left-hand side faced the screened window (Figure 4B, Figure 4.5). During their one-hour screened exposure, participants responded to questionnaires and performed office-like tasks on the computers provided on their workstation (Figure 4.5, Figure 4.6). Information on the types and frequency of indoor physical environmental data collected corresponding to a participant’s exposure inside the two set-ups is provided in Figure 4.6.

4.3. Data collection and metric calculations

The participants were asked to take a one-hour survey that was timed to proceed without the investigator’s intervention and their responses were recorded in an on-line secured survey portal (Qualtrics®). The survey consisted of a thermal questionnaire (Q1), a general indoor environmental questionnaire (Q2), and performance tasks involving math, typing, and sudoku (Figure 4.6). The survey Q1 asked participants to rate their thermal perception on pleasure, sensation, comfort, preference, and local body sensation on a five-point Likert scale (Figure 4.7A). Categorial versions of all the scales were used to record participant responses. Five-minutes of Q1 appeared at the 1st, 10th, 30th, and 40th minute during a typical one-hour exposure (Figure 4.6). During those five minutes of Q1, the question on thermal pleasure was asked thrice: at the first, the third, and the fifth minute (Figure 4.7A).

4.3.1. *Participant's subjective responses*

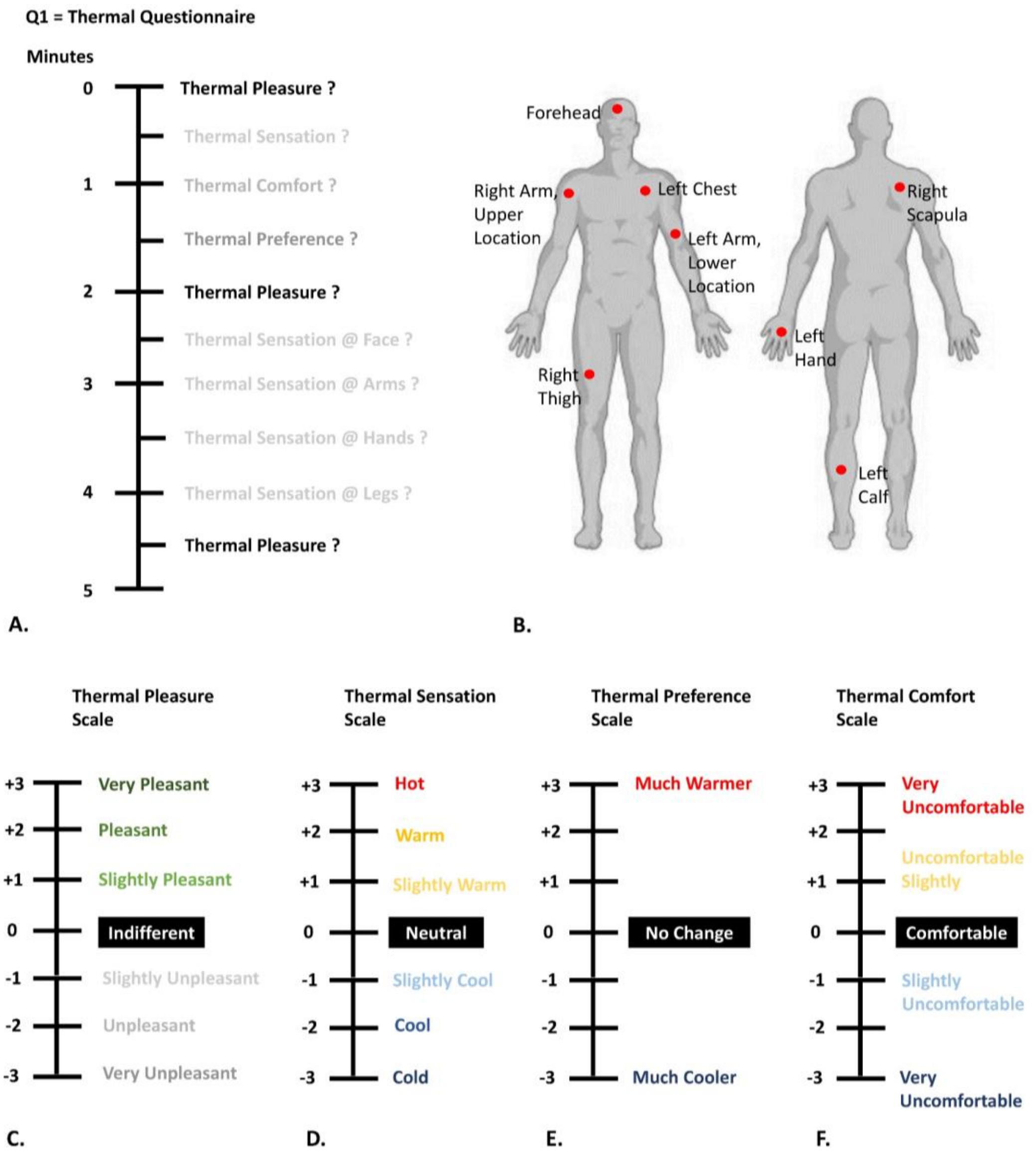


Figure 4.7 (A) Typical 5-minute questionnaire Q1 that appeared at the 1st, 10th, 30th, and 40th minutes during both types of screened exposures. (B) The eight locations from which the skin temperatures were collected from each participant's body. (C) The Likert scale for collection of thermal pleasure responses. (D), (E), and (F) The Likert scales for collection of thermal sensation, preference, and comfort responses.

All the performance tasks were of medium level difficulty following the approach of previous experiments that investigated human thermal perception and performance (Zhang et al., 2010 c). Further, the 15-minute Q2 was administered at the 50th minute. It consisted of questions from the indoor environmental quality evaluation questionnaire developed by the researchers at the Centre for Building Performance and Diagnostics at Carnegie Mellon University (Park et al., 2018). The scope of this paper is limited to the analysis of subjective reporting on thermal pleasure from the Q1 questionnaire only. The analysis of results from performance tasks and the Q2 questionnaire is not included in this work and is subject to future analysis.

4.3.2. Participant's physiological responses and indoor environmental data

Beginning from the pre-exposure phase, each participant's local skin temperatures were collected at 1-minute intervals from eight locations on the body (Figure 4.7B) as per ISO 9886 (2004) recommendations. Pre-programmable, waterproof, wire-less, i-Button sensors (Maxim Integrated, DS1921H-F5#, Accuracy ± 1°C, Range 0 °C to 45°C), which are specifically designed and recommended for human dermal temperature measurements, were used for this study. Similar equipment was used to record skin temperatures in previous studies (Parkinson et al., 2016; Parkinson & de Dear, 2016).

The indoor environmental data including, the dry bulb temperatures, relative humidity, globe temperatures, air velocity, and vertical and horizontal illuminance of the indoor environment for both set-ups were recorded every minute during the one-hour of screened exposures. Outdoor thermal and visual environmental data were recorded simultaneously.

4.3.3. Metrics and quantification of the measured parameters

Measured indoor thermal parameters were used to compute PMV values and operative temperatures at every minute of a participant's screened exposure. Fanger's PMV model (1970) built-in as a function in R software package 'comf' was used to calculate the PMV values (Schweiker, 2016). The mean radiant temperatures (MRTs) computed from the globe temperatures using Equation (1) (ISO.7726, 1998) measured at four locations in the set-up were averaged and used as inputs for PMV calculation.

$$t_{mr} = [(GT + 273)^4 + \{(1.1 \times 10^8 \times Va^{0.6} / \varepsilon \times D^{0.4}) \times (GT - Ta)]^{1/4} - 273 \quad (1)$$

where

t_{mr} = Mean Radiant Temperature (°C),

GT = Globe Temperature (°C),

Va = Air velocity at the level of the globe (m/s),

ε = the emissivity of the globe (0.95),

D = diameter of the globe (D = 0.15 m),

Ta = Air Temperature (°C).

Air temperature, RH, and air velocity collected at 1.1 m height were used for PMV calculation. Participants were pre-informed to wear light semi-formal clothing suited for summer. Their self-provided clothing information before the experimental exposure was used to calculate *clo* values. Participants' metabolic rate was assumed to be constant (1.2 met) as they were required to maintain sedentary physical activity during their screened exposures. The operative temperatures were calculated using Equation (2) as per ASHRAE-55 recommendations.

$$T_o = (t_a + t_{mr}) / 2 \quad (2)$$

where

T_o = Operative Temperature

t_a = Air Temperature

t_{mr} = Mean Radiant Temperature

Participant's mean skin temperatures were calculated using Equation (3), which incorporates weighing factors for each of eight distal locations (8-point weighing) as per ISO 9886 (2004) recommendations.

$$T_{sk} = 0.07 (T_{sk\_f}) + 0.175 (T_{sk\_rs}) + 0.175 (T_{sk\_lch}) + 0.07 (T_{sk\_ra}) + 0.07 (T_{sk\_la}) + 0.05 (T_{sk\_lh}) + 0.19 (T_{sk\_rt}) + 0.2 (T_{sk\_lc}) \quad (3)$$

where

T_{sk} = Mean skin temperature

T_{sk_f} = Skin Temperature at forehead

T_{sk_rs} = Skin Temperature at right scapula

T_{sk_lch} = Skin Temperature at left upper chest

T_{sk_ra} = Skin Temperature at right upper arm in upper location

T_{sk_la} = Skin Temperature at left upper arm in lower location

T_{sk_lh} = Skin Temperature at left hand

T_{sk_rt} = Skin Temperature at right anterior thigh

T_{sk_lc} = Skin Temperature at left calf

4.4. Results

The experiments were planned for sunny sky conditions of summer months and were carried out in August-September of a typical summer season in ASHRAE CZ-4C. Uncertainties in the outdoor climate during September led to the experimental exposures of 12 participants; out of 27; under overcast sky conditions. Each participant's attendance was appropriately scheduled based on the weather forecast to ensure similar sky conditions during his or her exposure to both static and dynamic screened set-ups; thus, confirming the with-in subject experimental design approach. First, the data corresponding to sunny and overcast conditions was analysed collectively for 27 participants: irrespective of the sky conditions. Thereafter, a separate analysis for the sunny and overcast conditions is presented. Statistical tests such as correlations, simple linear, and multiple regression were conducted to analyse the data. As highlighted in Tables 1 and 3, the following indoor thermal variables were investigated: PMV, ΔPMV (the change in PMV value from that of the previous minute's), operative temperature (OT), ΔOT (the change in OT from that of the previous minute's). The participants' physiological parameters analysed included the following: mean skin temperature (Tsk), ΔTsk_{HZ} (difference between left hand and right arm skin temperatures), and ΔTsk_{VT} (difference between head and left calf skin temperatures). Parameters, such as ΔTsk_{HZ} and ΔTsk_{VT} were used to investigate the temperature differences at the horizontal and vertical axis of a participant's body.

4.4.1. Linear relationships between subjective responses and thermal environment

Strong and significant linear relationships were found between thermal pleasure responses and thermal environmental variables including PMV, ΔPMV, OT, ΔOT, and ΔTsk_{HZ}. These relationships found from the initial analysis of the collective data (from sunny and overcast sky conditions) have been summarized and significant ones from those are highlighted in Table 4.1. For the dynamic condition, the strongest and most significant relationship of thermal pleasure was found to be with the thermal non-uniformity indicated by ΔPMV ($p \leq 0.001$) and ΔOT ($p \leq 0.001$). The mean skin temperature, Tsk ($p \leq 0.1$) also had some significance in influencing thermal pleasure inside this thermally non-uniform environmental setting created by the dynamic screen. Strong and significant linear relationships of thermal pleasure with PMV ($p \leq 0.05$) and OT ($p \leq 0.05$) were found inside the thermally uniform environment created by the static screen. Moreover, the variable ΔTsk_{HZ} ($p \leq 0.05$), suggesting the temperature difference along a human body's horizontal axis, had a strong impact on thermal pleasure perception in this case.

The variables having a significant impact on thermal pleasure were further evaluated for their combined impact using a general linear model. The significance of the null hypothesis was tested against the following alternative hypothesis: while controlling for all other variables in the model, thermal pleasure is linearly related to the independent variables being considered. Results from the analysis are presented in Table 4.2. Inside the thermally non-uniform condition created by the dynamic screen thermal pleasure was significantly impacted by a linear combination of PMV, ΔOT, and Tsk. Nearly 81% of the variability in thermal pleasure was found to be due to the changes in the three independent parameters while controlling for others. Inside the thermally uniform condition created by the static screen, thermal pleasure was significantly impacted by the linear combination of PMV and ΔTsk_{HZ}. Nearly 33% of the variability in thermal pleasure was explained by these two independent parameters while controlling for the others.

Table 4.1 Results from simple linear regression analysis exploring relationship between TP (Thermal Pleasure) and indoor environmental (PMV, ΔPMV, operative temperature (OT), and ΔOT), and participant's physiological variables (Tsk (mean skin temperature), ΔTsk_{HZ} (difference between left hand and right arm skin temperatures), and ΔTsk_{VT} (difference between head and calf skin temperatures). Significance codes: '***'≤ 0.001, '**'≤ 0.01, '*'≤ 0.05, '.' ≤ 0.1.

Relationship	Dynamic condition				Static condition			
	r-value	**p-value**	**r^2 value**	**Equation**	**r-value**	**p-value**	**r^2 value**	**Equation**
TP (y) vs. PMV (x)	**0.49**	**0.02 ***	**0.24**	**y = -0.7328x + 1.4503**	**0.6**	**0.00 ** **	**0.36**	**y = 0.6218x + 0.131**
TP (y) vs. ΔPMV (x)	**0.7**	**0.00 *****	**0.49**	**y = -6.4366x + 0.6314**	0.12	0.54	0.01	y = -5.0456x + 0.522
TP (y) vs. OT (x)	**0.46**	**0.02 ***	**0.21**	**y = -0.1009x + 9.2839**	**0.58**	**0.00 ** **	**0.33**	**y = 0.0747x - 5.677**
TP (y) vs. ΔOT (x)	**0.7**	**0.00 *****	**0.49**	**y = -1.1648x + 0.6353**	0.21	0.32	0.04	y = 1.3608x + 0.4668
TP (y) vs. Tsk(mean) (x)	**0.32**	**0.1.**	**0.1**	**y = 0.2968x - 25.71**	0.05	0.82	0	y = -0.0245x + 2.6845
TP (y) vs. ΔTsk_{HZ} (x)	0.04	0.84	0	y = 0.0239x + 0.6564	**0.48**	**0.02 ***	**0.23**	**y = 0.1527x + 0.5708**
TP (y) vs. ΔTsk_{VT} (x)	0.29	0.17	0.09	y = 0.4714x - 0.0763	0.27	0.2	0.07	y = -0.1895x + 0.9106

Table 4.2 Multiple regression analysis exploring the combined impact of indoor thermal environmental and participant's physiological variables on thermal pleasure perception inside thermally uniform and non-uniform conditions created by static and dynamic screens.

	Relationship	Equation	Multiple r^2	Adjusted r^2	p-value
Dynamic condition	y vs. (x_1, x_2, x_3) y = TP, x_1 = PMV, x_2 = Tsk (mean), x_3 = ΔOT	$y = -8.49 - 0.89\ x_1 + 0.11\ x_2 - 1.23\ x_3$	0.833	0.808	0.000000057
Static condition	y vs. (x_1, x_2) y = TP, x_1 = PMV, x_2 = ΔTsk_{HZ}	$y = -0.15 + 1.00\ x_1 - 0.13\ x_2$	0.3842	0.3256	0.006149

4.4.2. Independent analysis of data from sunny and overcast sky conditions

For this analysis, the data was classified into two groups, one corresponding to sunny sky condition with sample size, N = 15, and the other corresponding to overcast condition with N = 12. Subsequently, this data was investigated for the uniform and non-uniform thermal conditions created by static and dynamic screens.

4.4.2.1. Observational relationship of thermal pleasure with PMV

The averaged thermal pleasure responses of participants and the PMV trend were plotted for their one-hour exposure time inside the static and dynamic screened set-ups under sunny and overcast sky conditions (Figure 4.8). Inside the thermally uniform environment created by the static screen under the overcast sky conditions, the magnitude of thermal pleasure reported was low throughout the exposure (Figure 4.8D). The PMV values and the operative temperatures inside this condition were within a narrow range from -0.2 to 0.1 and 26.6 to 27.2 °C, respectively. Inside the thermally non-uniform environments within neutrality limits created by the static screen under sunny sky conditions and that of the dynamic screen under overcast sky conditions, the reported magnitude of thermal pleasure was high throughout the exposure (Figure 4.8B, Figure 4.8C). The PMV value in these conditions varied within an upper fringe (0.7 ≤ PMV ≤ 1) of the thermal neutrality limit (-1 ≤ PMV ≤ +1). The corresponding operative temperatures varied within the range of 27.7 to 29.4 °C and remained within the limits of the adaptive comfort zone for summer (22.23-29.4 °C, ASHRAE CZ-4C).

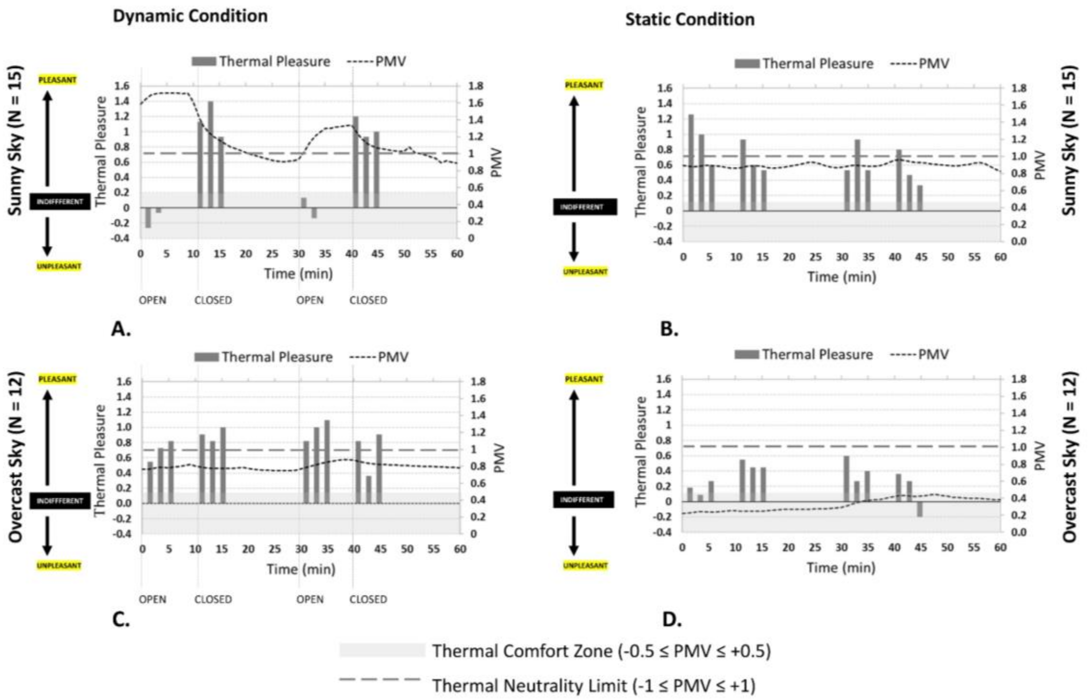


Figure 4.8 Averaged thermal pleasure responses and PMV values during 1-hour exposure inside the thermally uniform and non-uniform conditions created by static and dynamic screens, for N=15 and N=12 people under sunny and overcast sky conditions, respectively.

Inside the thermally non-uniform environment created by the dynamic screen under sunny sky conditions, the very high and very low magnitude of thermal pleasure was reported at different instances during the exposure (Figure 4.8A). The PMV value was outside the upper limit of the thermal neutrality zone when the dynamic screen was in the OPEN position. A very low magnitude of thermal pleasure was reported during this time (Figure 4.8A). However, the moment the screen was CLOSED, the PMV value started transitioning towards the thermal neutrality limit and further decreased as more time was spent in the same position. The operative temperature through this one-hour exposure remained around the upper fringes of the adaptive comfort zone for summer. The maximum operative temperature remained around 31.1 °C when the screen was in the OPEN position. The transition of the screen from OPEN to CLOSE position reduced the operative temperature by 1.7-2.8 °C and influenced the highest magnitude of thermal pleasure perception within five minutes of the screen's closing (Figure 4.8A).

4.4.2.2. Observational relationship of thermal pleasure with skin temperatures

The averaged thermal pleasure responses of the participants and their mean and the distal skin temperature trends were plotted for the thermally uniform and non-uniform environments of the solar screened set-ups in sunny and over-cast sky conditions (Figure 4.9).

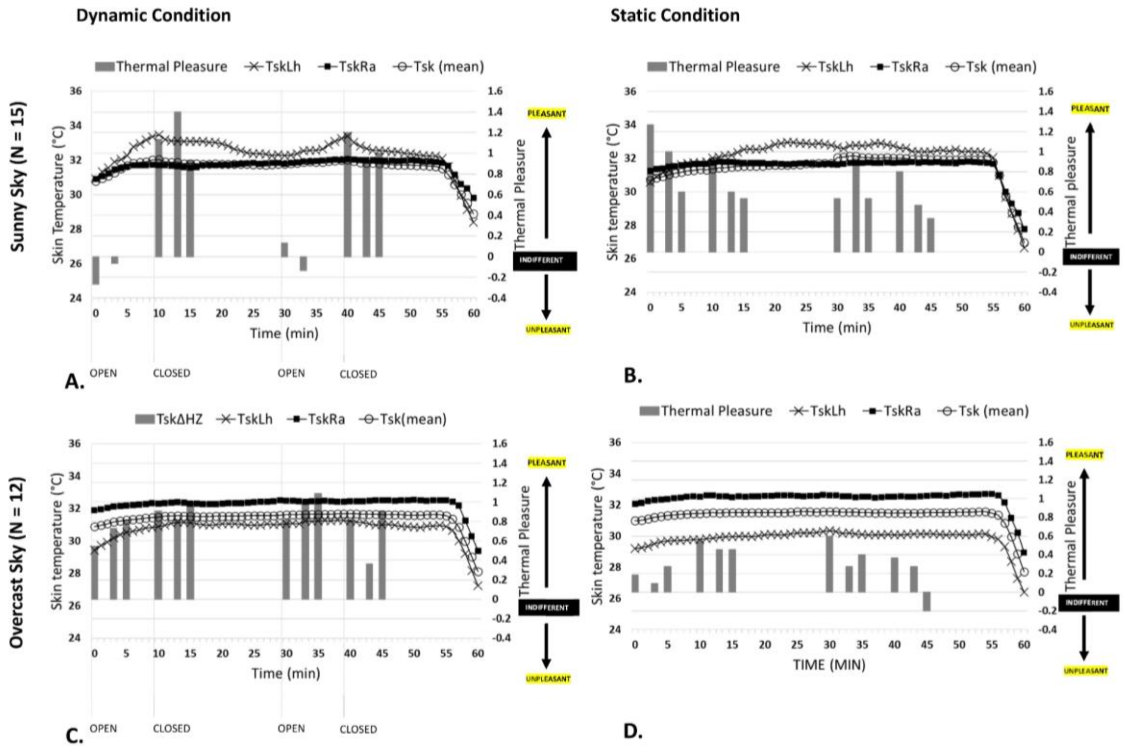


Figure 4.9 Averaged mean (Tskmean), left-hand (TskLh), and right-arm (TskRa) skin temperature responses plotted every minute for the 1-hour exposure of N=15 and N=12 people to thermally uniform and non-uniform conditions created by static and dynamic screens under sunny and overcast sky conditions.

The mean and right arm skin temperature trends were constant and consistent in the thermally uniform as well as non-uniform conditions of the screened set-ups. Under sunny sky conditions, the left-hand temperatures were found to be higher than the mean and right arm skin temperatures suggesting that the screened window side was warmer (Figure 4.9A, Figure 4.9B). A visual relationship can be observed between left-hand skin-temperature trend and subjective thermal pleasure inside the thermally non-uniform condition of the set-up shaded by the dynamic screen under sunny sky conditions (Figure 4.9A). Under overcast sky conditions, the left-hand skin temperatures were found to be lower than mean and right-arm skin temperatures indicating that the screened window side was cooler. Inside the thermally uniform environment created by the static screen, 3 to 4°C difference between left-hand and right-arm skin temperature prevailed steadily throughout the exposure (Figure 4.9D). This was the condition in which lowest rating on thermal pleasure was reported.

Table 4.3 Relationship of subjective thermal pleasure (TP) with physical environmental (PMV, ΔPMV, operative temperature (OT), and ΔOT) and physiological variables (Tsk (mean skin temperature), ΔTsk_{HZ} (difference between left hand and right arm skin temperatures), and ΔTsk_{VT} (difference between head and calf skin temperatures)); for the thermally uniform and non-uniform environments created by static and dynamic screens under sunny and overcast sky conditions. Significance codes: '***'≤ 0.001, '**' ≤ 0.01, '*'≤ 0.05, '.' ≤ 0.1.

Relationship	**Dynamic set-up**				**Static set-up**			
	Sunny sky condition (N=15)				**Sunny sky condition (N=15)**			
	r-value	p-value	r^2 value	Equation	r-value	p-value	r^2 value	Equation
TP (y) vs. PMV (x)	0.46	0.14	0.21	y = -1.1435x + 2.0363	0.30	0.32	0.09	y = -2.9618x + 3.3725
TP (y) vs. ΔPMV (x)	**0.86**	**0.0*** **	**0.74**	**y = -7.2652x + 0.4284**	0.02	0.93	0.0006	y = 0.8811x + 0.7087
TP (y) vs. OT (x)	0.46	0.12	0.22	y = -0.2168x + 19.443	**0.61**	**0.03***	**0.37**	**y = -0.4256x + 36.934**
TP (y) vs. ΔOT (x)	**0.86**	**0.0*** **	**0.73**	**y = -1.3236x + 0.4294**	0.50	0.92	0.257	y = 2.792x + 0.6254
TP (y) vs. Tsk(mean) (x)	**0.58**	**0.05***	**0.34**	**y = 0.1914x - 16.155**	**0.5**	**0.05***	**0.32**	**y = -0.1949x + 18.045**
TP (y) vs. ΔTsk_{HZ} (x)	**0.81**	**0.0*** **	**0.67**	**y = 1.1018x - 0.9204**	**0.61**	**0.03***	**0.38**	**y = -0.3106x + 0.8665**
TP vs. ΔTsk_{VT} (x)	0.22	0.47	0.05	y = 0.7538x - 0.5763	**0.60**	**0.03***	**0.36**	**y = -0.2948x + 1.3453**
	Overcast sky condition (N=12)				**Overcast sky condition (N=12)**			
TP (y) vs. PMV (x)	0.13	0.67	0.01	y = 0.8967x + 0.0963	0.28	0.37	0.08	y = -0.7516x + 0.5443
TP (y) vs. ΔPMV (x)	0.31	0.32	0.09	y = 5.4347x + 0.8135	0.11	0.71	0.01	y = 3.1003x + 0.2924
TP (y) vs. OT (x)	0.09	0.77	0.008	y = 0.0738x - 5.3342	0.28	0.36	0.08	y = -0.1221x + 10.129
TP (y) vs. ΔOT (x)	0.16	0.60	0.027	y = 0.4558x + 0.8135	0.027	0.93	0.0007	y = 0.1166x + 0.304
TP (y) vs. Tsk(mean) (x)	**0.78**	**0.0*** **	**0.61**	**y = 0.6839x - 60.402**	0.37	0.23	0.13	y = 0.2818x - 24.652
TP (y) vs. ΔTsk_{HZ} (x)	**0.54**	**0.06.**	**0.30**	**y = 0.3461x + 0.8711**	**0.54**	**0.06.**	**0.30**	**y = 1x + 1.6111**
TP vs. ΔTsk_{VT} (x)	0.28	0.36	0.08	y = 0.171x + 0.5258	0.045	0.88	0.002	y = -0.0312x + 0.3739

4.4.2.3. Linear relationships of thermal pleasure with indoor environmental and participants' physiological variable

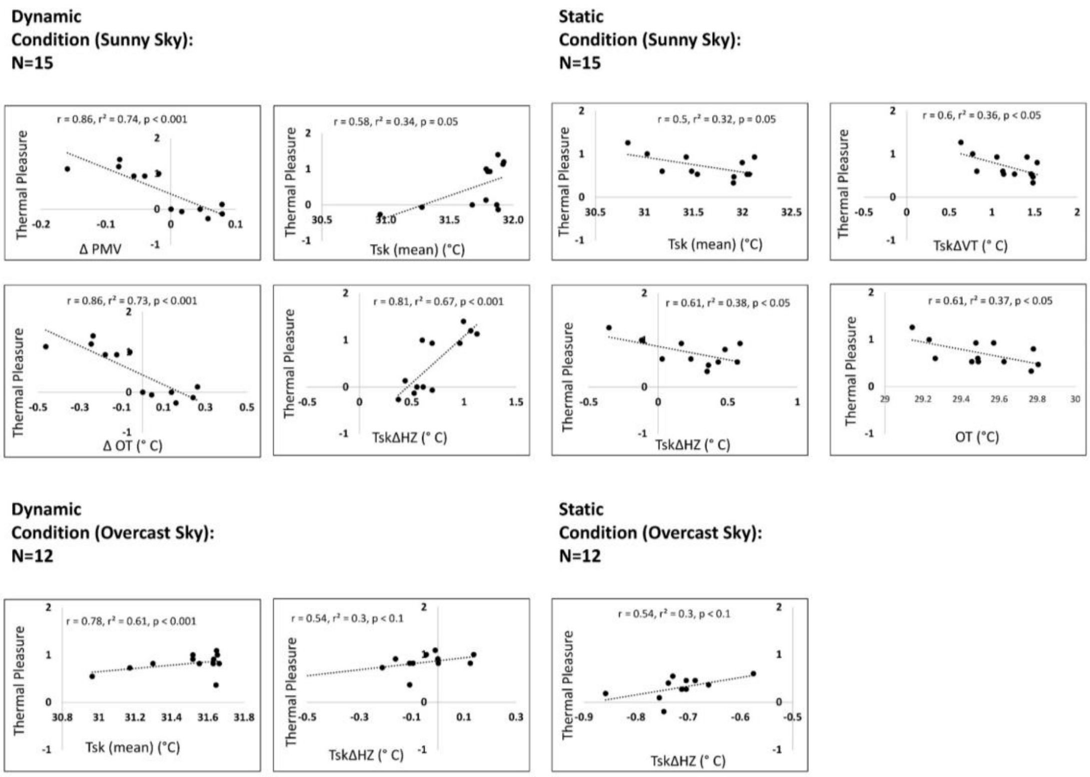


Figure 4.10 Significant relationships between thermal pleasure (TP) and physical environmental variables(ΔPMV (change in PMV value from that of the previous minute's), operative temperature (OT), and ΔOT (change in OT value from that of the previous minute's)) and physiological variables (Tsk (mean skin temperature), ΔTsk_{HZ} (difference between left hand and right arm skin temperatures), and ΔTsk_{VT} (difference between head and calf skin temperatures)); inside thermally uniform and non-uniform environments created by the static and dynamic screens under sunny and overcast conditions.

Following the graphical analysis, linear relationships of thermal pleasure with physical environment and participants' physiological variables were quantified for both the set-ups; individually for sunny and overcast sky conditions (Table 4.3). Significant relationships from this analysis are presented in Figure 4.10. Under sunny-sky conditions, the thermal pleasure was strongly correlated to both indoor environmental and participants' physiological variables (Figure 4.8A, Figure 4.8B, Figure 4.9A, Figure 4.9B, Table 4.3) whereas under overcast sky conditions, a strong correlation of the thermal pleasure was found to exist with physiological variables only (Figure 4.9C, Figure 4.9D, Table 4.3). Three variables, namely, ΔPMV, ΔOT, and ΔTsk_{HZ} of the non-uniform environment created by the dynamic screen under sunny sky conditions (Table 4.3) had the highest influence on thermal pleasure.

4.5. Discussion

Impacts of indoor physical and human physiological variables on thermal pleasure were investigated inside the static and dynamic screened, single-occupancy, perimeter office set-ups. The dynamic screen under sunny sky conditions successfully modulated the ramp up and down of the indoor operative temperatures by ±1.7-2.8 °C, which significantly influenced the thermal pleasure perception as observed from its strong relationship with ΔOT. Results from linear regression analysis (Figure 4.10A) predict that the drop in operative temperatures by 0.25-0.5 °C per minute within a base case range of 28-31 °C had a strong and significant influence ($r^2 = 0.73$, $p < 0.001$) on thermal pleasure. Next, slight non-uniformity (Figure 4.10B) in the indoor operative temperatures within a base case range of 29-30 °C also had a strong and significant relationship ($r^2 = 0.73$, $p < 0.05$) with thermal pleasure perception inside the static screened set-up under sunny sky conditions. These findings for the dynamic and static screened set-ups under sunny sky conditions align with those from previous studies (Parkinson et al., 2016; Traylor et al., 2019), within which it was found that temperature step-downs strongly influenced the thermal pleasure of a person in a sedentary state. Findings by Parkinson et al. (2016) applied to a wider ambient temperature range of 18-31 °C and findings by Traylor et al. (2016) were applied to a narrower and comfortable ambient temperature range of 22-26 °C.

Another finding from the present study is that the horizontal thermal asymmetry along the two sides of the body, ΔTsk_{HZ}, calculated as the difference between the skin temperatures of the left hand and right arm, had a strong influence on thermal pleasure inside the thermally uniform and non-uniform environments of the screened set-ups under both sunny and overcast conditions (Table 4.3, Figure 4.10). Under sunny sky conditions, a person's left side (facing the screen) was warmer than the right. In this situation, a horizontal skin temperature asymmetry of ±0.5 °C from its status quo in the screened set-ups influenced thermal pleasure (Figure 4.10A, Figure 4.10B). Under overcast sky conditions, a participant's left side (facing the screen) was cooler than the right side. In this situation the rise in horizontal skin temperature asymmetry by +0.2 °C from its status quo could evoke thermal pleasure in the dynamic and static set-ups (Figure 4.10B, Figure 4.10C). These findings align with those from the study by Parkinson and de Dear (2016), who found that "corrective differences in the rate of change in skin temperature between individual body segments" evokes thermal pleasure. The main difference between findings from the present study and from that by Parkinson and de Dear is that thermal pleasure, in their study, was generated through skin temperature differences inside ambient conditions that were in the lower fringes of the thermoneutral zone whereas, in the present study, the researchers found the impact of change in skin temperature differences on thermal pleasure inside ambient thermal conditions that were in the upper fringes of the thermoneutral zone.

Irrespective of the sky conditions, the contribution of thermal environment and human physiological variables in explaining variability in thermal pleasure inside the static and dynamic set-ups was 33% and 81%, respectively (Table 4.2). This implied the involvement of other non-thermal variables as well in influencing thermal pleasure. The solar screens also impacted daylighting, glare, aesthetics, and sensation of privacy in the indoor environment. To understand the influence of such non-thermal variables, the following general question was asked to the participants: *What did the screened exposure remind you of?* Their voluntary-experiential responses included the following statements: (i) "The patterns reminded me of snowflakes", (ii) "The screens reminded me of the garden fence", (iii) "It reminds me even more strongly of dappled sunlight under a tree.", (iv) "Reminds me of outside terrace with vines", (v) "It reminded me of dappled light underneath a tree or from a church window", (vi) "They remind me of regulating air-flow through the space". Such responses suggested that aesthetics and other cultural factors in the indoor environment possibly played a role in providing pleasure by giving thermo-visual memories to influence occupants' thermal perception during the exposure. The impact of aesthetics and cultural factors on thermal pleasure can be explored in the future.

4.6. Conclusions

The exposure of human participants to solar screened, single-occupancy, experimental, perimeter offices revealed the probability of the thermal environmental, physiological, and socio-cultural factors in influencing their thermal pleasure perception. The researchers built on existing work by Parkinson et al. (2016), Traylor et al. (2019), and Vargas et al., (2017) who investigated thermal alliesthesia in indoor environments. The original contribution of this work is that thermal alliesthesia was explored in building perimeter offices in which the operative temperatures remained in the upper fringes of the thermoneutrality limits. Through experiments, it was demonstrated how solar screens with static and dynamic operations can be designed as media to control the outdoor solar radiation and create temperature ramp cycles and horizontal thermal asymmetry, which generated thermal pleasure in seated occupants in ambient thermal conditions that were in the upper fringes of the thermoneutral zone. Moreover, findings from exposures under overcast sky conditions revealed that though the solar screens could not impact the indoor thermal conditions, they did impact other non-thermal environmental factors, which likely influenced the thermal pleasure perception.

The findings provide experimental evidence that expands the application of the thermal alliesthesia framework to building perimeter offices. Given the current need for investigations in occupant-centric building and indoor environmental design, these findings contribute to the field by showing how external facade shading can be designed to be occupant-centric. This work will be of interest to scholars, architects, building designers, engineers, and students interested in research on thermal comfort, indoor environmental quality, adaptive shading, and passive architecture. Globally, practicing architects and students in architectural academia have demonstrated interest in using solar screen shading for façade aesthetics (Attia et al., 2018). This article informs on how passive strategies can also be used to control the indoor environmental non-uniformities in the building perimeter spaces. The researchers propose the exploration and application of dynamic screens or similar adaptive shading on façade orientations that receive direct sunlight to provide for occupant thermal pleasure.

4.7. Limitations

The exploration of thermal alliesthesia in the present study was limited to a climate that does not experience large thermal swings. Moreover, an experimental research method was used involving a limited number of participants who were exposed to the solar screened set-ups for a finite timeframe. The findings from this work may not be applicable to other climates such as hot-humid, hot-dry, and to geographically, culturally, and demographically wider population. Next, the non-thermal indoor environmental variables such as aesthetics, privacy, daylighting, and glare might have impacted human thermal pleasure perception in some capacity, which have not been addressed in the present work.

Approval

This project was reviewed and approved by the Committee for Protection of Human Subjects (CPHS), the University of Oregon Institutional Review Board (IRB) (protocol number: 06292019.070).

CHAPTER V: SIGNIFICANCE OF DYNAMIC OVER STATIC SCREENS

A section of this chapter (5.3.3) has been published in the proceedings of Architectural Research Centres Consortium (ARCC-2021) conference and is co-authored by Prof. Ihab Elzeyadi and Prof. Virginia Cartwright. Major part of this chapter is prepared for submission to a journal for future publication.

This chapter reports on findings from further analysis of subjective data from the experiments with human participants (for N=27 participants) that were conducted inside single-occupancy, experimental offices shaded by the static and dynamic screens under sunny and overcast sky conditions. In the within-subject experimental design, 15 participants were exposed to both the screened offices under sunny sky conditions and 12 were exposed under overcast sky conditions.

The chapter specifically reports on the comparative analysis between the impact of dynamic and the static screens on the indoor thermal-visual environment of the set-ups, human thermal perception, general perception, and task performance under different sky conditions. Thermal perception encompassed the participants' responses on thermal comfort, thermal pleasure, thermal sensation, thermal preference, and local thermal sensation. General perception encompassed their satisfaction with the visual environment, aesthetics, privacy, and outdoor visual access.

The goal was to focus on understanding the significance of dynamic over static screens in influencing human thermal perception of pleasure under sunny and overcast sky conditions. Paired t-tests were used to quantify the significance of one over the other. It was found that the dynamic screen; in comparison to the static; significantly ($p \leq 0.05$) influenced thermal pleasure under both sunny and overcast sky conditions. It is evident that it was the thermal-visual environmental variability and the resulting transition in thermal sensation, which may have influenced thermal pleasure inside the dynamic screened office under sunny sky condition. Whereas inside the dynamic screened office under over-cast sky conditions, it was the general perception of satisfaction with the outdoor visual access that may have influenced thermal pleasure.

5.1. Introduction

Human thermal perception is shaped by the psychological processing of physiological responses inside the body against ambient thermal environmental conditions. An external thermal stimulus arouses a three-dimensional perception; (i) quantitative, which is the intensity of stimulus, (ii) qualitative, which is hot or cold nature of stimulus, and (iii) hedonic or affective, which explains the pleasure or displeasure giving characteristic of the stimulus (Cabanac, 1999). The limits of the hedonic dimension of a thermal sensation are a "continuum from extreme negative affectivity (distress) to extreme positive affectivity (delight), with indifference in the middle." The theory of '*thermal alliesthesia*' explains the physiological basis of thermal delight or pleasure.

The basic characteristics of a pleasure giving thermal perception are that; it is contingent, it indicates whether a stimulus is useful, it is transient, and it encourages behavior (Cabanac, 1999). Thermal pleasure depends on (i) the nature of the stimulus, (ii) the physiological state of a person; like body core temperature, body dehydration, peripheral stimuli at multiple locations on the skin; and (iii) the background of a person. Thermal pleasure is the sign of usefulness of the stimulus. Usefulness here, refers to the ability of the stimulus to rectify a physiological trouble or deficit. When human beings are in the context of situations like discomfort and the resulting fatigue and stress due to it, they seek for comfort. It is in this path towards seeking comfort that they attain pleasure. This motivates their voluntary or involuntary, physiology-oriented behavior, leading to "optimization of life" (Cabanac, 1979).

Thermal pleasure and comfort are different concepts. "Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment." (ASHRAE Standard 55, 2017). According to the thermal comfort standards, thermal comfort is possible in thermally neutral conditions in which thermal equilibrium can be maintained between the human body and its surrounding environment. "Comfort is the state of sensation with a nil hedonic dimension." Comfort can last indefinitely if the environment and the occupant remain in stable condition (Cabanac, 1979; Brager, 2015). Thermal pleasure, on the other hand is experienced in thermally non-neutral ambient environments where either one or both from the occupant and the environment are not steady. Thermal pleasure is short termed or transient. It lasts till the physiological state returns to normal. After this return to normal, the thermal stimulus that aroused pleasure earlier, can start being sensed as indifferent or even displeasing.

5.1.1. Research problem and questions

Thermally neutral indoor environments are characterized by conditions that have “cool, dry, and still air” that are controlled by heating, ventilation, and air-conditioning systems inside buildings. These conditions are regulated by thermal comfort standards (ASHRAE Standard-55; EN15251; ISO 7730). Thermal non-neutrality is characterized by “temperature ramps and cycles”, temperature asymmetries, air draughts, and surface temperature extremities. These non-neutral thermal conditions are regulated by models; in the thermal comfort standards; which predict adaptive thermal comfort and local thermal discomfort. Core-interior spaces of office buildings usually have controlled, thermally neutral environments. Personal comfort systems like foot-hand warmers, table fans, heated and cooled chairs; are popular tools that can provide the experience of thermal pleasure in these core spaces (Zhang et al., 2015; Rawal et al., 2020). On the other hand, perimeter spaces within 15’ of the office building facades have thermally non-neutral environments due to their exposure to outdoor environment through façade glazing and/or windows. The perimeter office spaces present a situation where an occupant is in a stable state and the surrounding non-stable environment is in motion. Passive cooling strategies like solar shading, in their static-fixed or dynamic-operable states are often applied to building facades to optimize building energy savings and control the thermal conditions inside the building perimeter spaces. Occupant perception of thermal pleasure and alliesthesia remains under-explored in building perimeter spaces. Moreover, the ability of passive cooling strategies like; static and dynamic façade shading in influencing occupant’s thermal perception that is; thermal comfort, thermal pleasure, thermal sensation, thermal preference, and local thermal sensation; remains unexplored.

In this study, the authors examined human thermal perception inside single-occupancy, perimeter office like set-ups shaded by static and dynamic solar screens using an experimental research method. Experiments involving human participants were conducted for summer months of ASHRAE Climate Zone (CZ)-4C using; (i) a static screen prototype with fixed geometric parameters that were optimized to maintain thermal neutrality and comfort and (ii) a dynamic screen prototype with geometric parameters that varied between very open and close configurations to create thermal non-neutrality and pleasure. In the pilot studies that the researchers conducted prior to the exposure of human participants, it was found that the indoor temperature of the static screened set-up varied by ± 0.5-1.6 °C (1-3 °F) and that of the dynamic screened set-up varied by ± 1.7-2.8°C (3-5 °F) under sunny sky conditions (Naik & Elzeyadi, 2020a). When human participant exposures were carried out in August-September, an additional variable that is sky conditions; was also in place. It was hypothesized that dynamic screened set-up would significantly outperform the static in evoking thermal pleasure, irrespective of different sky conditions.

In the research paper preceding this work, the researchers reported findings that were responding to questions like; what was the relationship of thermal environmental and human physiological variables with thermal pleasure inside the solar screen shaded perimeter spaces? and how much was the combined impact of indoor environmental thermal variables on thermal pleasure inside the static and dynamic screened set-ups. Irrespective of the sky conditions, 81% variability in thermal pleasure reporting inside the dynamic screened set-up and 33% variability in thermal pleasure responses inside the static screened set-up; was explained by the indoor thermal and human physiological parameters. In this article, the authors carried out a comparative analysis of the impact of dynamic screens with that of the static on the indoor thermal-visual environment of the set-ups, human thermal perception, general perception, and task performance under different sky conditions. They focused towards understanding the significance of dynamic over static screens in influencing thermal perception of pleasure under different sky conditions. This work responded to the questions that are; when, why, and how did one of the two screen types perform significantly better than the other in influencing thermal pleasure.

5.2. Methods: Participant exposure to full-scale prototypical set-ups

5.2.1. Solar screen prototypes in dynamic and static states

The researchers employed dynamic and static screen shading prototypes for this study (Figure 5.1). The rhombus shaped patterns of these prototypes were borrowed from vernacular solar screens. The geometric patterns of vernacular screens are based on the biophilic design principles that offer ‘experiential delight’ to occupants (Naik & Elzeyadi, 2020b; Brager, 2019). Architects and façade designers have shown an inclination towards using the design patterns of vernacular screens for creating contemporary solar screened facades in their static or dynamic states. The solar screens are well-acknowledged for their impact on indoor thermal comfort, which however remains under-researched. The performance of dynamic screens compared to that of their static counterparts is under-researched. Thus, in this work the researchers focused on reporting the comparison between dynamic and static screens in impacting indoor environment, human thermal and general perception, and task performance.

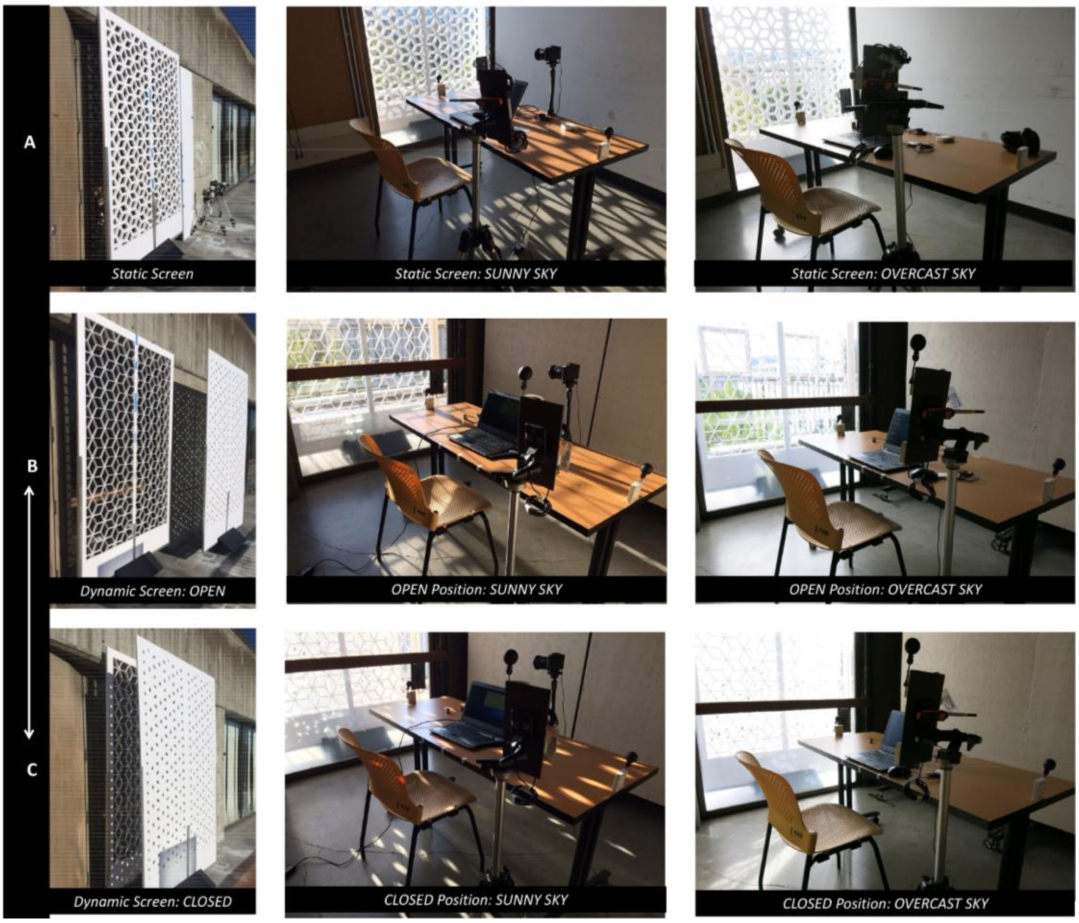


Figure 5.1 Shading prototypes and single occupancy set-ups under sunny and overcast sky conditions.

Design of the dynamic and static screen prototypes for this work was informed by a sensitivity study of predicted thermal comfort (Naik & Elzeyadi, 2020c) to different solar screen geometric parameters like perforation ratio (PR=% of perforation) and depth ratio (DR = perforation depth/perforation width) in the IES_VE computation environment. Using a static-fixed screen prototype with (PR, DR) = (50%, 0.1), it was intended to maintain thermal neutrality for majority of the time (Figure 5.1, A). Using the dynamic screen prototype that was designed to swap between OPEN and CLOSE positions with geometric parameters alternating between (PR, DR) = (90%, 0.1) and (PR, DR) = (10%, 0.1), the intention was to use the moving screen to cause controlled thermally non-neutral conditions to influence human perception (Figure 5.1, B-C).

5.2.2. Single-occupancy test set-ups in perimeter spaces

Two, 3 m x 3 m (10' x 10') full scale test set-ups were arranged on the east-facing perimeter spaces on the fourth floor of a building at University of Oregon's Eugene campus (Figure 5.1, Figure 5.2). Each set-up had a 1.52 m (5', wide) x 2.43 m (8', high), clear-glass, single-pane, fixed window (Tvis = 0.80, SHGC= 0.80) on its east facing wall. The dynamic and static screen prototypes were installed on the external surface of the window. Each set-up had a work-desk, personal computer arrangement, and equipment to measure the thermal and visual physical environmental parameters (Figure 5.2). Details on the make and accuracy of the indoor environmental data loggers have been described in previous articles related to this study (Naik & Elzeyadi, 2020a; Naik & Elzeyadi, 2021).

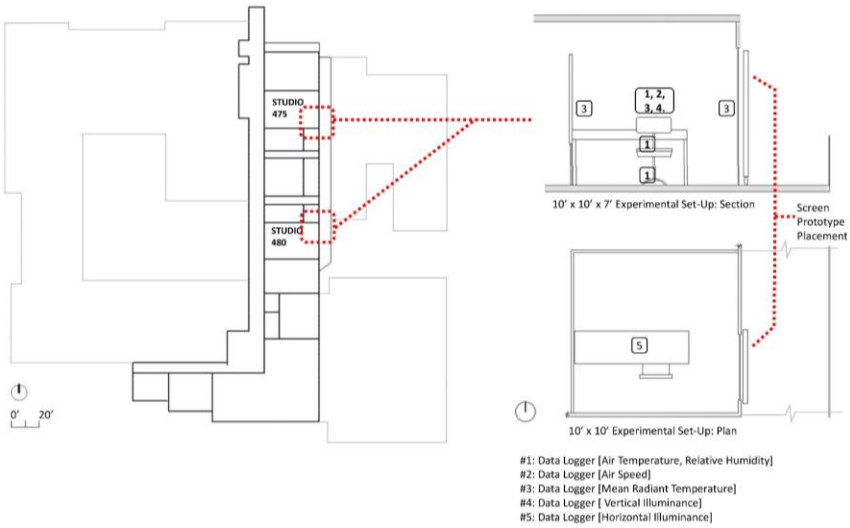


Figure 5.2 Location of the set-ups and placement of data loggers.

5.2.3. Participants

Human factor participation was conditional, confidential, and on a voluntary basis. Each person who agreed to participate was asked for a commitment to make themselves available for an exposure to the two set-ups; dynamic and static; which demanded total 3 hours' time, with 1.5 hours devoted to a study run assigned for each set-up. Each participant was compensated after the completion of total two study-runs that he/she promised. 27 people within an age-group of 22-50 years participated in the study. Thus, a total of 54 study-runs of 1.5 hours each were conducted. People without any background of cardiovascular, eye, or skin disease were recruited. They were selected on conditions that (i) they had a full or part-time involvement in doing desk-jobs in air-conditioned office environments, (ii) they were confident of responding to questionnaires in English, and (iii) they could work through computer-based tasks. While formally seeking participant consent and briefly explaining the experiment exposure, it was taken care to not reveal the study goals as a step to prevent the researcher's influence on the subjective responses.

5.2.4. Sky conditions

The experimental exposures carried out during August-September in ASHRAE CZ-4C offered an opportunity to explore the influence of two different sky conditions; sunny and overcast; on the indoor thermal environment and human perception in two different set-ups; dynamic and static. N=15 of the 27 participants were exposed to both the set-ups under sunny sky conditions and the remaining 12 under overcast sky conditions (Figure 5.3, A). A participant's exposure to both set-ups under similar sky conditions was ensured using the weekly weather forecast.

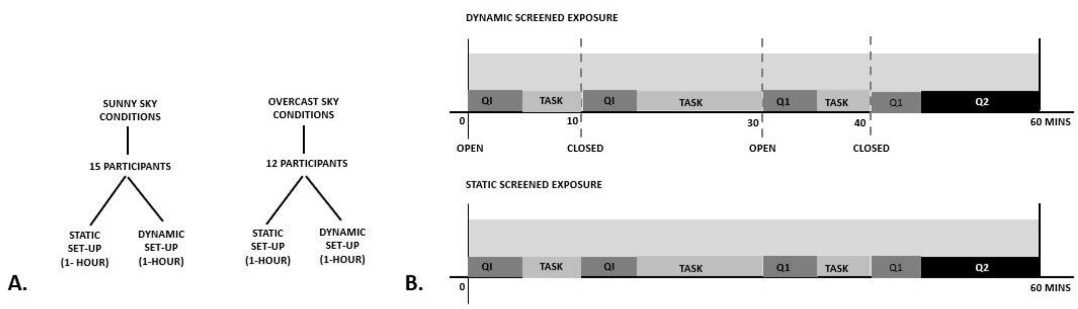


Figure 5.3 (A) Within subject, factorial design of experiments. (B) Plan of 1-hour exposure to the static and dynamic screened set-ups.

5.2.5. Design of experiments with human factors

The researchers used a with-in subject, factorial, experimental design to investigate the impacts of dynamic and static screens. Participant exposures to the screened set-ups were conducted in the morning within the timeframe of 8:00 to 10:30 AM. The 1.5 hour of a participant's involvement was divided into two phases that are: (i) initial 30 minutes of pre-exposure and (ii) following 1-hour of exposure to one of the two screened set-ups. In the 1-hour exposure to a screened set-up, a participant was required to be occupied with responding to questionnaires and carrying out office-like tasks (Figure 5.3, B). Hence, the pre-exposure phase was required to prepare a participant for the next phase. Moreover, the pre-exposure phase was also necessary to give a buffer to the participant, when he/she could bring one's body to a resting state. Thus, in this phase the participants were asked to maintain a sedentary state inside a thermally neutral, non-screened, comfortable space. During this time, they were given skin temperature sensors, which they had to tape at multiple locations on their body. Next, they were introduced to the task and the questionnaire types that they had to respond to. Moreover, they were asked to carry out sample tasks like the ones they were to encounter in the next phase. This was done to prevent a participant from getting stressed because of tasks during the following 1-hour of screened exposure.

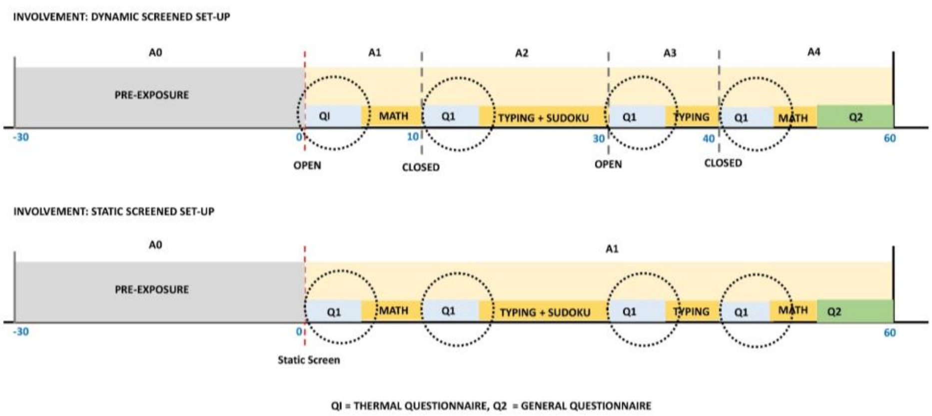


Figure 5.4 (A)1-hour exposure to the dynamic screened set-up, (B) 1-hour exposure to the static screened set-up.

At the beginning of the 1-hour exposure to the dynamic screened set-up, a participant was exposed to its OPEN position; with geometric parameters (PR, DR) = (90%, 0.1); for the first 10 minutes. Subsequently the screen position was changed to CLOSED; with geometric parameters (PR, DR) = (10%, 0.1); and was maintained for the next 20 minutes (Figure 5.4, A). This way the screen position was alternatively changed between OPEN and CLOSED states every 10-20 minutes during the 1-hour of exposure in a screened set-up (Figure 5.4, A). The frequency of the dynamic screen's movement was decided after conducting a pilot study, in which the impact of different movement frequencies on the set-up's indoor environment was tested (Naik & Elzeyadi, 2020a). The screen with (PR, DR) = (50%, 0.1); which shaded the static set-up was fixed and was not moved during the entire 1-hour exposure (Figure 5.4, B).

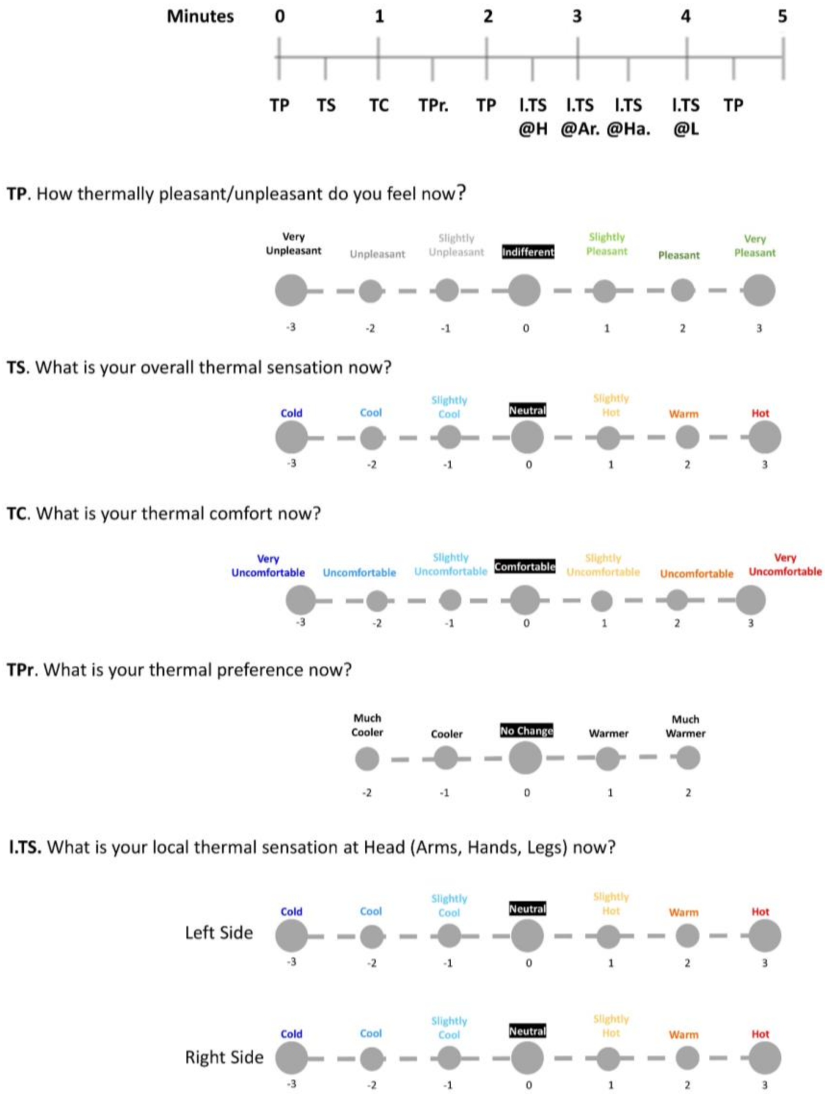


Figure 5.5 Questions posed during the five minutes of thermal questionnaire Q1.

In the dynamic screened set-up, a participant's thermal perception related votes were collected each time within 5-minutes after the screen's position change; using questionnaire Q1 on the desktops provided in the set-ups. After responding to Q1, the participants were assigned to carry out office-like tasks on computer screens. Later, during the last 10 minutes of the hour-long exposure, they were to respond on their general perception of the space through questionnaire Q2. The timing of questionnaires and tasks was maintained similar for exposures inside both the set-ups. The questionnaires Q1-Q2 and the tasks projected on the computer screens were programmed and timed to proceed without the researcher's intervention on the on-line secured survey portal (Qualtrics®).

Besides collecting subjective responses on tasks and questionnaires, objective data like a participant's skin temperature responses and indoor physical environmental parameters of the set-up like; dry bulb temperatures (DBT), black globe temperatures, relative humidity (RH), airspeed, surface temperatures, horizontal-vertical illuminance (light intensity) were recorded for each minute during every exposure. Parallel to the indoor environmental data, outdoor air temperature, outdoor horizontal-vertical illuminance, and global vertical-horizontal solar radiation was measured.

5.2.6. Thermal Questionnaire (Q1)

The thermal questionnaire was composed of standardized questions that required the participants to respond to their thermal perception 'now' when it was posed. Questions like; how thermally pleasant/unpleasant you feel, what is your overall thermal sensation, what is your thermal preference, and what is your thermal comfort were asked. Moreover, individual questions on local thermal perception on the two sides of body parts like; head, arms, hands, and legs; were also asked. The ten-questions were timed to appear at a time-gap of 30 seconds in the 5-minutes of Q1 (Figure 5.5). The question on thermal pleasure appeared thrice that is at the beginning, middle, and end of Q1. Responses to the questions on thermal pleasure, thermal sensation, and local thermal sensation, were sought using categorical, seven-point Likert scales specified by ASHRAE Standard-55 (2017) (Figure 5.5). Next, responses to questions on thermal comfort and preference were sought using categorial, seven-point Bedford scale and five-point Nicol scale, respectively. It should be noted that, the researchers explained this questionnaire to the participants in the pre-exposure period, when it was specified that their responses to the thermal pleasure question should be independent of their thermal sensation that is how hot-cold they felt.

5.2.7. Tasks

The Q1 questionnaires were followed by office-like tasks involving medium difficulty math questions, sudoku, and typing (Figure 5.4). In the pre-exposure phase the participants were familiarized with the tasks and were given scratch-sheets for ease of doing math and sudoku during the 1-hour screened exposure. These tasks were like the ones used by the researchers at Center for Built Environment at UC Berkeley (Zhang et.al, 2010) in their experiments investigating human thermal perception and performance in spaces with low-powered air-conditioning systems. Two math tasks; each for 5-minutes; were administered during the first 10 and last 20 minutes of the screened exposures (Figure 5.4). Each 5-minute of math task comprised of 15-questions on fraction multiplication; examples of which are provided in the Appendix (1). Next, the participants were given 10-minutes to solve a sudoku question; extracted from https://www.7sudoku.com/moderate and reproduced in the Qualtrics® survey. A sample sudoku question is provided in the Appendix (2). Two typing tasks, each for 5-minutes administered during different times of an exposure, required a participant to type sections of text presented to them in an image format in the Qualtrics® survey. A sample paragraph of this text is presented in Appendix (3).

5.2.8. General Questionnaire (Q2)

The general spatial perception questionnaire was based on the indoor environmental quality evaluation questionnaire developed by the researchers at Center for Building Performance and Diagnostics at Carnegie Mellon University (Park et.al, 2018). The questionnaire Q2 was administered during the last 10-minutes of the 1-hour screened exposure (Figure 5.4). It comprised of questions using which the researchers attempted to understand a participant’s satisfaction with; (i) the overall lighting condition, (ii) the light for computer work, (iii)aesthetic quality, (iv) acoustic or sound privacy, (v) privacy, (vi) outdoor visual access, and (vii) air movement in the screened set-ups. Next, there were questions posed to investigate a participant’s perception about the frequency and the source of glare. Lastly, they were asked to describe in typed words about; “what the screened exposure reminded them of?”

5.3. Comparative analysis of human perception in dynamic versus static

The data for sunny and overcast sky conditions were analysed separately for 15 participants under sunny and 12 participants under overcast sky conditions in dynamic and static screened set-ups. Every participant's response on perception and performance on tasks inside dynamic screened set-up were directly compared to his/her responses in the static screened set-up. Two sampled, unequal variance t-tests were employed to analyze the significance of dynamic screens over static screens on a participant's thermal perception, task performance, and general performance. The measured indoor thermal-visual environmental data was also corelated with participants' subjective responses using simple linear regression analysis.

5.3.1. Indoor thermal and visual environmental conditions

The indoor thermal and visual conditions inside the dynamic and static screened set-ups were studied by plotting the data that was measured during the participants' exposures under sunny sky conditions; N= 15 in each set-up; and over-cast sky conditions; N=12 in each set-up. Data on operative temperature, predicted mean vote, and horizontal or work-plane illuminance; was extracted for the following four intervals of the hour-long exposure; (i) 0-5 minutes, (ii) 10-15 minutes, (iv) 30-35 minutes, and (iv) 40-45 minutes. These four intervals correspond to timeslots that the participants responded to the thermal questionnaire (Q1). The operative temperature was calculated as an average of air-temperature and mean radiant temperature. The PMV values were calculated using measured values of air temperature, mean radiant temperature, relative humidity, air speed, participants' self-reported clothing values 'clo', and airspeed. The set-ups were an isolated enclosed space, where the airspeed remained in the range of 0.1 to 0.15 m/s. Fanger's PMV model built-in as a function in R package 'comf' was used to compute the PMV values (Fanger, 1970; Schweiker, 2016).

Under sunny-sky conditions, the operative temperatures remained in the range of; 87°-100° F in the dynamic screened set-up and 78°-90° F in the static screened set-up (Figure 5.6, A-B). The opening and closing of dynamic screen created rise and drop in the operative temperature by 3-5°F (1.7 – 2.8 °C) (Figure 5.6, A). Whereas, in the static screened set-up the operative temperature trend remained constant (Figure 5.6, B).

The thermal sensation as predicted by the PMV values has a saw tooth like trend moving between hot-warm to warm-slightly warm zones in the dynamic screened set-up (Figure 5.6, C). The predicted thermal sensation in the static screened set-up remained within slightly warm to warm zone (Figure 5.6, D). The horizontal illuminance values dropped from 2500-4000 lux to 1000-1800 lux when the screened closed from open position in the dynamic screened set-up (Figure 5.6, E). Whereas the horizontal illuminance values remained in the range of 2000-3000 lux in the static screened set-up (Figure 5.6, F).

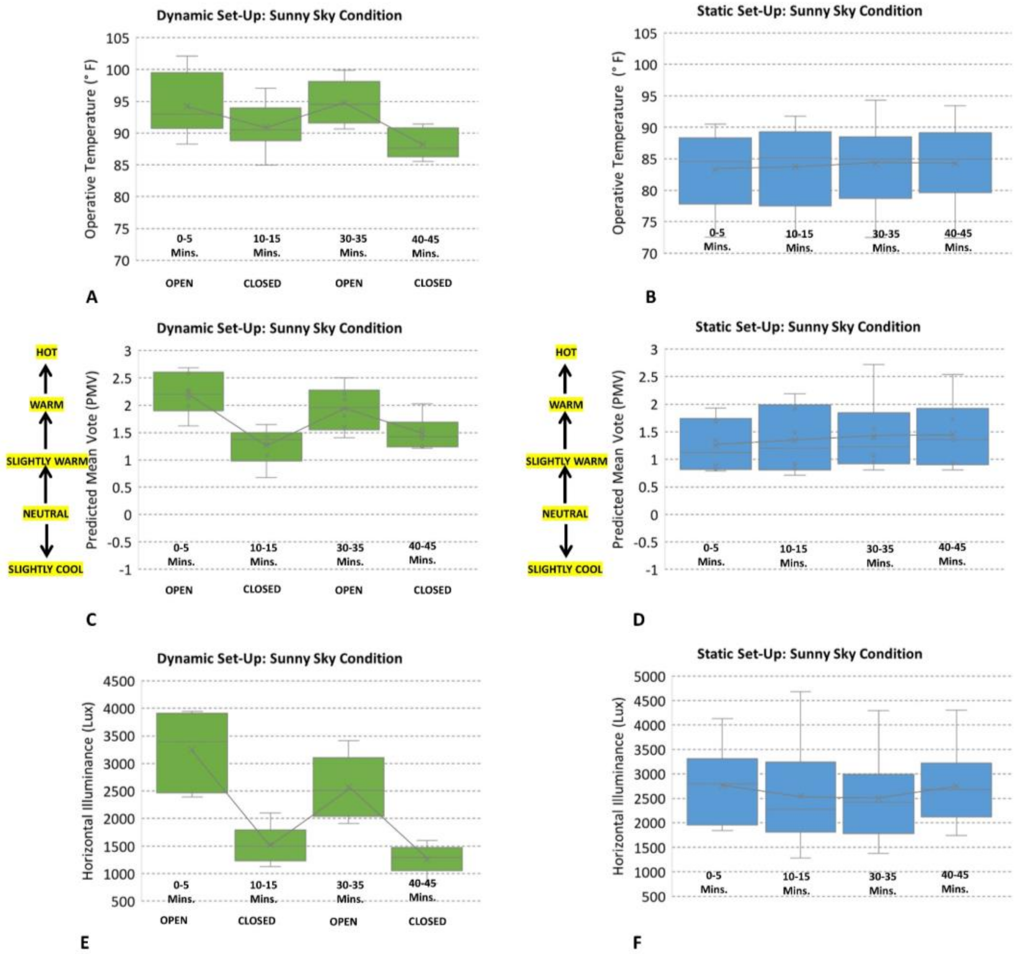


Figure 5.6 Indoor thermal and visual environmental conditions inside the static and dynamic screened set-ups under sunny sky conditions.

Under overcast-sky conditions, the operative temperatures remained in the range of; 82°-85° F in the dynamic screened set-up and 78°-90° F in the static screened set-up (Figure 5.7, A-B). The movement of the screen did not seem to impact the operative temperature and PMV values inside the dynamic screened set-up (Figure 5.7, A-C). The static screened set-up had steady state, comfortable thermal conditions maintained as observed from the operative temperature and PMV values that remained within the range of neutral (0) and slightly warm (1) (Figure 5.7, D). It was only the visual environment, which changed significantly due to the screened movement inside the dynamic screened set-up as observed by the horizontal illuminance that increased or decreased by 200-250 lux (Figure 5.7, E). Such visual environmental changes were not prevalent inside the static screened set-up (Figure 5.7, F).

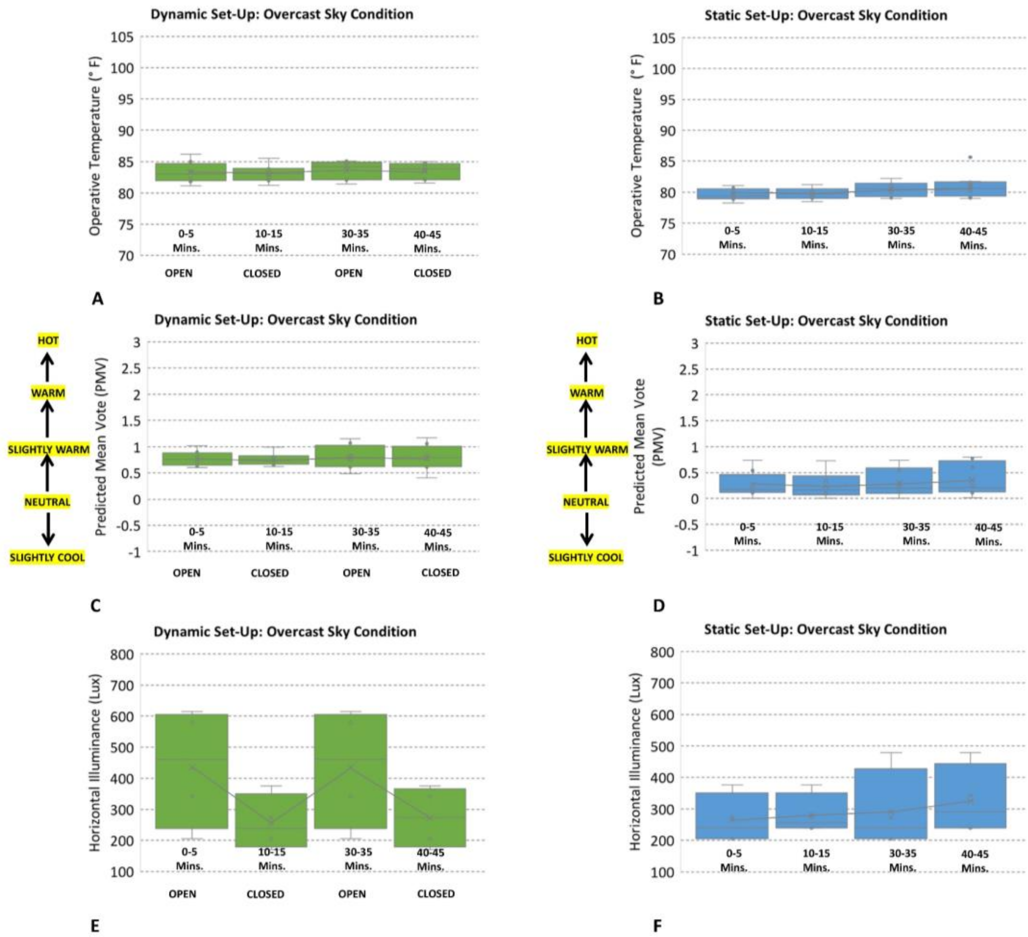


Figure 5.7 Indoor thermal and visual environmental conditions inside the static and dynamic screened set-ups under overcast sky conditions.

5.3.2. Participants' thermal and general perception and task performance:

5.3.2.1. Thermal pleasure

Participants' responses on their perception of thermal pleasure were sought at the beginning (first minute), middle (third minute), and end (fifth minute) of Q1 (Figure 5). These responses were analyzed separately for sunny and overcast sky conditions for

N=15 and N=12 participants, respectively. Moreover, comparative analysis of the responses to the question on thermal pleasure during the first, third, and fifth minute of Q1 in the dynamic and static screened set-up was carried out individually (Figure 5.8).

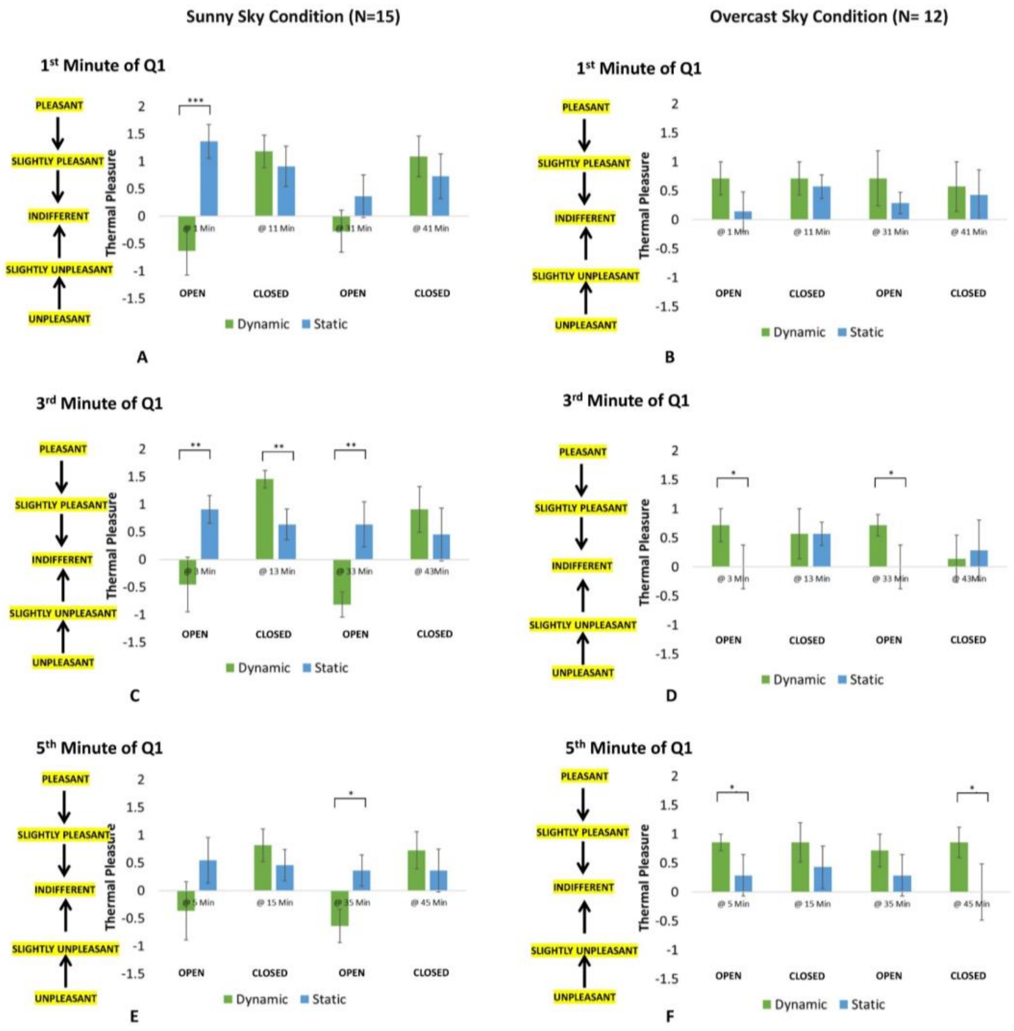


Figure 5.8 Comparative analysis of the participants’ thermal pleasure responses during the first, third, and fifth minutes of thermal questionnaire Q1. (* indicates $p \leq 0.05$, ** indicates $p \leq 0.01$, *** indicates $p \leq 0.001$).

Under sunny sky conditions, the participants’ thermal pleasure remained on the positive side throughout their exposure to the static screened set-up (Figure 5.8, A-C-E). Moreover, the magnitude of their self-reported thermal pleasure was the highest when the question was asked for the first time (Figure 5.8, A); first minute of Q1; decreasing gradually with time during the third (Figure 5.8, C) and fifth minutes (Figure 5.8, D). Participants’ thermal perception of both, pleasure and displeasure were reported inside the dynamic screened set-up. Displeasure on the negative side and pleasure on the positive side were reported when the screen was in OPEN and CLOSED positions, respectively (Figure 5.8, A-C-E). Highest magnitude of thermal pleasure or displeasure was perceived few minutes after the screen's position change to CLOSED from OPEN. This can be observed from the magnitude of self-reported thermal pleasure or displeasure during the third (Figure 5.8, C) and fifth minutes (Figure 5.8, E) of Q1 as compared to that during the first minute. Significant difference ($p < 0.05$) of the participants' thermal pleasure inside dynamic and static screened set-ups could be observed during the third minute of Q1 (Table 5.1, left side).

Under overcast sky conditions, participants' thermal pleasure remained on the positive side throughout the hour-long exposure inside both, dynamic and static screened set-ups (Figure 5.8, B-C-D). There is no indication of increase or decrease in the magnitude of thermal pleasure with time that is from first to fifth minute; inside either of the two set-ups. Like the sunny sky condition, significant difference ($p <0.05$) of the participants' thermal perception inside dynamic and static screened set-ups could be observed during the third minute of Q1 (Table 5.1, right side). However, this difference was significant only when the dynamic screen was in OPEN position. The dynamic screened condition outperformed the static in garnering higher magnitude of thermal pleasure in OPEN position under overcast sky condition (Figure 5.8, D), as opposed to CLOSED position in sunny sky condition (Figure 5.8, C).

Table 5.1 Difference between the participants' perception of thermal pleasure inside the dynamic and static screened set-ups. (* indicates $p \leq 0.05$, ** indicates $p \leq 0.01$, *** indicates $p \leq 0.001$).

		Sunny Sky Conditions (N = 15)								Overcast Sky Conditions (N = 12)					
First Minute of Q1								First Minute of Q1							
	Dynamic Mean	Static Mean	Dynamic Std. Er.	Static Std. Er.	Dynamic Std. Dev.	Static Std. Dev.	P-value		Dynamic Mean	Static Mean	Dynamic Std. Er.	Static Std. Er.	Dynamic Std. Dev.	Static Std. Dev.	P-value
@ 1 Min	-0.64	1.36	0.43	0.31	1.43	1.03	0.00 ***	@ 1 Min	0.71	0.14	0.29	0.34	0.76	0.90	0.14
@ 11 Min	1.18	0.91	0.30	0.37	0.98	1.22	0.14	@ 11 Min	0.71	0.57	0.29	0.20	0.76	0.53	0.37
@ 31 Min	-0.27	0.36	0.38	0.39	1.27	1.29	0.10	@ 31 Min	0.71	0.29	0.47	0.18	1.25	0.49	0.18
@ 41 Min	1.09	0.73	0.37	0.41	1.22	1.35	0.24	@ 41 Min	0.57	0.43	0.43	0.43	1.13	1.13	0.40
Third Minute of Q1								Third Minute of Q1							
@ 3 Min	-0.45	0.91	0.49	0.25	1.63	0.83	0.01**	@ 3 Min	0.71	0.00	0.29	0.38	0.76	1.00	0.05*
@ 13 Min	1.45	0.64	0.16	0.28	0.52	0.92	0.01**	@ 13 Min	0.57	0.57	0.43	0.20	1.13	0.53	0.50
@ 33 Min	-0.82	0.64	0.23	0.41	0.75	1.36	0.01**	@ 33 Min	0.71	0.00	0.18	0.38	0.49	1.00	0.02*
@ 43Min	0.91	0.45	0.41	0.47	1.38	1.57	0.19	@ 43Min	0.14	0.29	0.40	0.52	1.07	1.38	0.37
Fifth Minute of Q1								Fifth Minute of Q1							
@ 5 Min	-0.36	0.55	0.53	0.41	1.75	1.37	0.07	@ 5 Min	0.86	0.29	0.14	0.36	0.38	0.95	0.02*
@ 15 Min	0.82	0.45	0.30	0.28	0.98	0.93	0.17	@ 15 Min	0.86	0.43	0.34	0.37	0.90	0.98	0.18
@ 35 Min	-0.64	0.36	0.30	0.28	0.81	1.36	0.02*	@ 35 Min	0.71	0.29	0.29	0.36	0.76	0.95	0.20
@ 45 Min	0.73	0.36	0.33	0.39	1.10	1.29	0.21	@ 45 Min	0.86	0.00	0.26	0.49	0.69	1.29	0.02*

5.3.2.2. Thermal sensation

Participants' responses on thermal sensation that is; how hot or cold they felt were sought once; at the first minute of Q1. Under sunny sky conditions, the participants felt that indoor thermal environment of the dynamic screened set-up transited from the warmer side to slightly cool, when the screen's position changed from OPEN to CLOSE (Figure 5.9, A). The same group of participants felt the indoor environment of the static screened set-up under sunny sky conditions was neither warm nor cool; neutral. There was a significant difference between the participants' responses between dynamic and static screened set-ups under sunny sky conditions (Figure 5.9, A; Table 5.2, left side). Under overcast sky conditions, the group of 12 participants felt that the indoor environment of both; the dynamic and static set-ups was between neutral and slightly cool (Figure 5.9, B). The opening and closing of the dynamic screen under overcast sky condition did not influence the change in people's thermal sensation like it did under sunny sky condition (Table 5.2, right side).

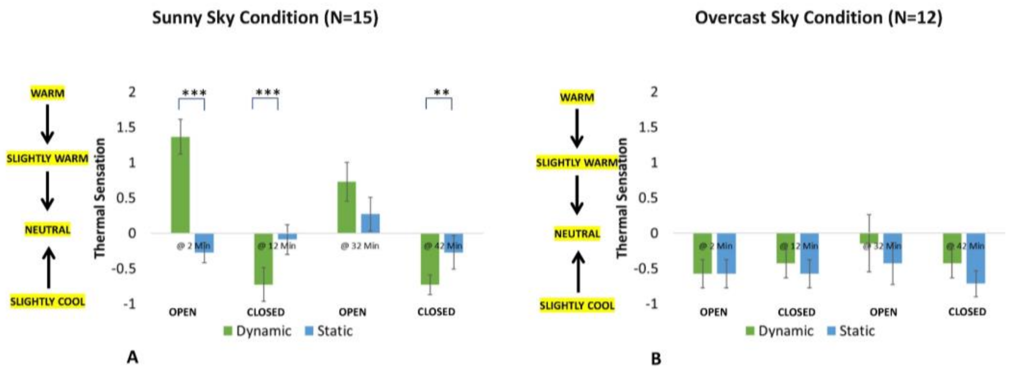


Figure 5.9 Comparative analysis of the participants' thermal sensation responses during the first minute of thermal questionnaire Q1. (** indicates $p \leq 0.01$, *** indicates $p \leq 0.001$).

Table 0.2 Difference between the participants' perception of thermal sensation inside the dynamic and static screened set-ups (** indicates $p \leq 0.01$, *** indicates $p \leq 0.001$).

		Sunny Sky Conditions (N = 15)								Overcast Sky Conditions (N = 12)					
Second Minute of Q1								Second Minute of Q1							
	Dynamic	Static	Dynamic	Static	Dynamic	Static			Dynamic	Static	Dynamic	Static	Dynamic	Static	
	Mean	Mean	Std Er.	Std Er.	Std Dev.	Std Dev.	P-value		Mean	Mean	Std Er.	Std Er.	Std Dev.	Std Dev.	P-value
@ 2 Min	1.36	-0.27	0.24	0.14	0.81	0.47	0.000***	@ 2 Min	-0.57	-0.57	0.20	0.20	0.53	0.53	0.50
@ 12 Min	-0.73	-0.09	0.24	0.21	0.79	0.70	0.000***	@ 12 Min	-0.43	-0.57	0.20	0.20	0.53	0.53	0.30
@ 32 Min	0.73	0.27	0.27	0.24	0.90	0.79	0.11	@ 32 Min	-0.14	-0.43	0.40	0.30	1.07	0.79	0.34
@ 42 Min	-0.73	-0.27	0.14	0.24	0.47	0.79	0.01**	@ 42 Min	-0.43	-0.71	0.20	0.18	0.53	0.49	0.18

5.3.2.3. *Thermal preference*

Participants' responses on thermal preference were sought once at the second minute of Q1. Static set-up was preferred to be significantly warmer than the dynamic under sunny and the overcast-sky conditions (Figure 5.10, Table 5.3). However, participants' responses on thermal preference (Figure 5.10, A) did not correspond to their perception of displeasure (Figure 5.8, A-C-E) and slightly warm to warm sensation (Figure 5.9, A) in the OPEN position inside dynamic set-up under sunny sky condition.

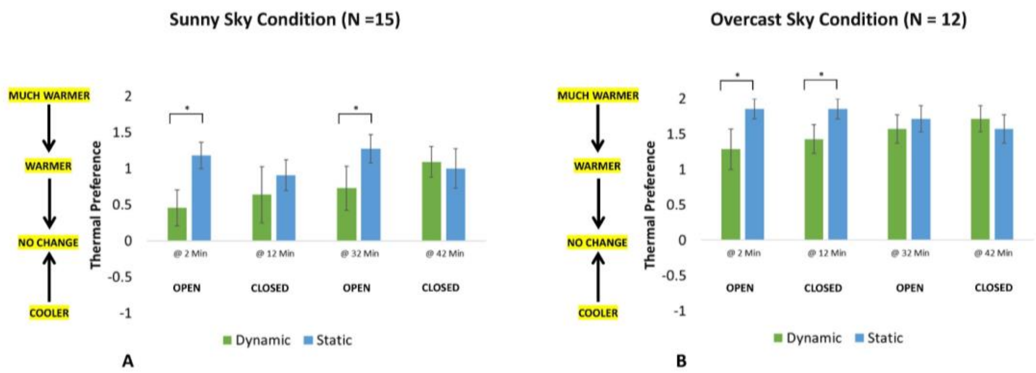


Figure 5.10 Comparative analysis of the participants' thermal preference responses during the second minute of thermal questionnaire Q1. (* indicates $p \leq 0.05$).

Table 5.3 Difference between the participants' perception of thermal preference inside the dynamic and static screened set-ups (* indicates $p \leq 0.05$).

		Sunny Sky Conditions (N=15)							Sunny Sky Conditions (N=15)					
Second Minute of Q1							Second Minute of Q1							
	Dynamic	Static	Dynamic	Static	Dynamic	Static			Dynamic	Static	Dynamic	Static	Dynamic	Static
	Mean	Mean	Std. Er.	Std. Er.	Std Dev.	Std. Dev.	P-value		Mean	Mean	Std. Er.	Std. Er.	Std Dev.	Std. Dev.	P-value
@ 2 Min	0.45	118	0.25	0.18	0.82	0.60	0.01*	@ 2 Min	129	186	0.29	0.14	0.76	0.38	0.05*
@ 12 Min	0.64	0.91	0.39	0.21	129	0.70	0.27	@ 12 Min	143	186	0.20	0.14	0.53	0.38	0.05*
@ 32 Min	0.73	127	0.30	0.19	101	0.65	0.05*	@ 32 Min	157	171	0.20	0.18	0.53	0.49	0.31
@ 42 Min	109	100	0.21	0.27	0.70	0.89	0.40	@ 42 Min	171	157	0.18	0.20	0.49	0.53	0.31

5.3.2.4. *Thermal comfort*

The Bedford scale was inconclusive in accurate understanding of thermal comfort perception inside the building perimeter, screened set-ups. Most participants felt thermally comfortable inside the set-ups under sunny and overcast sky conditions. Participants' rating on thermal comfort viz-a-viz its relationship to thermal pleasure and sensation could only be established under sunny sky conditions when the screen was in OPEN position in the initial part of the exposure (Figure 5.11, Table 5.4).

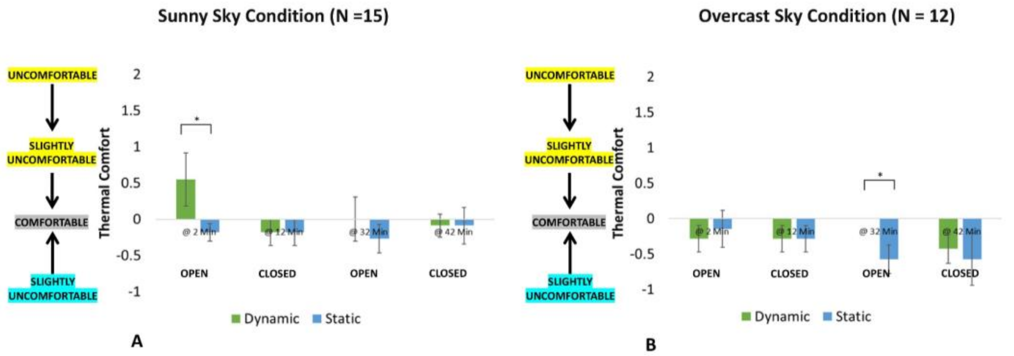


Figure 5.11 Comparative analysis of the participants' thermal comfort responses during the second minute of thermal questionnaire Q1. (* indicates $p \leq 0.05$).

Table 5.4 Difference between the participants' perception of thermal comfort inside the dynamic and static screened set-ups (* indicates $p \leq 0.05$).

		Sunny Sky Conditions (N=15)								Overcast Sky Conditions (N =12)					
Second Minute of Q1								Second Minute of Q1							
	Dynamic Mean	Static Mean	Dynamic Std Er.	Static Std. Er.	Dynamic Std. Dev.	Static Std. Dev.	P-value		Dynamic Mean	Static Mean	Dynamic Std Er.	Static Std. Er.	Dynamic Std. Dev.	Static Std. Dev.	P-value
@ 2 Min	0.55	-0.18	0.37	0.12	1.21	0.40	0.04*	@ 2 Min	-0.29	-0.14	0.18	0.26	0.49	0.69	0.33
@ 12 Min	-0.18	-0.18	0.18	0.18	0.60	0.60	0.50	@ 12 Min	-0.29	-0.29	0.18	0.18	0.49	0.49	0.50
@ 32 Min	0.00	-0.27	0.30	0.19	1.00	0.65	0.23	@ 32 Min	0.00	-0.57	0.00	0.20	0.00	0.53	0.02*
@ 42 Min	-0.09	-0.09	0.16	0.25	0.54	0.83	0.50	@ 42 Min	-0.43	-0.57	0.20	0.37	0.53	0.98	0.37

5.3.2.5. Sensation of local thermal asymmetry

Four questions on the sensation of local thermal asymmetry at head, arms, hands, and legs were asked during the last two minutes of Q1. Each question on local asymmetry had two parts. A single question: what your thermal sensation at head is, sought two responses for the left and right side of the head individually (Figure 5). The authors have presented the difference (Δ) of local sensation between left and right side in Figure 5.12 (A to H).

Under sunny sky conditions, it is evident that a participant's left side was warmer than the right inside both the set-ups (Figure 5.12, A-C-E). Moreover, the upper body thermal asymmetry was higher than that of the lower body inside these set-ups (Figure 5.12, A-C). Further, changing of screen position from OPEN to CLOSED inside the dynamic screened set-up led to a decrease in sensation of thermal asymmetry at the upper body. It was in the CLOSED position when the sensation of local asymmetry was found to be significantly different and lower than that inside the static screened set-up (Figure 5.12, A-C, Table 5.5- left side). Under overcast sky conditions, some evidence of local thermal asymmetry sensation at the upper body is observed in the dynamic and static screened set-ups (Figure 5.12, B-D). The left side was slightly warmer than the right and inside the static screened set-up. While, for the dynamic screened set-up the left was felt to be slightly cooler than the right. However, the difference between the participants' sensation in dynamic versus the static set-ups was not significant.

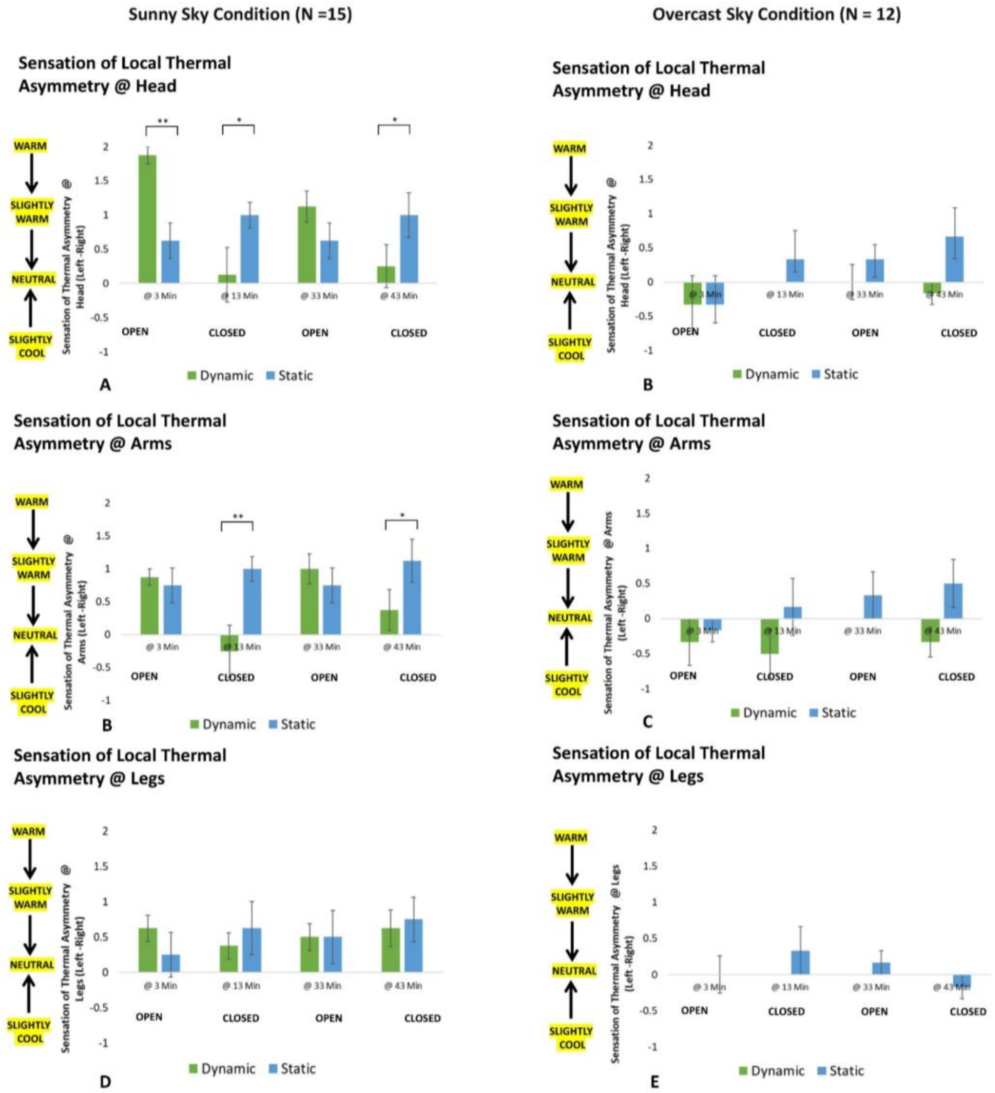


Figure 5.12 Comparative analysis of the participants' perception of local thermal asymmetry at head, hands, and legs during the third and fourth minute of thermal questionnaire Q1. (* indicates $p \leq 0.05$, ** indicates $p \leq 0.01$).

Table 5.5 Difference between the participants' perception of local thermal asymmetry inside the dynamic and static screened set-ups. (* indicates $p \leq 0.05$, ** indicates $p \leq 0.01$).

		Sunny Sky Conditions (N = 15)								Overcast Sky Conditions (N = 12)					
Sensation of Local Thermal Asymmetry @ Head								Sensation of Local Thermal Asymmetry @ Head							
	Dynamic Mean	Static Mean	Dynamic Std. Er.	Static Std. Er.	Dynamic Std. Dev.	Static Std. Dev.	P-value		Dynamic Mean	Static Mean	Dynamic Std. Er.	Static Std. Er.	Dynamic Std Dev.	Static Std. Dev.	P-value
@ 3 Min	1.88	0.63	0.13	0.26	0.35	0.74	0.002**	@ 3 Min	-0.33	-0.33	0.42	0.42	1.03	1.03	0.50
@ 13 Min	0.13	1.00	0.40	0.19	1.13	0.53	0.02*	@ 13 Min	0.00	0.33	0.00	0.42	0.00	1.03	0.23
@ 33 Min	1.13	0.63	0.23	0.26	0.64	0.74	0.14	@ 33 Min	0.00	0.33	0.26	0.21	0.00	1.03	0.23
@ 43 Min	0.25	1.00	0.31	0.33	0.89	0.93	0.02*	@ 43 Min	-0.17	0.67	0.17	0.42	0.41	1.03	0.09
Sensation of Local Thermal Asymmetry @ Arms								Sensation of Local Thermal Asymmetry @ Arms							
@ 3 Min	0.88	0.75	0.35	0.37	0.99	1.04	0.39	@ 3 Min	-0.33	-0.17	0.33	0.17	0.82	0.41	0.35
@ 13 Min	-0.25	1.00	0.37	0.27	1.04	0.76	0.00**	@ 13 Min	-0.50	0.17	0.34	0.40	0.84	0.98	0.18
@ 33 Min	1.00	0.75	0.33	0.25	0.93	0.71	0.18	@ 33 Min	0.00	0.33	0.00	0.33	0.00	0.82	0.18
@ 43 Min	0.38	1.13	0.32	0.40	0.92	1.13	0.04*	@ 43 Min	-0.33	0.50	0.21	0.34	0.52	0.84	0.07
Sensation of Local Thermal Asymmetry @ Legs								Sensation of Local Thermal Asymmetry @ Legs							
@ 3 Min	0.63	0.25	0.18	0.31	0.52	0.89	0.18	@ 3 Min	0.00	0.00	0.00	0.26	0.00	0.63	0.50
@ 13 Min	0.38	0.63	0.18	0.38	0.52	1.06	0.30	@ 13 Min	0.00	0.33	0.00	0.33	0.00	0.82	0.18
@ 33 Min	0.50	0.50	0.19	0.38	0.53	1.07	0.50	@ 33 Min	0.00	0.17	0.00	0.17	0.00	0.82	0.18
@ 43 Min	0.63	0.75	0.26	0.31	0.74	0.89	0.38	@ 43 Min	0.00	-0.17	0.00	0.17	0.00	0.41	0.18

5.3.2.6. *Task performance*

The scores on the tasks like, math, typing, and sudoku were normalized to compare the participants' performance in the dynamic versus the static set-up under different sky conditions. Every participant's task performance in the dynamic set-up was directly compared with his/her own, inside the static set-up. The score for math task was based on the number of questions answered correctly. The score on typing task was calculated as the ratio of correctly typed words to the number of words given. The score on sudoku was calculated as the ratio of correct ones to the total required responses. There was no significant difference of participants' task performance between the dynamic and static screened set-ups under sunny sky conditions (Figure 5.13, A). However, it was significantly better inside the dynamic screened set-up, when the screen was in its' OPEN position (Figure 5.13, B, Table 5.6-right side).

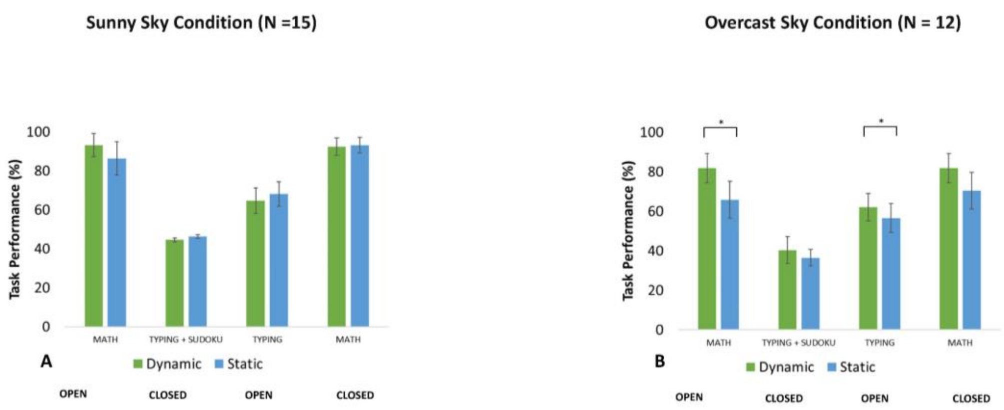


Figure 5.13 Comparative analysis of the participants' task performance. (* indicates $p \leq 0.05$).

Table 5.6 Difference between the participants' task performance inside the dynamic and static screened set-ups. (* indicates $p \leq 0.05$).

		Sunny Sky Conditions (N = 15)								Overcast Sky Conditions (N = 12)					
	Dynamic Mean	Static Mean	Dynamic Std. Er.	Static Std. Er.	Dynamic Std. Dev.	Static Std. Dev.	P-value		Dynamic Mean	Static Mean	Dynamic Std. Er.	Static Std. Er.	Dynamic Std. Dev.	Static Std. Dev.	P-value
MATH	93.18	86.36	6.03	8.58	20.01	28.45	0.14	MATH	81.82	65.91	7.35	9.36	24.39	31.06	0.05 *
TYPING + SUDOKU	44.53	46.30	1.00	1.00	3.32	3.32	0.25	TYPING + SUDOKU	40.28	36.50	6.84	4.19	22.69	13.89	0.15
TYPING	64.73	68.10	6.61	6.32	21.93	20.95	0.20	TYPING	62.01	56.56	7.03	7.26	23.33	24.09	0.02 *
MATH	92.42	93.18	4.56	4.02	15.12	13.34	0.36	MATH	81.82	70.45	7.35	9.36	24.39	31.04	0.15

5.3.2.7. *Linear co-relation between indoor environmental variables and thermal pleasure*

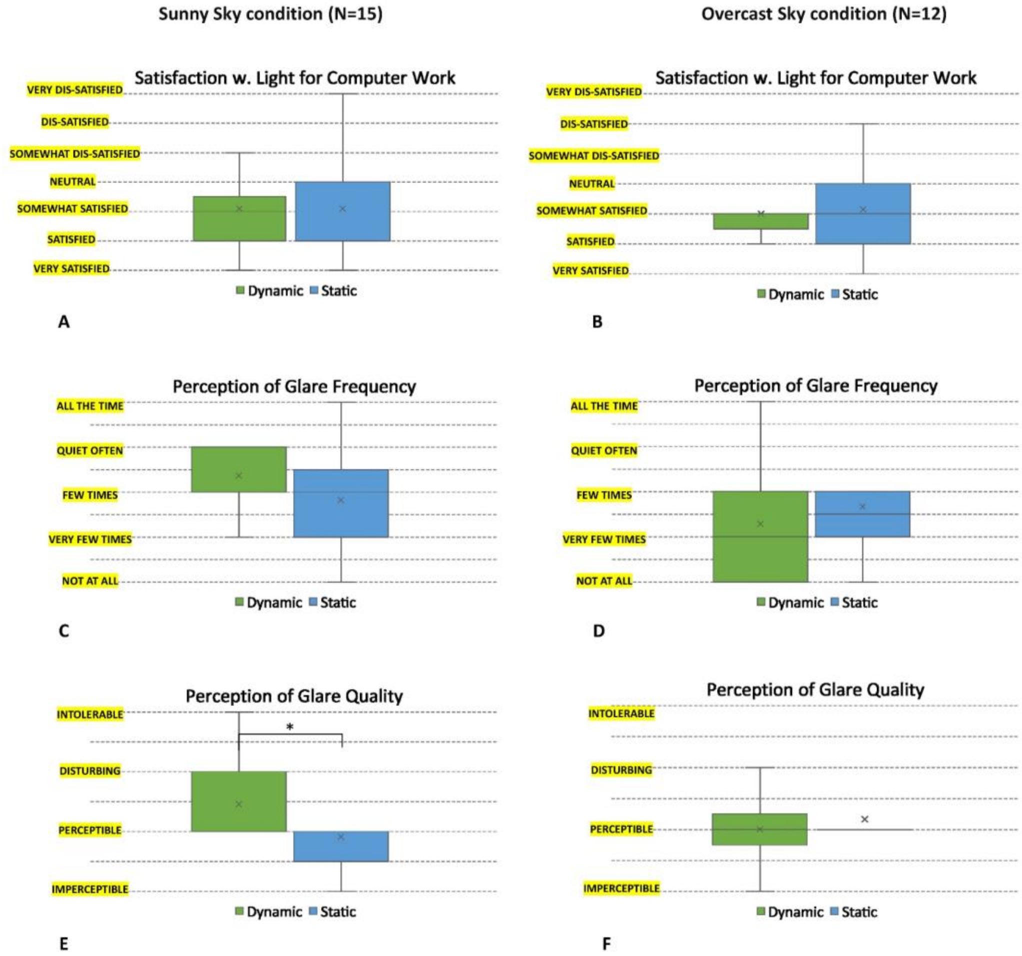


Figure 5.14 Comparative analysis of the participants' perception of the visual environment. (* indicates $p \leq 0.05$).

Inside dynamic set-up under sunny sky conditions, highest and lowest magnitude of thermal pleasure was reported when the screen was in CLOSED and OPEN positions, respectively. Thermal pleasure had a strong, significant, and negative linear relationships with ΔPMV, ΔOT, and horizontal illuminance (Table 5.7, left side). ΔPMV, ΔOT, suggest change in PMV value and Operative Temperature (OT) at a point in time, from that at its previous minute. The negative relationship indicated that the decrease in difference of PMV and OT values from that of the previous minute, increased the chance of a participant sensing thermal pleasure and vice-versa. The operative temperature or ΔOT was the common factor that strongly and significantly influenced thermal pleasure inside sunny sky conditions irrespective of the set-up. Under overcast sky conditions though, it was the relative humidity, which was the only variable that significantly impacted thermal pleasure (Table 5.7, right side). Inside dynamic screened set-up it had a positive relationship with thermal pleasure. While inside the static screened set-up; irrespective of the sky conditions; it had a negative relationship with thermal pleasure.

Table 5.7 Linear relationship of thermal pleasure with indoor environmental variables.

Sunny Sky Condition (N = 15)					Overcast Sky Conditions (N = 12)				
Dynamic Screened Set-Up	r-value	p-value	r^2 value	Equation	**Dynamic Screened Set-Up**	r-value	p-value	r^2 value	Equation
Thermal Pleasure - PMV	0.46	0.14	0.21	y = -1.1435x + 2.0363	Thermal Pleasure - PMV	0.13576	0.67	0.02	y = 0.8967x + 0.0963
Thermal Pleasure - ΔPMV	0.86	0.00***	0.74	y = -7.2652x + 0.4284	Thermal Pleasure - ΔPMV	0.31	0.32	0.10	y = 5.4347x + 0.8135
Thermal Pleasure - OT	0.46	0.13	0.22	y = -0.2168x + 19.443	Thermal Pleasure - OT	0.09	0.78	0.01	y = 0.0738x - 5.3342
Thermal Pleasure - ΔOT	0.86	0.00***	0.73	y = -1.3236x + 0.4294	Thermal Pleasure - ΔOT	0.17	0.61	0.03	y = 0.4558x + 0.8135
Thermal Pleasure - RH	0.19	0.17	0.03	y = 0.7903x + 46.851	Thermal Pleasure - RH	0.42	0.01*	0.17	y = 0.6791x + 55.457
Thermal Pleasure - H. Illuminanc	0.32	0.03*	0.1	y = -4E-05x + 0.8726	Thermal Pleasure - H. Illuminance	0.28	0.07	0.08	y = 0.0002x + 0.407
Static Screened Set-Up	r-value	p-value	r^2 value	Equation	**Static Screened Set-Up**	r-value	p-value	r^2 value	Equation
Thermal Pleasure - PMV	0.31	0.33	0.10	y = -2.9618x + 3.3725	Thermal Pleasure - PMV	0.283975	0.37	0.08	y = -0.7516x + 0.5443
Thermal Pleasure - ΔPMV	0.02	0.94	0.00	y = 0.8811x + 0.7087	Thermal Pleasure - ΔPMV	0.12	0.71	0.01	y = 3.1003x + 0.2924
Thermal Pleasure - OT	0.61	0.03*	0.38	y = -0.4256x + 36.934	Thermal Pleasure - OT	0.29	0.37	0.08	y = -0.1221x + 10.129
Thermal Pleasure - ΔOT	0.51	0.09	0.26	y = 2.792x + 0.6254	Thermal Pleasure - ΔOT	0.03	0.93	0.00	y = 0.1166x + 0.304
Thermal Pleasure - RH	0.36	0.005**	0.12	y = -4.2571x + 42.373	Thermal Pleasure - RH	0.32	0.03*	0.10	y = -3.5913x + 62.612
Thermal Pleasure - H. Illuminanc	0.111	0.398	0.01	y = 834.34x + 8500.7	Thermal Pleasure - H. Illuminance	0.42	0.34	0.02	y = 225.63x + 1358.4

5.3.2.8. General perception

Majority of the participants were satisfied with the lighting for computer related tasks inside the dynamic and static set-ups in both the sky conditions (Figure 5.14). However, glare perception and the incidents of feeling disturbed due to it were significantly higher inside the dynamic set-up compared to that inside the static under sunny sky conditions (Figure 5.14, C-E). Another important finding was that there were significant differences in the participants' perception of outdoor visual access and privacy between dynamic and static screened conditions under overcast sky conditions (Figure 5.15). While the participants were satisfied with the degree of privacy inside both the set-ups, the static was rated to be significantly better than the dynamic (Figure 5.15, D). On the other hand, the dynamic set-up significantly outperformed the static in offering satisfaction with respect to an access to outdoor view (Figure 5.15, E). There was not a significant difference in the participants' satisfaction with privacy and outdoor visual access between dynamic and static screened set-ups under sunny sky conditions. This is also indicative of that people's desire for outdoor visual access may not be important when a façade receives direct sunlight.

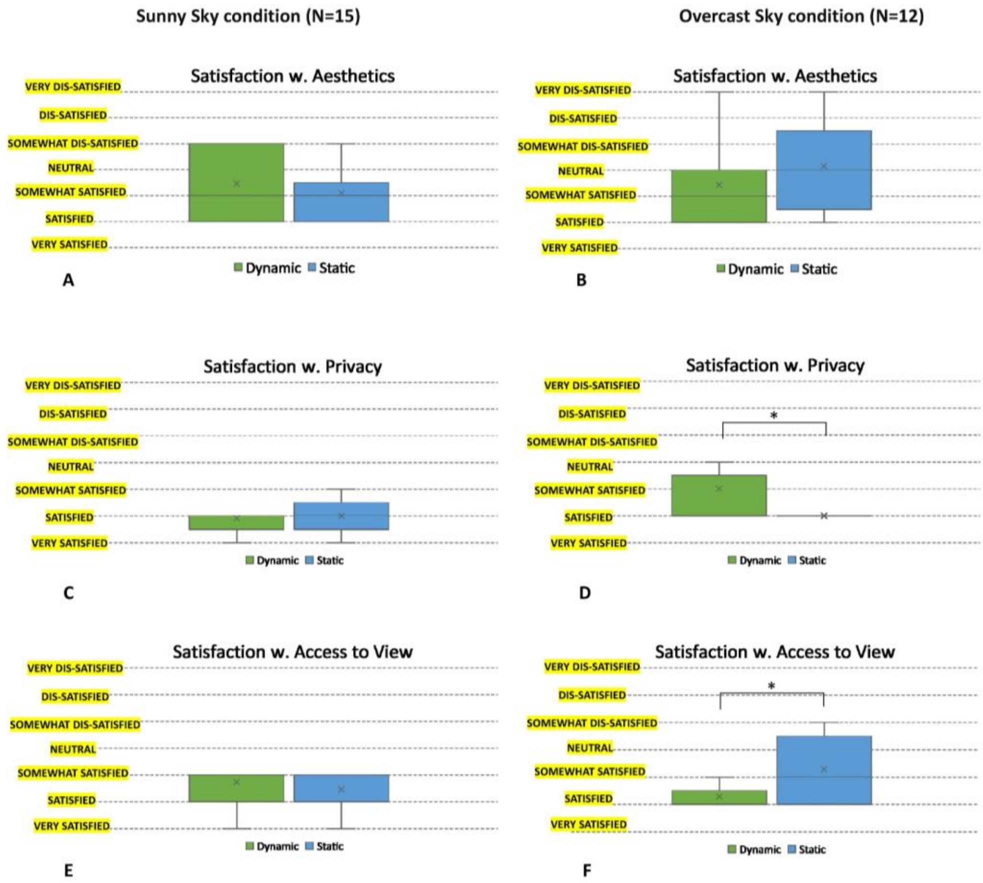


Figure 5.15 Comparative analysis of the participants' perception of aesthetics, privacy, and outdoor visual access. (* indicates $p \leq 0.05$).

5.3.2.9. Further Analysis

This analysis was focused on (i) highlighting the difference between predicted and actual thermal comfort, (ii) observing the relationship between thermal pleasure and thermal sensation responses, and (iii) observing the relationship changes in the visual environment with that of thermal pleasure.

As shown in Figure 5.16, PMV trends for static and dynamic set-ups under sunny sky conditions, predicted the thermal environment of the set-ups as thermally discomforting, towards the warmer side (Figure 5.16 - A, B). Whereas the actual subjective thermal sensation was reported to be transiting between slightly warm and slight cool, within the comfort zone. The PMV trends for static and dynamic screened set-ups under overcast sky conditions predicted the indoor thermal environment to be between slightly warm and neutral (Figure 5.16- B, C). But the participants sensed these thermal environmental conditions between neutral and slightly cool. This visual analysis reinforces the observations in previous studies that the predicted mean vote (PMV) metric over-predicts an occupant's thermal discomfort.

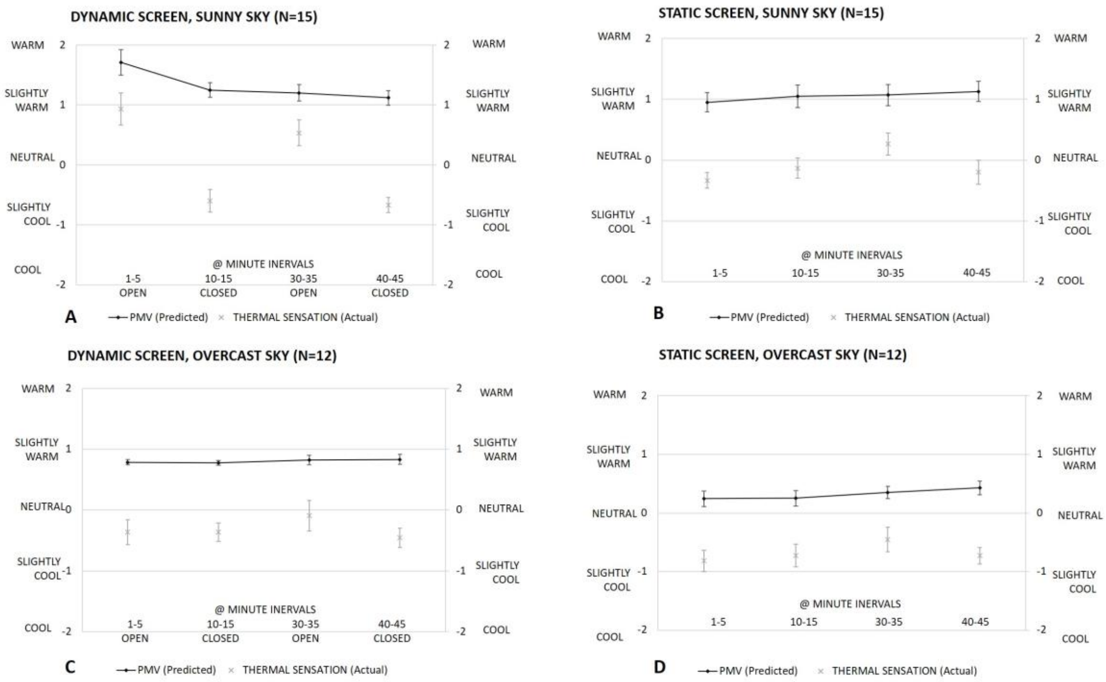


Figure 5.16 Difference between predicted and actual thermal sensation.

A participant's reporting of thermal pleasure was dependent upon (i) his/her base case thermal sensation and (ii) change in his/her thermal sensation from that of the base case feeling (Figure 5.17). For the dynamic screened set-up under sunny sky conditions, the base case thermal condition was sensed to be slightly warm (Figure 5.17 - A). When the screen CLOSED from OPEN position, participants sensed the change in the indoor thermal environment from slightly warm to slightly cool, which is when they reported thermal pleasure. Similarly, for dynamic set-up under overcast sky conditions (Figure 5.17 - C) and static set-up under sunny sky conditions (Figure 5.17 - D), the base case thermal environment was sensed as slightly cool. A higher magnitude of thermal pleasure was reported when transition in the indoor environment was sensed from slightly cool towards neutral when the screen changed to OPEN from a CLOSED position (Figure 5.17- C). A strong co-relation between horizontal illuminance and thermal pleasure under sunny sky conditions can be observed in Figure 5.18.

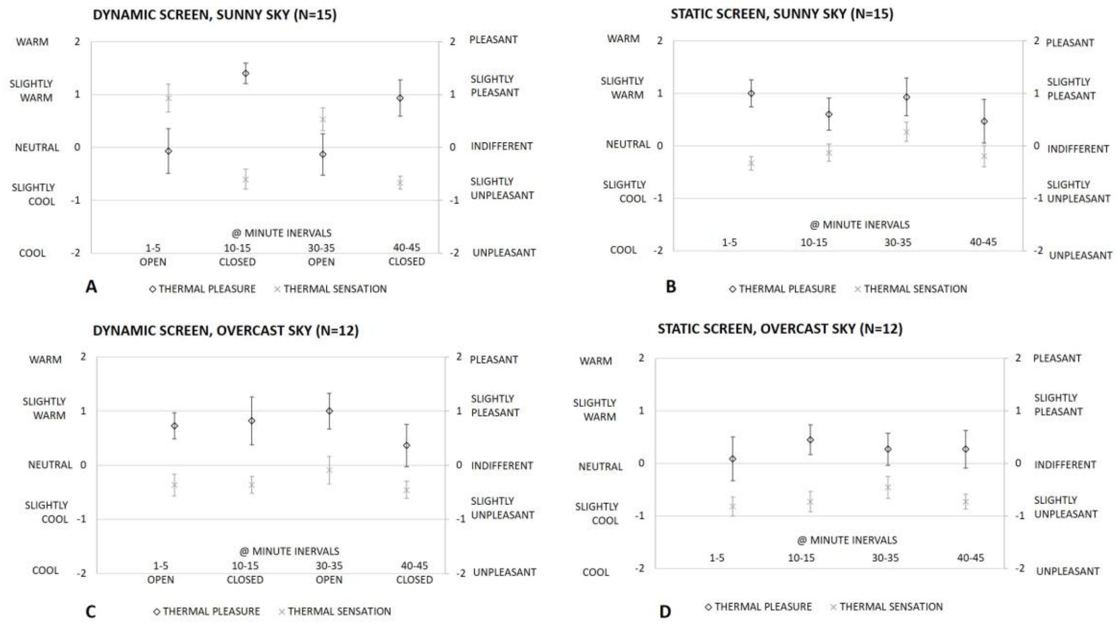


Figure 5.17 Participants' thermal sensation and its relationship with their thermal pleasure reporting.

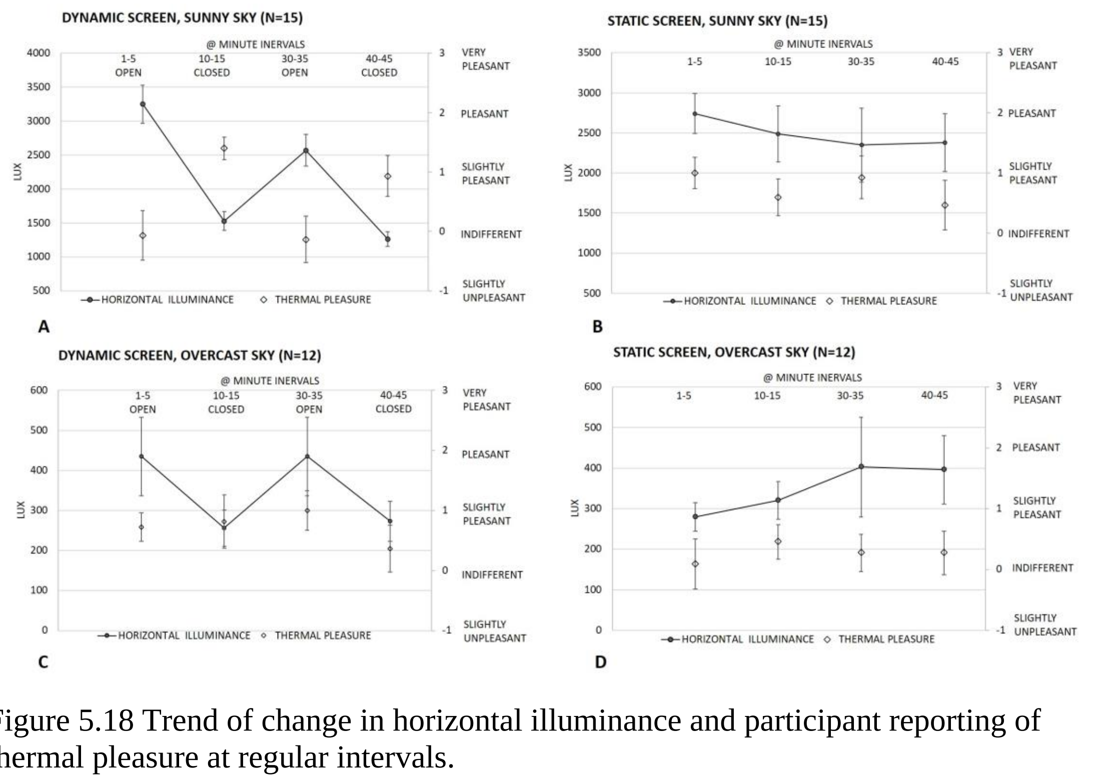


Figure 5.18 Trend of change in horizontal illuminance and participant reporting of thermal pleasure at regular intervals.

5.4. Summary: significance of the dynamic over the static screens

Compared to the static, the dynamic screen had a significant influence on the participants' thermal perception. The significance in difference on thermal pleasure was possible when the dynamic screen was in its' CLOSED position under sunny sky condition and in OPEN position under overcast sky condition. Co-relations established between the participants' thermal pleasure with variables like ΔPMV, ΔOT, and horizontal illuminance, suggests that the dynamic screen' closing led to decrease in the indoor environmental parameters, which prompted the hedonic sensation in the participants inside the set-up under sunny sky conditions. Co-relation of thermal pleasure with horizontal illuminance under sunny sky conditions showed that visual environmental variability may also influence an occupant's thermal perception.

The data analysis indicates the participants' displeasure with higher operative temperature and illuminance values in the OPEN position. The instance of the screen's closing from OPEN position reduced these thermal-visual parameters and significantly impacted a participant's perception of (i) transition of overall thermal sensation from warm to cool and (ii) the local sensation of reduction in the upper body thermal asymmetry. A sharp drop in horizontal illuminance values from around 3000 lux (300 fc) to lower values indicated a potential reduction in thermal stress associated with higher illuminance. Thus, it can be concluded that dynamic screen movement could successfully create a physiological load error in human participants; in OPEN position; and correct it by facilitating the generation of a useful thermal stimulus; in CLOSED position; to influence the hedonic sensation under sunny sky condition.

Under overcast sky condition, it was in the OPEN position when the dynamic screen outperformed the thermal pleasure than that inside the static. The dynamic screen movement, however, did not influence a participant's overall and local thermal sensation any differently than the static screen. The analysis of linear relationships of thermal pleasure with indoor environmental thermal-visual variables suggests that except the relative humidity none of those factors impacted the hedonic sensation under overcast sky conditions. The general perception analysis indicates that the outdoor visual access possibly influenced the significance of the dynamic over the static screen on thermal pleasure. Thus, while the application of a dynamic screen shading may seem more suitable for an occupant-centric design for thermal perception in climates with sunny sky conditions, it does have benefits in overcast sky conditions also. Next, this experiment provided some evidence that dynamic screened set-up outperformed the static in impacting task performance under overcast sky conditions. However, it should be noted that the participant's exposure to the set-ups was only for an hour and that longer exposures involving robust tasks will be required to arrive at a stronger conclusion.

The findings from this study are applicable for summer months of moderate climatic conditions of ASHRAE CZ-4C. The positive impact of dynamic screens under overcast sky conditions is encouraging and suggestive of investigating their impact on overall sensory pleasure, preference, and task performance during the permanently overcast sky conditions in winter months of ASHRAE CZ-4C. Next, the study proved that dynamic screens can significantly impact thermal pleasure and sensation under sunny sky conditions. The researchers propose studies to investigate dynamic screen's impact on thermal perception in tropical climates with hot-dry, warm-dry, hot-humid, and warm-humid conditions. Moreover, besides single occupancy offices, the researchers also propose to investigate the impact of dynamic screens on thermal perception in space types like, waiting rooms, hotel rooms, and home offices.

CHAPTER VI: FINDINGS, IMPLICATIONS, AND FUTURE WORK

The goal, through this dissertation research, was to explore thermal pleasure in perimeter office spaces using solar screens as the media that controlled the indoor environment. This exploration was intended during the summer months of Eugene, Oregon (44.4 °N 123.5 °E), ASHRAE Climate Zone (CZ)-4C. The series of objectives that followed to achieve the goal were (i) to determine suitable solar screen typologies for thermal environmental control, (ii) to design and fabricate dynamic and static screens that can influence thermal pleasure in ASHRAE-CZ-4C, (iii) to investigate the impact of dynamic and static screens on the indoor thermal environment and human physiological variables (iv) to quantify the relationships of subjective thermal pleasure with human physiological variables, and the thermal environmental parameters inside the dynamic and static screened spaces (iv) to compare the impact of the dynamic versus the static screen in influencing thermal pleasure under different sky conditions, and (v) to observe the impact of sky conditions on thermal pleasure. The following sections summarize the main findings from the studies that were conducted to address each objective.

6.1. Solar screens suitable for thermal environmental control

The review of previous work on solar screens helped to identify that frequently studied solar screen typologies were (i) massive static, (ii) light-weight static, (iii) dense dynamic, and (iv) 3-D geometric dynamic. Massive static and dense dynamic screens essentially have higher number and smaller sized perforations in a unit area of thick shading panels. Whereas light-weight static and 3-D geometric dynamic screens have lower number and larger sized perforations in a unit shading area that is mounted on light-weight structures. Screen panel thickness is not accounted in light-weight static and 3-D geometric dynamic screens.

The meta-analysis of the thermal performance of these screens revealed that the impact of solar screens on occupant thermal perception was under-researched. But the analysis clarified that massive static and deep dynamic screen can potentially increase 10-15% energy savings on building cooling and reduce solar heat gain by 20-25%

compared to the light-weight static and 3-D geometric screens. Thus, massive static and dense dynamic screens are the suitable shading typologies for indoor thermal environmental control.

Unlike the movable-dense dynamic screens, designs of the non-moveable massive static screens are optimized for the worst-case climate conditions. From an observational field study carried out inside a building shaded by the massive static screens, it was found that the screened areas achieved thermal uniformity and comfortable conditions (as predicted by the thermal comfort metrics). However, people frequenting the building preferred to occupy zones that had thermally non-uniform conditions, which were predicted to be slightly discomforting on the warmer side. These observations were suggestive towards the importance of providing thermally non-uniform environments for occupant preference. Moreover, it was also conceptualized that dense dynamic screen if designed to change between geometric parameters that were less and more than their optimised values, may achieve desirable thermal non-uniformity compared to the massive static screens.

6.2. Design of the solar screens and respective thermal environments to elicit thermal pleasure during human exposure

Application of a static screen (massive static), with optimized geometric parameters (PR, DR) = (50%, 0.1); perforation ratio (PR) = % of void and depth ratio (DR) = void depth/ void width; to the east-façade of an office predicted occupant thermal sensation close to neutrality (PMV close to 0) in spaces located within 15’ (4.5 m) from the façade. For an office with the static screen, it was hypothesized that the thermal non-uniformity created by naturally occurring outdoor environmental changes like; solar transit would mildly influence the perception of thermal pleasure.

Application of a dynamic screen (dense dynamic), that could change its geometric parameters between (PR, DR) = (90%, 0.1) and (PR, DR) = (10%, 0.1), to the east-façade of an office predicted transition in occupant sensation from slightly hot (PMV close +0.5) to slightly cool (PMV close -0.5) conditions. For an office with the dynamic screen, it was hypothesized that the indoor thermal non-uniformity created by it would substantially influence the perception of thermal pleasure.

The full-scale, static screen prototype was a fixed screen panel with the optimized geometric parameters (PR, DR) = (50%, 0.1). The full-scale, dynamic screen prototype was composed of two sliding panels that could alternatively overlap between OPEN and CLOSED positions. The position in which the panels were not overlapping was named OPEN that is when the screen with (PR, DR) = (90%, 0.1) shaded the window. The CLOSED position was when the screen with (PR, DR) = (10%, 0.1) overlapped the screen with (PR, DR) = (90%, 0.1) through the sliding mechanism.

Pilot monitoring of the thermal conditions inside the screened set-ups informed that 8:00 to 11:00 AM was the time when the intended thermally non-uniform conditions were achieved in both the experimental office set-ups. Changes in the dynamic screen led to a drop or rise in the indoor operative temperature by 4-6°F (1.7-2.8 °C) within five minutes of the screen's position change. The dynamic screen's movement was finalized to change between OPEN and CLOSED positions in 10-20-10 minute intervals during human exposure. With this movement frequency, it was possible to keep the indoor environment comfortable for most of the time besides creating short instances (10 minutes) of a slightly warm environment when in an OPEN position.

6.3. Relationship of thermal pleasure with physiological variables, and parameters inside the static and dynamic screened spaces under different sky conditions

Under sunny-sky conditions, the thermal pleasure strongly correlated with both indoor environmental and participants' physiological variables namely ΔPMV (the change in PMV value from that of the previous minute's), OT (operative temperature), ΔOT (the change in OT from that of the previous minute's), and ΔTsk_{HZ} (difference between left-hand and right-arm skin temperatures. Under overcast sky conditions, a strong correlation of the thermal pleasure was found to exist with physiological variables only that is with ΔTsk_{HZ}.

A drop in operative temperatures by 0.25-0.5 °C per minute within a base case range of 28-31 °C had a strong and significant influence ($r^2 = 0.73$, $p < 0.001$) on thermal pleasure inside dynamic screened set-up under sunny sky conditions. Next, even slight non-uniformity in the indoor operative temperatures within a base case range of 29-30 °C also had a strong and significant relationship with thermal pleasure perception inside the static screened set-up under sunny sky conditions. These findings align with those from previous studies (Parkinson et al., 2016; Traylor et al., 2019), within which it was found that temperature step-downs strongly influenced the thermal pleasure of a person in a sedentary state. Findings by Parkinson et al. (2016) applied to a wider ambient temperature range of 18-31 °C and findings by Traylor et al. (2019) were applied to a narrower and comfortable ambient temperature range of 22-26 °C. Thermal pleasure reporting inside the dynamic and static screened set-ups built on the existing findings that it is possible to provide for hedonic thermal sensations by designing slight changes in base case temperatures that are in the upper fringes of the thermal neutrality limits.

Next, under sunny sky conditions, a person's left side (facing the screen) was warmer than the right. In this situation, changes in the horizontal skin temperature asymmetry by ±0.5 °C from its status quo in the screened set-ups influenced thermal pleasure. Under overcast sky conditions, a participant's left side (facing the screen) was cooler than the right side. In this situation the rise in horizontal skin temperature asymmetry by +0.2 °C from its status quo could evoke thermal pleasure in the dynamic and static set-ups. These findings align with those from the study by Parkinson and de Dear (2016), who found that "corrective differences in the rate of change in skin temperature between individual body segments" evokes thermal pleasure.

Irrespective of the sky conditions, the contribution of thermal environment and human physiological variables in explaining variability in thermal pleasure inside the static and dynamic set-ups was 33% and 81%, respectively. This implied the involvement of other non-thermal variables as well in influencing thermal pleasure.

6.4. Influence of dynamic versus static screens on thermal and general environmental perception under different sky conditions

The dynamic screen outperformed the static in significantly influencing the participants' overall and localized thermal sensation, and thermal pleasure under sunny sky conditions. A significant difference in thermal pleasure perception was observed when the dynamic screen was in its' CLOSED position. The instance of the screen's closing from the OPEN position impacted the participants' perception of (i) transition of overall thermal sensation from slightly warm to slightly cool, and (ii) the localized sensation of reduction in the upper body thermal asymmetry, which as conceptualized by thermal alliesthesia, explained thermal pleasure inside dynamic screened set-up under sunny sky conditions.

The dynamic screen outperformed the static in influencing the participants' thermal pleasure responses and task performance under overcast sky conditions. A significant difference in thermal pleasure perception was observed when the dynamic screen was in its' OPEN position. The dynamic screen movement, under overcast sky conditions, however, did not influence a participant's overall and local thermal sensation any differently than the static screen. The general environmental perception analysis indicated that the participants' satisfaction with the outdoor visual access could have possibly influenced the significance of the dynamic over the static screen on thermal pleasure.

6.5. Impact of visual environment and sky conditions on thermal pleasure

Besides the indoor thermal parameters, thermal pleasure also had a strong co-relation with the visual environmental parameter that is the horizontal illuminance, inside the dynamic screened set-up under sunny sky conditions. A sharp drop in horizontal illuminance values from around 3000 lux (300 fc) to lower values, when the screen changed positions, indicated a potential reduction in thermal stress associated with higher illuminance. Thus, it can be understood that higher magnitude of thermal pleasure reporting was observed when there was a transition from discomfort/stress towards comfort/destress.

Thermal pleasure reporting under overcast sky conditions did not respond to the movement of the dynamic screen as much as that observed under sunny sky conditions. This may suggest that designing dynamic screens for thermal pleasure could be a more appropriate design application for buildings in climates that have higher number of days with sunny sky conditions, annually. However, this does not negate the possibility of dynamic screen applications to buildings in climates that have higher number of days with overcast sky conditions. While the dynamic screens can provide for thermal pleasure during warm summers in such climates, their designs can be targeted for visual pleasure and environmental variability for overall sensory pleasure.

6.6. Implications, limitations, and future work

The findings provide experimental evidence that expands the application of the thermal alliesthesia framework to building perimeter offices. They show a possibility to invoke pleasurable thermal sensations by designing slight changes in base case temperatures that are outside the upper fringes of the thermal neutrality limits. The importance of indoor thermal environmental variability for occupant pleasure and well-being is demonstrated through this work. Given the current need for investigations in occupant-centric building and indoor environmental design, these findings contribute to the field by showing how external facade shading can be designed to be occupant-centric. This work will be of interest to scholars, architects, building designers, engineers, and students interested in research on thermal comfort, indoor environmental quality, adaptive shading, and passive architecture. Globally, practicing architects and students in architectural academia have demonstrated interest in using solar screen shading for façade aesthetics. This work informs on how passive strategies like façade shading can also be used to control the indoor environmental variability in the building perimeter spaces.

During the experiment with human participants, the dynamic screen operation was time-dependent and was manually controlled by the researcher. The strong and significant relationship of thermal pleasure with indoor thermal environmental and human physiological variables in the dynamic screened set-up under sunny sky conditions suggested that real-time sensing of these variables can be used to guide the dynamic screen automation design for thermal pleasure in future work related to this study in ASHRAE CZ-4C. Events like (i) drop in operative temperatures by 0.5-1 °F inside ambient temperatures of 80-89 °F or (ii) change in horizontal skin temperature asymmetry by ±1 °F under sunny sky conditions and +0.5 °F under overcast sky conditions can be used to automate the screen closing to influence thermal pleasure. Further, the manual control of the screen opening from its automated closed position should be allowed to the occupants/human participants because lack of such control may lead to their dissatisfaction.

The exploration of thermal alliesthesia in the present study was limited to a climate that does not experience large thermal swings. Moreover, an experimental research method was used involving a limited number of participants who were exposed to the solar screened set-ups for a finite timeframe. The findings from this work may not be applicable to other climates such as hot-humid, hot-dry, and to geographically, culturally, and demographically wider population. Next, the non-thermal indoor environmental variables such as aesthetics, privacy, daylighting, and glare might have impacted thermal pleasure perception in some capacity. However, their impact has not been investigated in this research.

For future work, it is intended to expand this exploration of thermal alliesthesia inside south and west facing perimeter spaces and at different timeframes during the day and year in ASHRAE-CZ-4C. Moreover, developing this work for buildings in tropical climates is intended. It is expected that the application of solar screens for thermal pleasure in tropical climates, specifically for buildings in countries of the Global South may prove very beneficial for occupant health and well-being. Technologically driven sustainable development measures like Net-Zero and Net-Positive buildings are proposed as responses to the climate change for countries in the Global North. But these buildings can be made possible with expensive consultation and sophisticated technologies like efficient air-conditioning systems, triple-glazing systems, high-performance envelopes etc., which cannot be afforded for majority building lot in the Global South. Thermal comfort comes at a very high cost in these countries. Moreover, the people who occupy the tightly controlled and conditioned buildings in the warm and hot tropical climates of the countries in Global South become less adaptive and resilient to environmental variability (Manu et.al, 2016). Thus, provision for thermal pleasure instead of thermal comfort need to be examined more for occupant well-being and building energy efficiency for buildings of countries of the Global South. Solar screens being the age-old and proven strategies for thermal environmental control should thus be reimagined and used for thermal pleasure. In addition to single occupancy offices, the exploration and application of dynamic screens for thermal pleasure and multi-comfort inside space types like hospital waiting rooms, hotel rooms, home offices, and open dining facilities; will provide vital findings for developing healthy, naturally ventilated buildings of the new world that is prone to pandemics.

Next, it was identified that other non-thermal variables like; outdoor visual access, privacy, aesthetics, and visual environmental parameters could have impacted the thermal pleasure perception. The impact of these non-thermal variables on thermal pleasure should be investigated using experimental approaches that may allow a robust control over outdoor environmental parameters. It is recommended that the impact of these variables can be best examined through user-perception studies on VR headsets in enclosed environments like environmental chambers that allow for the control of all the thermal environmental parameters. Lastly, the positive impact of dynamic screens on thermal pleasure and task performance under overcast sky conditions during winter months of ASHRAE CZ-4C encourages to investigate them further by involving more participants for longer experimental exposures.

APPENDIX

A.1 Sample Math Questions

1) $\frac{3}{10} \times \frac{2}{3} =$

2) $\frac{2}{4} \times \frac{1}{2} =$

3) $\frac{3}{10} \times \frac{2}{4} =$

4) $\frac{2}{5} \times \frac{2}{10} =$

5) $\frac{2}{4} \times \frac{2}{3} =$

6) $\frac{1}{2} \times \frac{1}{4} =$

7) $\frac{1}{2} \times \frac{3}{5} =$

8) $\frac{7}{10} \times \frac{2}{5} =$

9) $\frac{2}{3} \times \frac{1}{2} =$

10) $\frac{2}{3} \times \frac{1}{10} =$

A.2 Sample Sudoku Question

SUDOKU

5	4			2		8		6
	1	9			7			3
			3			2	1	
9			4		5		2	
		1				6		4
6		4		3	2		8	
	6					1	9	
4		2			9			5
	9			7		4		2

ANSWER:

5	4	3	9	2	1	8	7	6
2	1	9	6	8	7	5	4	3
8	7	6	3	5	4	2	1	9
9	8	7	4	6	5	3	2	1
3	2	1	7	9	8	6	5	4
6	5	4	1	3	2	9	8	7
7	6	5	2	4	3	1	9	8
4	3	2	8	1	9	7	6	5
1	9	8	5	7	6	4	3	2

A.3 Sample Typing Question Content

Abstract: The indoor environmental quality (IEQ) of buildings can have a strong influence on occupants' comfort, productivity, and health. Post-occupancy evaluation (POE) is necessary in assessing the IEQ of the built environment, and it typically relies on the subjective surveys of thermal quality, air quality, visual quality, and acoustic quality. In this research, we expanded POE to include both objective IEQ measurements and the technical attributes of building systems (TABS) that may affect indoor environment and user satisfaction. The suite of three tools, including user satisfaction survey, workstation IEQ measurements, and TABS in the National Environmental Assessment Toolkit (NEAT) has been deployed in 1601 workstations in 64 office buildings, generating a rich database for statistical evaluation of possible correlations between the physical attributes of workstations, environmental conditions, and user satisfaction. Multivariate regression and multiple correlation coefficient statistical analysis revealed the relationship between measured and perceived IEQ indices, interdependencies between IEQ indices, and other satisfaction variables of significance. The results showed that overall, 55% of occupants responded as "satisfied" or "neutral", and 45% reported being "dissatisfied" in their thermal quality. Given the dataset, air temperature in work area, size of thermal zone, window quality, level of temperature control, and radiant temperature asymmetry with façade are the critical factors for thermal quality satisfaction in the field. As a result, the outcome of this research contributes to identifying correlations between occupant satisfaction, measured data, and technical attributes of building systems. The presented integrated IEQ assessment method can further afford robust predictions of building performance against metrics and guidelines for IEQ standards to capture revised IEQ thresholds that impact building occupants' satisfaction.

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