External Dynamic Screens for Thermal Delight and 'Alliesthesia'

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External dynamic screens, inspired from geometric patterns of vernacular screens, are popular building facade treatments because of their aesthetic significance. Their potential to impact building cooling energy demand and visual comfort has been well-realized, However, their impact on occupant comfort has been under-researched. This study is part of a larger research problem that investigates the impact of external dynamic screens on occupants' thermal comfort and 'alliesthesia'/thermal pleasure. This paper focuses on investigating the sensitivity of predicted thermal comfort to geometric parameters of a screen using computational simulations. Results from this sensitivity analysis were used to address the question, as to how can external dynamic screens be designed to create transient yet comfortable thermal environments. The present study formed a basis to inform the design and development of screen prototypes and experiments involving human subjects. It provides architects and architecture students with an approach, where design intentions impact occupant thermal delight, beyond aesthetics.

1. INTRODUCTION

1.1 Significance of External Dynamic Screens.

External dynamic screens (EDSc) are operable, perforated shading elements that reduce solar loads on building facades. Unlike static/fixed screens, EDSc can be designed to change their geometric properties in response to the temporal variability in the outdoor environmental factors as well as occupant's multi-comfort demands. Their interlined perforations form small shading equivalents to the horizontal overhangs and vertical fins due to which EDSc can potentially reduce cooling energy demand and impact visual comfort in building perimeter zones within 15' of a building envelope.[1-4]

Some examples of EDSc found globally have been illustrated in Fig. 1. Many among these designs and EDSc concepts found in current building trends are inspired from the screens of the vernacular building facades of North Africa, Middle East, and the Indian sub-continent. The vernacular screens are one of the major elements of visual interest due to their geometric patterns.[5] These properties borrowed from vernacular screens offer an aesthetic importance to the EDSc, setting them apart from other adaptive façade types. Because of their ability to control high and low angle sun, add biophilic elements to the indoor environment, and regulate view and privacy, EDSc have prominent environmental, aesthetic and cultural significance.[6-8]

Despite this significance, EDSc's aesthetic factor is the only reason due to which architects' and building patrons' have an interest in using these technologies.[9] Buildings with EDSc are scarce and scattered globally with no available post-occupancy studies to understand their impacts on occupants. Though several computational studies have researched EDSc's significance in achieving building energy savings, there is a knowledge gap on how these systems would influence occupant's comfort.[10-12] Quantification of EDSc's impact on occupants is essential to inform its future designs and market adaptability.

An extensive literature review was conducted in the fields of EDSc and adaptive facades, static screen shading, and thermal comfort. This literature has been briefly discussed in the following section. This review helped identify gaps in current research on EDSc and adaptive facades. Moreover, review of current research in thermal comfort influenced questions to design for occupant centric EDSc.

1.2 Previous Investigations

1.2.1 EDSc and adaptive facades, current research and assessment methods

Major studies on EDSc and adaptive facades were focused on creating a classification framework based on their operational mechanism; primarily their 'movement' and 'control'.[13-15] With the advancement in material technologies and computational capabilities, new possibilities to design EDSc operation are available.[16-18] This makes every EDSc design to be unique and customized for respective location, geography, orientation, client requirement, budget, building type and many other parameters.[19] The common aspect about all EDSc types is their ability to change.

Energy consumption, indoor environmental quality (IEQ), and socio-cultural aspects (view-privacy) are the building performance variables which will be directly impacted by EDSc;

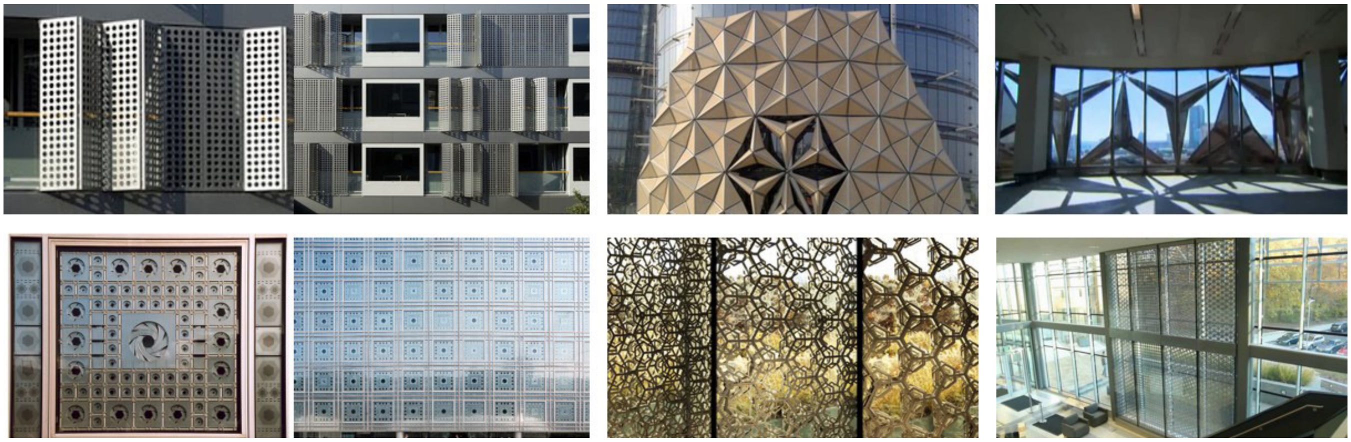

Figure 1. Examples of EDSc globally. (Top Left) EDSc of Ljubljana University Housing, Slovenia; (Top Right) EDSc of Al Bahr Towers, Abu Dhabi , (Bottom Left) EDSc of Arab World Institute, France, (Bottom Right) EDSc of Simons Center of Geometry and Physics, NY. Image credits. http://kinet-icfacade.blogspot.com/2010/04/ljubljana-university-housing-by-bevk.html; https://inhabitat.com/exclusive-photos-worlds-largest-computerized-facade-cools-aedas-al-bahr-towers/al-bahar-towers-lead/; http://www.archdata.org/buildings/12/arab-world-institute#image-19; https://www.azahner.com/blog/perfect-perforated-metal-inspiration

ultimately affecting the indoor occupant. Most of the investigations on dynamic facade shading performance were conducted using computational simulations. [20-22] These studies focused on developing algorithms or tools that predicted EDSc shade positions to achieve optimized visual comfort performance for specific time of a day and year. [23,24]

Computational simulations are efficient and inexpensive with respect to cost and time. They offer flexibility of modeling and testing design alternatives in different outdoor environmental conditions. However, their major limitation is the inability to predict impacts of the shading systems on occupants. With an intent to investigate EDSc impact on occupants, Attia attempted to conduct a field study at Al Bahr Towers, Abu Dhabi collecting occupant responses on thermal and visual comfort in the building.[25] However, these occupant responses were not correlated with the indoor environmental physical measurements of the building.

Field studies are ideal methods to investigate actual building performance and occupant comfort under the influence of EDSc. However, most of the EDSc shaded buildings are scarce and have tightly secured access.[26] Due to which, experimental methods with full scale EDSc prototypes on test cells involving human subjects are suitable to study EDSc's impact on occupants. The limitation with the experimental method is the amount of cost and time investment that is involved with construction and testing of the actual prototypes. Moreover, testing different alternatives of EDSc prototypes is very challenging with this method. Performing computational simulations prior to conducting experiments can help define the scope of experiments. A sensitivity analysis of various design parameters can be performed using simulations and the results can be used to plan the experiment in the most efficient manner. To be able to test different EDSc alternatives and to understand their impact on occupants, use of mixed methods have been preferred in previous studies that have investigated window blinds and roller shades.[27,28]

1.2.2 EDSc and associated geometric variables

Over twenty-two recent studies have focused their investigations on static screens. Many of these studies documented the geometric parameters of vernacular screens. Screens, based on the documented geometric parameters, were modelled in computational environments with an objective of optimizing them for energy and visual comfort performance for different climates.[29-32] The geometric parameters of screens that have been frequently researched are perforation ratios (PR, i.e., % of open), depth ratios (DR, i.e., opening depth to opening width ratio) and perforation geometry. Screens with PR = 80 to 90% and DR = 0.5 or 1 provided optimum daylighting and cooling energy savings compared to non-shaded conditions.[33-35] These recommended parameters resulted into a light-weight screen typology with large and deep openings that do not perform very well at controlling glare.[36-38] Massive screens with higher distribution of small openings in 1"- 3" thick panels increase diffused daylight and reduce glare.[39]

Massive screens with 30 to 50 % PR and 1"- 3" thicknesses are found to provide optimum cooling energy savings compared to non-shaded conditions. Also, they are recommended for achieving thermal comfort.[40-43] Screens with 50% PR and 1" thickness, as optimized geometric parameters, are suggested for balanced daylighting performance and cooling energy savings across different climates.[44-45] Furthermore, rhombus shaped perforations offer better daylighting performance compared to square, triangular, circular, hexagonal or octagonal shapes.[46]

From this comprehensive review of over twenty-two studies it is concluded that screens were largely investigated for impact on a building's cooling energy, daylighting, and visual comfort performance. Their prominent impact on thermal comfort is acknowledged across all the studies, however the topic remains under-researched. Furthermore, screens have been mostly researched for hot-dry, hot-humid, and hot-arid climates. Their performance in moderate climates also needs further studies as it has been identified that they have the potential to increase about 9 to 13% of occupant's comfort hours during summer months in such climates.[47]

1.2.3 EDSc and thermal comfort-alliesthesia

Current thermal comfort standards prescribe narrow limits of thermal conditions as 'comfortable' (ASHRAE-55, 2017). Abiding by these standards lead to 'neutral' and 'uniform' thermal environments. Not only do these 'neutral thermal' conditions demand high energy but also bring 'thermal boredom' to occupants.[48]

A fundamental paradigm shift in the conception of comfort was observed since the last decade.[49,50] Design for thermally dynamic and non-uniform environments are recommended as they are believed to be pleasing, delightful, and energizing for occupants. Use of passive and climate responsive building strategies is encouraged as they can create non-uniform environments and can nullify or reduce the requirement of centralized mechanical systems.[51-52]

Non-uniform indoor environments can produce "alliesthesia" in occupants. "Alliesthesia" is a term used in physiology to explain conditions when an external stimulus can induce pleasant/unpleasant experiences in people depending on their internal state.[53-55] Thermal alliesthesia occurs when the body is in a less thermally comfortable state and perceives pleasure from external thermal stimuli that brings the body towards comfort. Design strategies that can help evaporative, conductive or radiative heat transfer by heating and/or cooling the body or local body surfaces can generate thermal alliesthesia in occupants.[56]

Thermal environments in the building perimeter spaces are non-uniform, characterized by conditions such as radiant temperature asymmetry, vertical temperature difference, floor temperature extremes, draft etc. EDSc designs can be explored to control the indoor environmental non-uniformity to create the sensation of thermal alliesthesia or thermal delight among occupants.

1.3 Present Work

This study is a part of a research project that seeks to quantify the impact of EDSc 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 geomtric parameters were researched in Integrated Environmental Simulations Virtual Environment (IESVE) software. Sensitivity of predicted thermal comfort to screen geometric parameters such as PR and DR was 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 EDSc 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 EDSc and static screen shaded full-scale set-ups.

2. SENSITIVITY ANALYSIS USING COMPUTATIONAL

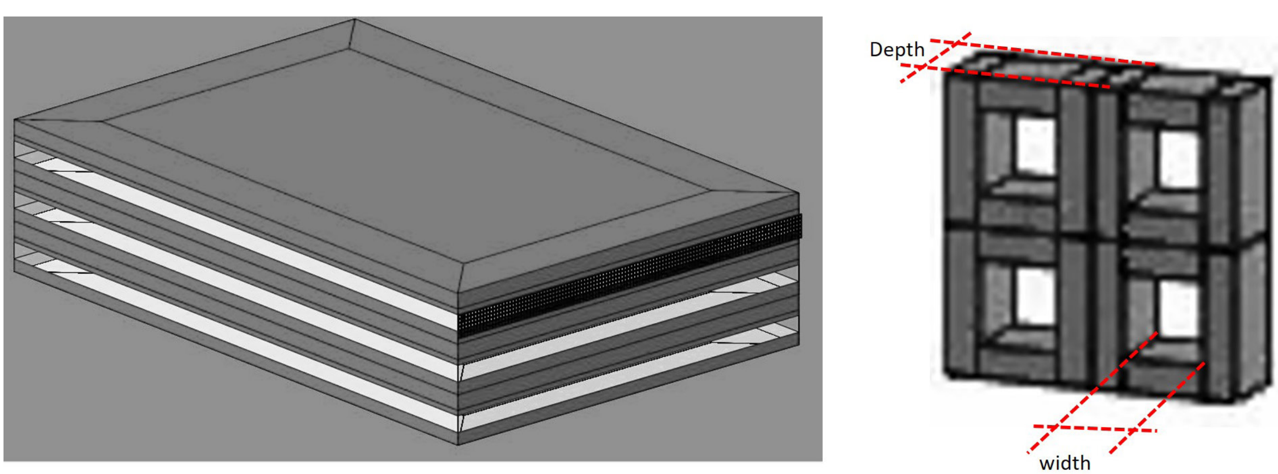

Figure 2. Mid-sized office building with screen modelled on its east facade. Screens typical modelled geometry (PR = % of open, DR = depth/width)

SIMULATIONS

2.1 Description of the model

A mid-sized, typical office building, based on ASHRAE (2013) model shown in fig. 2, 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 modeled on east facing perimeter space of the top floor of the building. Modelled screens were of simplest geometry (as illustrated in Fig. 2) 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.

2.2 The Study Variable: Predicted Thermal Comfort

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)

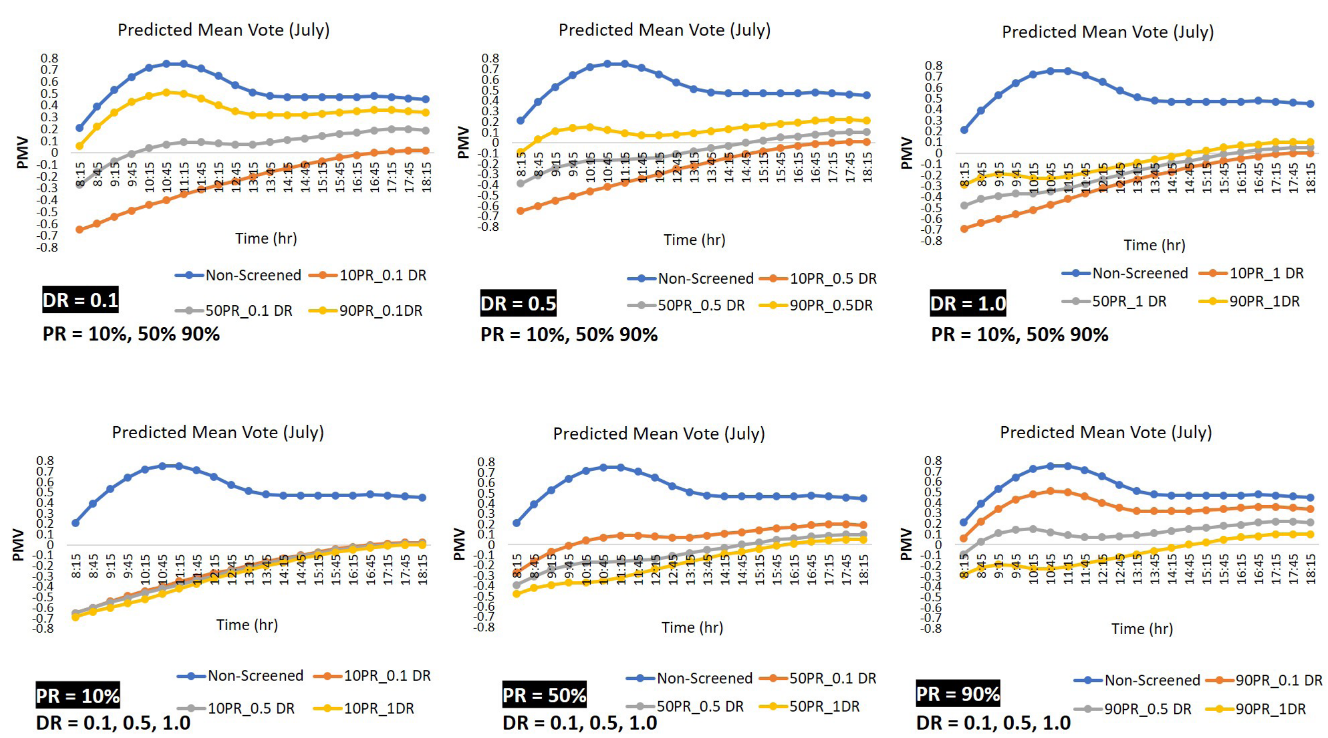

Figure 3. Sensitivity analysis of indoor predicted thermal comfort due to screens with different combinations of PR and DR for the design day in month of July. PMV values plotted at every thirty minutes. (Top Row) Impact of PR on variability in PMV can be observed at lower DR value. (Bottom Row) Impact of DR on variability in PMV values can be observed at a higher PR value

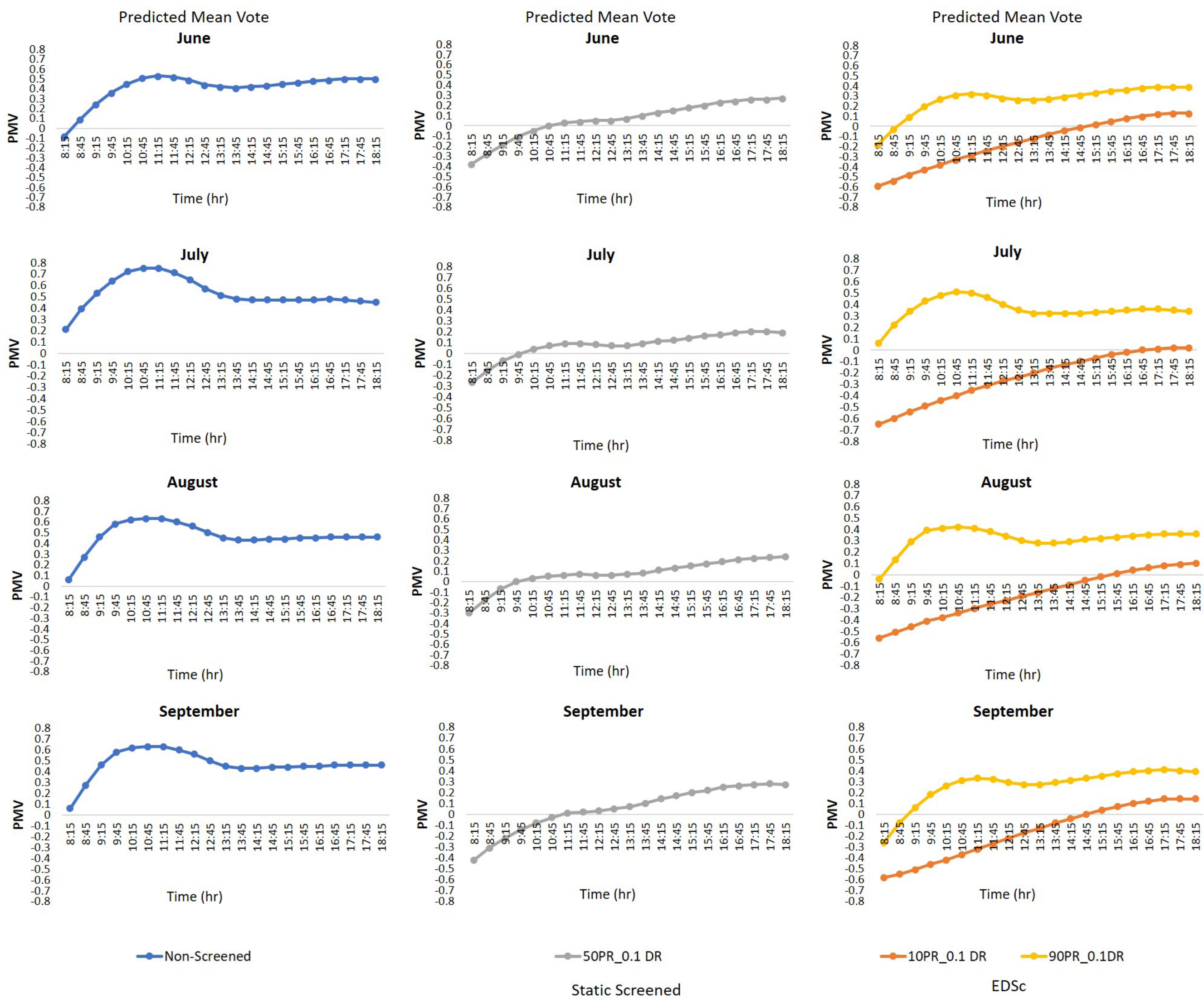

Figure 4. Predicted thermal comfort in non-screened (left), static screened (center) and EDSc (right) shaded east facing perimeter space during summer months in Eugene, Oregon

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 the area of 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.[57]

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.

2.3 Analysis of Results

In Fig. 3, 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 period 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.

2. FINDINGS AND APPLICATION

Results on predicted thermal comfort during morning to noon hours, plotted in fig. 4, 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.[47] An EDSc 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

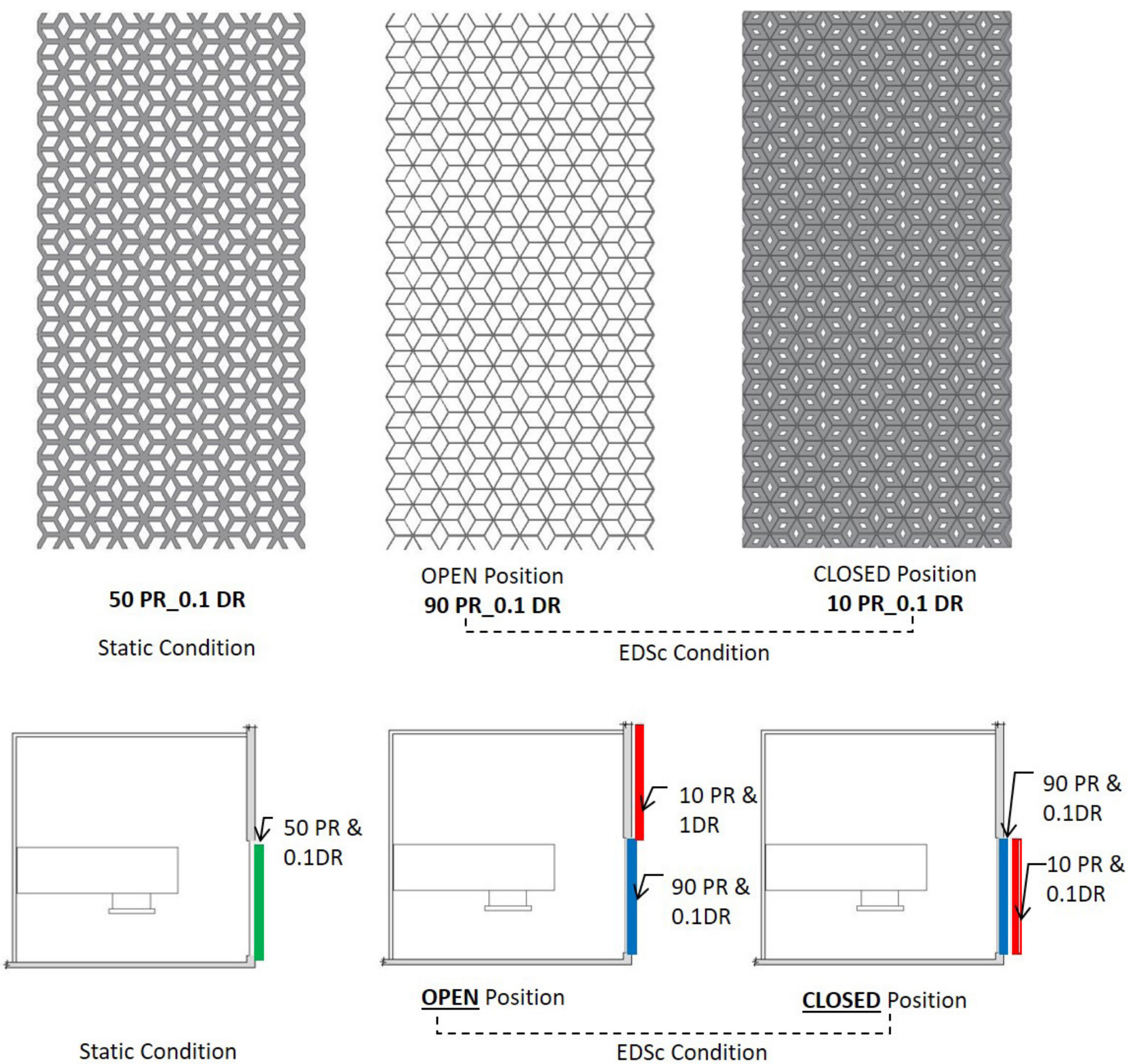

Figure 5. Static screened and EDSc shaded conditions as arranged for one-person office set-ups

slightly cool, at a time due to its potential to transit between PMV = +0.5 and PMV = -0.5.

In creating an EDSc 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. An EDSc 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.

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 EDSc and static screen prototypes, which are illustrated in fig. 5. Further, based on recommendations from a recent study, geometric patterns formed by rhombus-based shapes were created as perforations in the actual prototypes.[58]

Both, the static screened and EDSc 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. EDSc 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.

4. CONCLUSIONS

The impact of screen geometric parameters on predicted thermal comfort in the east facing perimeter space of a mid-size office building in Eugene during summer months has been analyzed using computational simulations. Results demonstrate that EDSc can be designed to create transient/non-uniform indoor environment in perimeter spaces of buildings. One way to design EDSc 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.By conducting this study, the authors intend to build on the scholarly work in the field of thermal comfort and 'alliesthesia' by Parkinson and de Dear. [59]

Results from this study cannot be generalized for different climates. However, the process reported to design dynamic shading for occupant thermal pleasure is thorough, simple and straightforward to be repeated for different climates and building types. Because of their aesthetic significance, EDSc are popular design strategies among practicing architects and students in architecture. The present work can help demonstrate on how to design EDSc or similar adaptive facades while considering occupants' comfort and delight.

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