The Impact of Static and Dynamic Solar Screens on the Indoor Thermal Environment and Predicted Thermal Comfort

NIYATI NAIK1 and IHAB ELZIYADI1
1School of Architecture and Environment, University of Oregon, Eugene, USA

ABSTRACT: Vernacular solar screens are popular design inspirations for contemporary facades which can be either static (i.e., fixed) or dynamic (i.e., operable). This study presents a comparative assessment of the impacts of static and dynamic screen prototypes on the indoor thermal conditions in an experimental, single occupancy office set-up, in ASHRAE Climate Zone 4C. Results demonstrate that static screen led to uniform indoor conditions within thermal neutrality limit established by ASHRAE-55 (2017). In comparison to the static screen prototype, the dynamic screen led to indoor environmental transience between thermal comfort and thermal neutrality zones. This non-uniformity in the indoor environment produced by the dynamic screen encourages exploration of their design potential in eliciting thermal pleasure and a state of alliesthesia for occupants. This work proposes an approach to design building envelopes with dynamic shading opportunities for occupant’s comfort and pleasure.

KEYWORDS: Dynamic screens, thermal comfort, thermal pleasure, alliesthesia

1. EXTERNAL DYNAMIC SOLAR SCREENS: RESEARCH GAPS AND OPPORTUNITIES

Vernacular solar screens applied to exterior surfaces of building facades have aesthetic, environmental, and cultural significance. Due to these aspects, they are popular as design inspirations for contemporary façade design, both in their static or dynamic state. Static screens are non-moveable/non-operable “bris de soliel” with optimized designs to respond to extreme solar conditions. On the contrary, dynamic screens are movable/operable that are typically designed to change their geometric parameters to respond to outdoor-indoor climatic conditions and/or occupants’ needs.

The complex designs of dynamic screens have led to substantial research dealing with their movement and control technologies [1]. Few investigations on dynamic screens conducted using computational simulations have proven their high building energy efficiency and provision of occupant’s visual comfort performance [2, 3, 4]. In addition, dynamic screens were able to reduce cooling loads on mechanical systems and provided thermal regulations to perimeter spaces within 15’ (6 meters) of the building envelope, resulting in 12%-33% energy savings [2]. Despite promising results on building performance, their impact on thermal comfort remains unknown [5,6]. Quantifying their impacts on occupant’s comfort is important to inform logical building envelope designs and their market adaptability.

1.1 Existing research on static solar screens: parameters investigated and findings

Unlike their dynamic counterparts, static screens have been extensively investigated for their building energy and occupant comfort performance [8, 9,10]. More than twenty-five studies have researched static screens in recent years. Most of them carried out optimization of screen geometric parameters such as perforation ratio (PR = % of open) and depth ratio (DR = perforation depth/perforation width) to determine the most suitable static design for building energy efficiency and occupant’s comfort during a worst case climatic condition (i.e., extreme summers).

Static screens with 30 to 50% PR and 1:1 DR are recommended for maximum building cooling energy savings in hot climates [9]. For composite climates that have characteristics of hot-dry, warm-humid, and cold conditions, static screen designs optimized for hot-dry summers lead to over-shading and thermal discomfort during moderate winters [11]. As opposed to the optimized static screens, dynamic screens are climate responsive. Thus, if designed appropriately, dynamic screens have the potential to outperform the static types [12].

1.2 Occupant’s thermal comfort in buildings

Building envelopes and mechanical systems are designed to maintain thermally uniform indoor conditions as required by the thermal comfort standards [13-15]. These standards prescribe narrow limits of thermal conditions as ‘comfortable’. Predicted mean vote (PMV) is a widely used metric for thermal comfort assessment [13]. 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 [13,14].

1.3 Advances in thermal comfort research and opportunities for contribution

Over the past twenty years, there has been a paradigm shift in the conception of provision for thermal comfort [16]. 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 [17-21].

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 [17,22,23]. They can evoke perception of thermal pleasure among occupants [20]. 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 [17]. These environments can potentially affect occupants’ resilience and adaptability to their surroundings, thereby positively influencing long-term well-being [22,23]. These studies provide a motivation for deeper investigations to uncover occupant’s thermal perception and satisfaction in a wide variety of non-uniform environments.

Although there can be multiple techniques to create thermally non-uniform indoor environment, the operability of dynamic screens provides a unique opportunity to design them for creating non-uniform thermal environments within the broader comfort range that can potentially induce thermal pleasure among occupants. The present study aims to explore this opportunity.

2. CURRENT WORK, SOLAR SCREEN PROTOTYPES, AND STUDY DESIGN

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.

2.1 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 [24]. 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 [24].

![Figure 1: (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).](image-url)
dynamic conditions respectively (Fig. 1). Based on results of the simulations [24], the optimized static screen prototype was designed to have (PR, DR) = (50%, 0.1) (Fig. 1b) which were predicted to produce uniform thermal condition close to the neutral line (PMV = 0) within the thermal comfort zone [13]. 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 (Fig. 1, c-d).

2.2 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 2 shows the details of the set-up.

![Figure 2: (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).](image)

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/m²) consisted of a calibrated pyranometer sensor (LI-COR LI-200R) connected to a calibrated transconductance amplifier (UTA for LI-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.

2.3 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) overlap 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. Starting 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 Fig. 3, 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: 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.](image)

3. DATA COLLECTION AND ANALYSIS

Outdoor and indoor environmental data consisting of solar radiation (W/m²), 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 [27]. 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.

4. 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 (Fig. 4). In the case of dynamic screened condition, transition from ‘O’ to ‘C’ reduces indoor surface temperature further by an additional 6° F (Fig. 4 c-d).

Both static and dynamic screened conditions created an indoor environment consisting of patterned solar patches (Fig. 4) 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 (Fig. 5). 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 [13].

![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.](image1)

![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).](image2)

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 Fig. 6 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 latter 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 (i.e. PMV=1).

As depicted in Fig. 7, 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.

5. CONCLUSION
A comparative evaluation of effects of external static and dynamic screens on the indoor thermal conditions for a single occupancy office set-up in the moderate climate of Eugene, Oregon (USA) (ASHRAE, Climate Zone 4C) has been presented. As hypothesized, the static screen produces more comfortable indoor conditions with PMV < 1 as compared to the non-shaded set-up. The dynamic screened condition with an appropriate movement design, introduce thermal variability in the indoor conditions that can potentially create instances of slight discomfort and comfort when the screen is, in the open ‘O’ (high PR) position and slides to closed ‘C’ (low PR) position, respectively.

These findings indicate the potential of dynamic screens to evoke sensation of ‘temporal’ and/or ‘spatial alliesthesia’ in occupants. ‘Temporal alliesthesia’ is the feeling of pleasure perceived because of a thermal stimulus, which brings human body from a slightly less comfortable state towards comfort. ‘Spatial alliesthesia’ is the perception of pleasure felt when there are differences in local skin temperatures across a person’s body [17]. It should be noted that this study is specific to ASHRAE Climate Zone 4C and east facing single occupancy office settings. Future studies should investigate the applicability of these findings to different climate zones, orientations, and space types. The study suggests an approach to design and employ dynamic solar screens for occupant’s thermal pleasure in work environments. This provides a novel perspective, which can be followed by architects and façade designers. This work proposes and emphasizes that designs for external dynamic façade shading systems need to be occupant centric and should expand our thermal comfort provisions to include thermal pleasure and alliesthesia.

6. EQUATIONS
The globe temperature, GT, is computed using Eq. (1) [26]:

$$GT = \frac{1.8}{A + A_1 + A_2} - 459.67 \degreeC$$  \hspace{1cm} (1)

Where

\[ A = 1.12886430756012 \times 10^{-3}, \]
\[ A_1 = 8 \times LN(10000) / V - 1), \]
\[ A_2 = C \times LN(10000) / V - 1) \]
\[ B = 2.34149078860173 \times 10^{-4}, \]
\[ C = 8.77065543744161 \times 10^{-8}, \]
\[ V = \text{voltage equivalent to the resistance measured through US sensor 10,000 } \Omega \text{ curve “J” thermistor.} \]

The mean radiant temperature, MRT, is computed using Eq. (2) [30]:

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

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), \( \varepsilon = 0.95 \) is the emissivity of the globe, \( D = 0.15 \) is the diameter of the globe, and \( T_s \) is the air temperature (°C).
REFERENCES
15. ISO 7730, Ergonomics of the thermal environment - analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (2005)