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Visual Comfort Assessment of Different Shading Strategies in a Commercial Office Building in the Southeastern US

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ABSTRACT

It is challenging to design buildings that simultaneously consider both the dynamic nature of daylight and specific occupant preferences. The authors have investigated this problem by studying the performance of four specific shading strategies using quantitative measurements of occupants visual comfort: discomfort glare and daylight availability. This paper specifically evaluates the performance of four shading strategies, two types of electrochromic (EC) glass, an automated fabric roller shade, and a venetian blind in a building located in the Southeastern United States. This paper examines how these technologies impact occupant visual comfort and it also examines how the buildings perform relative to the two metrics outlined in IES LM-83-12. Horizontal illuminance and high dynamic range images were recorded to assess the existing luminous environment in order to better understand the potential of various shading strategies. Calibrated daylighting models were also constructed in DIVA. Our results suggest that perimeter-zone occupants benefits from EC glass as it can reduce more than 40% of glare annually in this zone. Findings from the interior zones are shown that all four shading strategies perform quite similarly in regards to reducing the glare. This study suggest that by providing a designer at early-design-stage with direct information related to the level of daylight availability and glare condition within a space will lead to improve occupant's visual comfort.

KEYWORDS

Visual comfort; Shading strategies; Office building; Daylight Glare Probability (DGP)

INTRODUCTION

Designing a well-daylit space requires to satisfy both qualitative and quantitative aspects of daylight by balancing daylight provision with occupant visual comfort in both core and perimeter zones of the work environment. Over the past two decades, much of the available literature on visual comfort deals with glare and the amount of light as the two most reliable metrics. Similarly, Carlucci (2015) reviewed the literature of several studies and highlighted that over 75% of metrics employed glare and amount of light to assess the visual comfort. Daylight Autonomy (DA) is one of the most common used approach to assess the annual amount of daylight in a space (Reinhart and Wienold, 2011). Results of various studies showed while DGP performs better than the other metrics in predicting discomfort glare when the direct sun is present, the DGP isn't effective at predicting contrast-based discomfort glare (Van Den Wymelenberg et al., 2010; Pierson et al., 2018; Jakubiec and Reinhart, 2012; Kleindienst and Andersen, 2009). This view is supported by Konis (2014) who found that simple contrast ratios predicted discomfort best in 'core' zones of buildings further than 6m from the facade. Together, in all the studies reviewed here, DGP is recognized as the most robust glare metric as it is least likely to produce inaccurate glare prediction and also has a stronger correlation with vertical illuminance on the eye when bright, direct sunlight is generally associated with glare such as perimeter zone. In modern office spaces with large glazing facades, natural light coming in through the window can increase the visual comfort of occupants by providing the access to views, treating sleep disorder, and improving concentration and productivity of the working environment (Andersen, 2015; Keis et al., 2014). However, direct sunlight can cause visual discomfort in the form of glare. Therefore, the goal of shading technologies is to control the direct entry of sunlight from the windows in order to prevent severe glare. In order to avoid glare related problem which is the main cause of visual discomfort within office spaces, the direct sunlight should be blocked by using advanced glazings and innovative shading systems (Tzempelikos and Athienitis, 2007). Unlike the conventional shading strategies, the dynamic shading strategies, such as electrochromic glass, prevent severe glare, while also maintaining access to daylight and outdoor views. Electrochromic glass as an active device respond to various sensors (illumination and temperature) and the voltage causing the change in transmission. Following those works, this paper aim to investigate the visual comfort using the simulation-based visual comfort to evaluate the performance of various shading strategies in an open-office space. The objective of this paper is to assess the ability of four different shading strategies to reduce excessive glare while maintaining sufficient daylight through the space.

METHODOLOGY

This study was conducted on the southwest side at the upper floor of a side-lit open office located in Charlotte, NC. The Southwest side of the office is chosen due to extreme condition related to sun exposure. The building form is square shape with a 22m deep floor plate. It is important to note that the core of the building (length 26.5m and width 22m) including stairs, elevators, and bathrooms, is excluded from the analysis. To analyse daylight sufficiency of the space, annual illuminance is used to quantify Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE) on horizontal surface for window without shading. $\text{sDA}_{300lux50\%}$ expressing the percentage of analysed floor area that meet or exceed a threshold of 300 lx for more than 50% of occupied hours. Then, DA is used to compare the daylight availability for four shading strategies. 1534 sensors are distributed with 0.5m spacing on a horizontal measurement grid 76cm above the floor to assess daylight availability for different scenarios. In addition, annual glare and point-in-time glare were investigated to analyse the appearance of discomfort glare across two locations (Loc a and Loc b), positioned 1.2m above the floor to represent occupant's seated eye-height. For analysing point-in-time glare, the CIE clear sky was selected as direct sunlight reported the most important cause of discomfort for building occupants in modern spaces with large windows (Jakubiec and Reinhart, 2012) and simulation can predict discomfort glare of real lighting environments more accurately on sunny days than overcast sky (Kong et al., 2015). The method of this study consists of two steps. In the first step, an office without shading device is assessed using HDR image technique and compared with Radiance model to determine the accuracy of the model as a substitution tool. In this step, two HDR cameras are placed at Loc b, one towards southwest window and the other one facing southeast side, at the seated eye height level of 1.2m to collect data related to discomfort glare. Figure 1 shows the location and directions of the two HDR cameras. An office space is modeled based upon a real office space in Rhinoceros 3D modeling software where room geometry and orientation are assigned to the model. After that, Radiance materials are assigned to all surfaces using the open-source plugin DIVA 4.0. The model properties and Radiance simulation parameters are presented in Table 1 and Table 2, respectively. It is important to note that the HDR images were taken on a sunny day, January 14th, 2016 from 8 AM to 6 PM in fifteen minute time intervals. Evaglare developed by (Wienold et al., 2004) is used in this study to calculate the results of DGP to compare the HDR images with simulated scenes. Second, Radiance model is used to evaluate the performance of the four proposed shading strategies (see Table 3) to control glare and provide sufficient daylight within the space in comparison with the base case scenario. The yearly hour-by-hour glare for both Loc a and Loc b for view direction perpendicular to southwest window is analysed for all proposed alternatives to identify intolerable and disturbing glare appearance for entire year. Moreover, automated glare control as a dynamic shading strategies applied in DIVA to avoid excessive interior daylighting levels and also block direct sunlight as a main cause of discomfort glare.

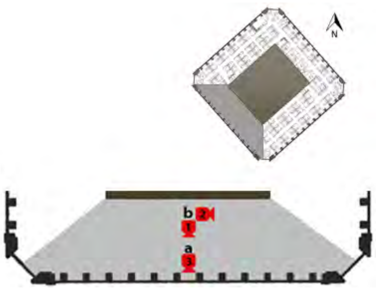

Figure 1: Plan view of the office building model presenting two different seating positions (loc a and loc b) across view 1-3 at the Southwest side.

Window to wall ratio	76%
Climate	Charlotte, NC
Analysis grid spacing	0.5 m
Number of view vectors per grid point	12
Ceiling height	3 m
Surface reflectance (interior floor)	20%
Surface reflectance (interior wall)	50%
Surface reflectance (interior ceiling)	80%
Surface reflectance (mullion)	90%
Glazing visible light transmittance (VLT)	65%
Floor plate length (NW-SE)	48.5 m
Floor plate length (NE-SW)	48.5 m
Location a distance from southwest window	1.5 m
Location b distance from southwest window	6 m

Table 1: Model properties.

Table 2: Model radiance parameters.

Parameters					
aa = 0.1	ab = 4	ad = 1024	sj= 1	lr =6	dj=0
ar= 256	dr= 2	ds=0.2	st= 0.15	Lw =0.004	

Table 3: Main characteristics of various shading strategies.

Strategies	Shading system	Control strategy	Visible light transmittance (%)
1	Electrochromic glazing	Clear state	58
		Intermediate state	40
		Intermediate state	6
		Fully tinted	1
2	Electrochromic glazing	Clear state	60
		Intermediate state	18
		Intermediate state	6
		Fully tinted	1
3	Roller Shade	Half down	0.04
		Quarter down	0.04
		Fully down	0.04
4	Venetian blind	Horizontal	-
		30 degree	-
		60 degree	-

RESULTS

Comparison between the captured HDR images and simulated scenes

In order to have consistency with captured images, the same 82 scenes were recreated in DIVA to simulate time of the day of each captured HDR image. The results of DGP scores for view 1 and view 2 are plotted in Figure 3 according to four glare levels, with imperceptible glare in green (DGP<0.35), perceptible glare (0.4>DGP≥0.35) in yellow, disturbing

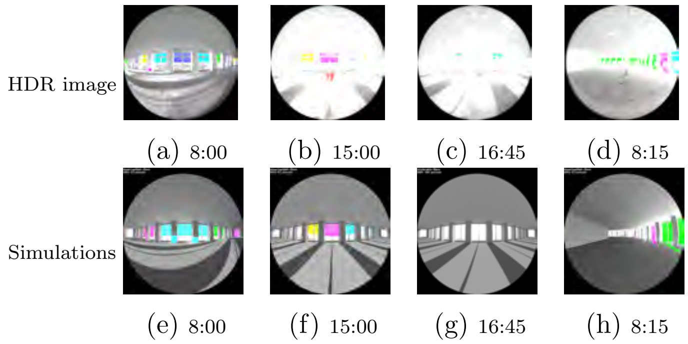

Figure 2: The HDR images and the simulations for different glare levels across view 1 and 2.

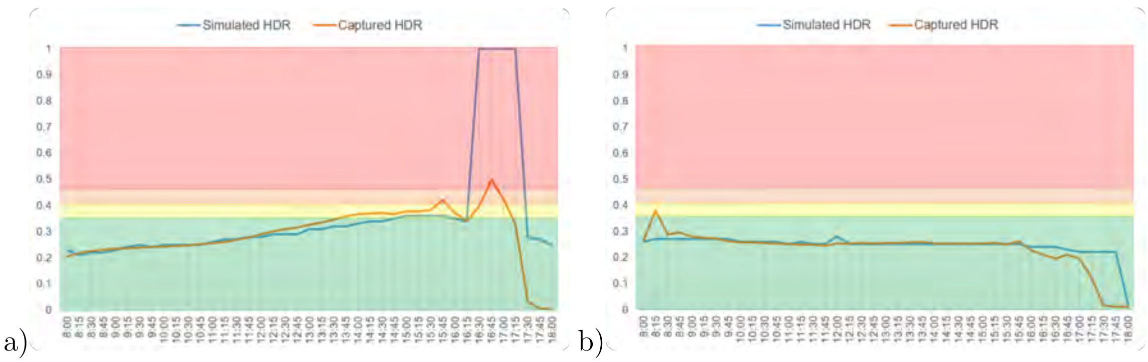

Figure 3: DGP score comparison between captured HDR image and simulated HDR scenes of a) view 1 and b) view 2 at Loc b.

glare in orange (0.45>DGP≥0.4), and intolerable glare in red (DGP≥0.45)(Jakubiec and Reinhart, 2010). The captured HDR images and simulations can be compared visually for different glare levels in Figure 2. In view 2, more than 98% of HDR images and 100% of simulations generated DGP values were in the range of imperceptible glare (see Figure 3b). The only exception is at 8:15am, where the DGP value of the HDR image was higher than the simulation one. In contrast, for view 1, although 10% of simulated HDR scenes were fell into the range of intolerable glare, only 2% of captured HDR image were fell within this range (see Figure 3a). Although the amount of DGP for simulations were higher than captured HDR images between 16:15 to 18:00, but for the rest of the time the DGP value for both captured HDR images and simulated HDR scenes are comparable. As the simulated model has no light-shelf that allows considerable amount of direct sunlight hit the sensor in view 1 from 16:15 to 18 which may be the cause of deviation between simulated and HDR images generated DGP values during this period. Taken together, the difference between HDR images and simulations for all 82 scenes are about 16%, these results are in line with those of previous studies and confirm the association between HDR images and simulations which indicate that simulation can accurately predict real lighting spaces in terms of glare analysis, even though, the results of HDR images and simulations may not exactly match together (Rushmeier et al., 1995; Kong et al., 2015).

Assessment of various shading strategies

In order to improve the visual comfort of the common space, four shading strategies have been proposed to provide a comprehensive annual glare analysis within the space (see Table 3). The total annual hours of occupancy of 3650 is assumed for the purpose of this study. The view 1 and view 3 at loc b are used to analyze the performance of all shading strategies as the view point with extreme amount of sunlight in comparison with

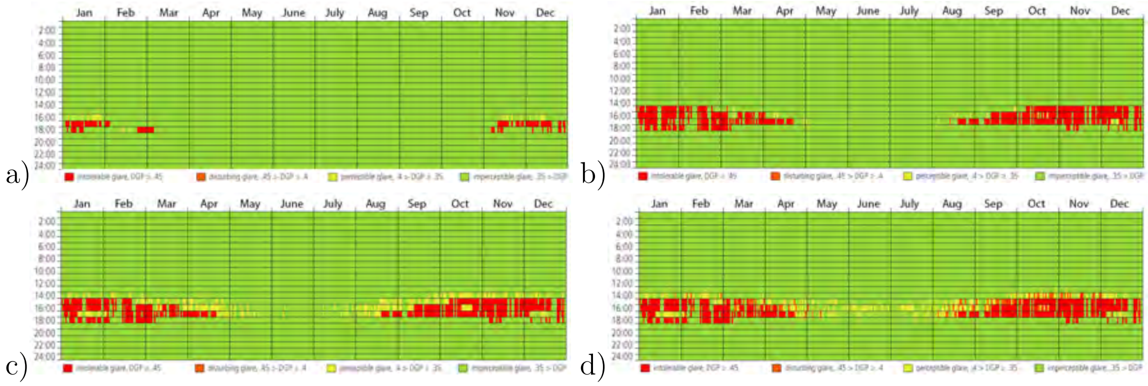

Figure 4: Annual glare calculations of view 3 at Loc a for strategies a)1, b)2, c)3, and d)4

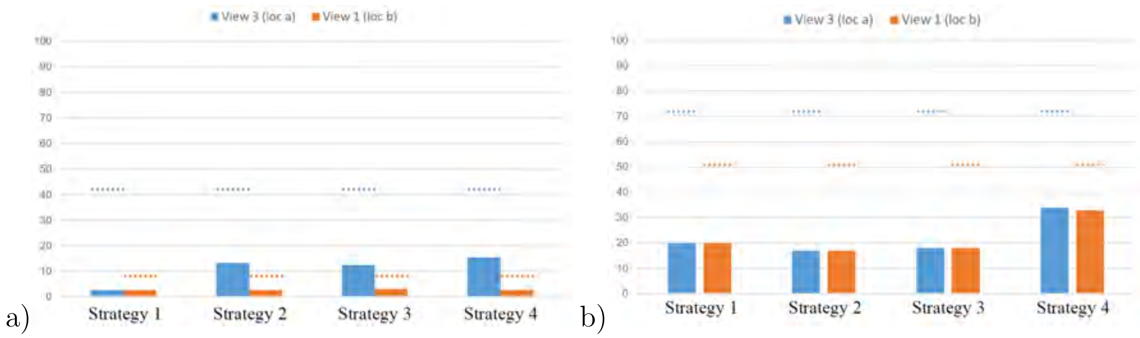

Figure 5: Reduction of a)Annual glare and b)DA of four shading strategies for view 1 and 3.

other view directions. The disturbing and intolerable glare (DGP$\geq$0.4) as a worse glare condition is reported 47.5% for view 3 and 10.2% for view 1 without a shading device. In addition, sDA and ASE were calculated for the southwest side of the model to analyse daylight sufficiency. The results show that 42.4% of the southwest side has sDA 300lux value for more than 50% of occupied hours, and 34.5% of the space has an ASE greater than 250 hours. As the accuracy of Radiance model is demonstrated, this model is used to investigate the performance of different shading strategies. The results of these four shading strategies for view 3 are presented in Figure 4. The same colours green, yellow, orange, and red represent the four different levels of glare as Figure 2. Vertical axis represents the hours of the day and 365 days in a year are shown in horizontal axis. As the worst glare condition (DGP$\geq$0.4) occurred during winter when the sun is in the low angles, Strategy 1 performs significantly better in controlling annual glare rather than other strategies for view 3 (see Figure 4). Figure 5a indicates the annual glare reduction of each shading strategies for view 3 and view 1. The results shows that the level of annual glare for location a is significantly higher than location b due to excessive amount of direct sunlight. Strategy 1 has the best potential for controlling glare as it reduces over 40% of glare annually, but the other three strategies can decrease between 27% and 31% of the annual glare in location a. In location b, all the four strategies have the same performance by reducing around 6% of the annual glare. Figure 5b shows the reduction in the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylit alone. The results indicate that strategy 4 caused the lowest reduction (about 40%) of DA through the space followed by strategy 1. Overall, comparing four shading strategies reveal that Strategy 1 performed better in terms of balancing between daylight provision and control discomfort glare than other strategies.

DISCUSSION AND CONCLUSION

This study was conducted in an office space as an example to show the importance of considering different shading strategies to control discomfort glare as the most cause of visual discomfort reported by office occupants. For the purpose of this study, four shading strategies were applied to evaluate their potential in controlling discomfort glare and daylight sufficancy. Dynamic electrochromic window which can be switched from 58% visible transmittance (Tvis) to a fully tinted state with 1% Tvis had a better performance in comparison with other shading alternatives by reducing over 40% of glare annually when excessive amount of sunlight is present. While Venetian blind shows the better performance in terms of DA than other strategies, it allows entering considerable amount of direct sunlight into the interior space. Therefore, Electrochromic glazing had a better performance than other strategies in this study by considering the ability to control glare and provide view to the outside as two important criteria for assessing visual comfort. In addition, the accuracy of simulation tool is determined and can be used by designers in early-stage design process to better understand the performance of various shading strategies by combining both annual glare and point-in-time lighting simulations of the space. A reliable prediction of glare with metrics is an important challenges among designers as visual comfort strongly depends on both daylight availability and the observer's position. Therefore, providing a designer at early-design-stage with direct information related to the level of daylight availability and glare condition within a space will lead to improve occupant's visual comfort. As the quality of the luminous environment produced by EC glazing is considered as an important factor for user acceptance, future research might investigate the non-visual effect of different Electrochromic windows on occupant's health and well-being.

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