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Sarey Khanie, Mandana; Ślipek, M.; Zukowska-Tejsen, Daria; Kolarik, Jakub; Nielsen, Toke Rammer

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# An Evaluation Method for Façade Renovation Strategies in Residential Buildings Using Gaze Responsive Visual Comfort Assessments

Sarey Khanie, M., Ślipek, M., Zukowska D., Kolarik J., Nielsen T.R.

Department of Civil Engineering  
Technical University of Denmark  
Kongens Lyngby, Denmark  
masak@byg.dtu.dk

**Abstract**— Maintaining daylight quality while ensuring thermal comfort during periods of high solar gain proves to be a challenge in renovated multi-story housing. The objective of this study was to develop guidelines for facade renovation, where overheating problems can only be avoided through façade solutions. As a first step, different shading systems have been investigated and compared in terms of their daylight performance, visual comfort and gaze responsive characteristics. This trio evaluation method is going to be further developed and used for a larger set of selected shading devices.

**Keywords:** Daylighting, Gaze Behaviour, Overheating, Residential Buildings, Visual Comfort

## I. INTRODUCTION

Enhanced daylight quality in indoor environment is dependent on a series of multi-dimensional and dynamic physical and psychological parameters. Each pragmatic combination of these parameters at pre-design phase can lead to a different design outcome. The main challenge is to reach an embrative energy efficient and human-centric decision that allows for maximum use of daylight with energy saving benefits to enrich tenants' health and visual quality while avoiding visual and overheating. Most studies on daylighting and energy savings target commercial buildings with less focus on residential buildings' needs [1]. It is, however, commonly known that in residential buildings direct sunlight penetration is desirable and several countries have regulations to ensure a minimum required amount of direct daylight penetration [2]. Concurrently, advancing energy efficient solutions in renovation phase necessitate adopting high-insulation and air-tightness to avoid heat loss through transmission or infiltration. In addition, residential ventilation systems in many countries are only designed to ensure proper indoor air quality and not to cool indoor air [3] because air conditioning is not an energy efficient option [4]. Venting by opening of windows can be used for cooling purposes in moderate climates, but has limitations related to theft risks and outside noise. In combination with an increase in occupancy hours in residences due to the possibility of remote working, risk of being exposed to high indoor temperatures has increased. This has a negative effect on occupants health, wellbeing and productivity [5] especially among vulnerable groups such as children and elderly [6]. Moreover, elevated temperatures during day-time are followed by consequent high temperatures during night-time day which distorts the sleep quality [7].

To prevent overheating, one solution is to limit the solar heat gains through the façade. Experiences from high performance buildings show that cost-efficient dynamic solar shading can lead to energy savings related to cooling of up to 62% [8]. If the façade strategies are wisely set, an optimized use of daylight can enhance the energy efficiency of the buildings as well [9]. However, the selection of appropriate shading systems for residential buildings proves to be a challenge. This is partially due to limitations on appearance change of certain residential buildings rising from e.g. public preferences and acceptance. Weather conditions mainly in terms of external shading devices can also restrict the use of certain types of devices. Finally, fewer studies with focus on subjective preferences in this type of buildings add on to the complexity of the design decision-making process in such cases.

The objective of the presented study was to evaluate shading systems for façade renovation strategies based on daylight performance and daylight-induced visual risks.

### A. Daylight Performance

When renovating residential buildings, one of the objectives should be to ensure maximum use of daylight to ensure tenants' enhanced health, well-being and visual quality, while avoiding visual and thermal discomfort caused by excessive daylight penetration and overheating. Daylight performance can be predicted by use of daylight metrics developed in the past decades. These metrics can mainly be categorized as either static or dynamic. Daylight factor (DF) is a static metric and it is used to measure the amount of diffuse daylight delivered to a point in space under overcast daylit conditions. DF is hence insensitive to climate, orientation, and surrounding of the building [10]. This metric limits exploiting the daylight potentials in buildings while neglecting eventual visual discomfort risks [11]. A

number of Climate-Based Daylight Modelling (CBDM) metrics have, however, been proposed in order to overcome this shortcoming. In recent years the metrics such as Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) have been used for dynamic evaluation of daylight potentials in indoor environments [11].

### B. Visual Discomfort

While playing a crucial role in any building's overall performance, discomfort glare is very hard to predict and design for [12] and it is a major concern in developing the right façade typology for its daylight performance. Several studies on discomfort glare in the past decades have led to mathematical models for discomfort glare quantification. These models have a larger focus on artificial lighting conditions and fewer attempt on daylighting with use of artificial lighting base experiments [13] and, more recently, under daylight conditions for Daylight Glare Probability (DGP) [12]. The models are mainly based on empirical methods where human subjective assessments are associated with relevant photometric relations linked with visual visibility and luminance contrast.

Additionally, a few studies have explored objective measures such as certain pupil fluctuation [14] and activities of facial muscles in the vicinity of the eye [15] to identify a source of discomfort. More recent studies have reported physiological responses such as degree of eye opening [16], eye movements and pupil constrictions [17] as indicators for discomfort glare. However, so far, only studies based on subjective assessments by means of questionnaires have been used to quantify discomfort glare.

### C. Gaze and Visual Comfort

Gaze direction is where we direct our line of sight by jointly moving our eyes, head and body. With each gaze shift the luminance distribution in the field of view (FOV) changes and the visual system needs to re-adapt. Knowing that visual comfort perception is mainly dependent on the luminance distribution across different parts of the FOV [18], the gaze shifts and the eventual changes in adaptation level can impact the subjective or objective responses to luminous environment. So far, an assumption behind development of existing discomfort glare prediction metrics has been that the gaze direction is fixed towards a task area. In early design phases or in certain building types such as residential buildings, the "task area" is not the main design criteria. However, the visual comfort assessment for these types of buildings still proves to be beneficial.

Several recent studies have addressed the eye physiological response such as an eye opening in relation to glare [16]. Interpretation of the gaze shifts and re-adaptation process have been, however, (arbitrarily) addressed by extending gaze directions to a preferred angular range [19]. The dynamic gaze shifts responses to light and implementation of them in visual comfort assessments was then advanced [20] through a series of experimental studies where gaze observations with eye-tracking techniques coupled with photometric observations with high dynamic range (HDR) imaging techniques were used. The latter study led to development of a new gaze responsive method for discomfort glare evaluations based on prediction of gaze shifts as result of excessive glare patches in the field of view. This is done by means of a predictive model termed Light-driven gaze responsive ( $GR_L$ ) which calculates the gaze shifts as response to glare patches in the FOV, their size and position in the FOV, and the average luminance the eye is adapted to. The predictive behaviour always sways away from the glare patches.

## II. METHODOLOGY

In the present simulation-based study, six shading systems were evaluated for their daylight performance and afterwards four of them (due to time constraints) were evaluated for gaze responsive comfort. Daylight performance of the six shading systems with manual control were investigated using Diva for Rhino for three floors of the building, two neighbouring density scenarios (with or without) and two vegetation scenarios (with or without). Visual comfort simulations were done based on immersive spatial approach [21] in order to assess the photometric behaviour in a larger visual span. Based on this method several HDR renderings over a range of gaze (view) directions were simulated and evaluated for gaze responsiveness using the  $GR_L$  model [21] and visual comfort using the DGP model [12]. The visual span was set to  $112.5^\circ$ , which started from a perpendicular vector to the south-facing window, and ended at  $112.5^\circ$  inside the room where the window disappeared from the FOV. This visual span was divided into six gaze (view) directions and six  $180^\circ$  angular fisheye HDR images. The occupant position in a room (a viewpoint) was assumed to be at 1500 mm from the window and 1000 mm from the wall behind. All visual comfort related simulations were done for four time points during the occupancy hours set for residences (in time periods of 7 a.m. – 10 a.m. and 4 p.m. – 6 p.m.) for one day in a year May 30 using Radiance rendering tool [22] and Evalglare tool [12].

### A. Case study

The case study building is a 4-storey residential building with heritage value located in central Copenhagen. The building represents a larger range of buildings in Denmark built in the period between 1850 and mid-1950s. The floors of the building (except the basement, which is not considered for the daylight conditions assessment) have identical layouts. The relevant specifications of the case study can be seen in Table I. Among the six apartment types, the more common layout with a south facing living room was chosen for the investigation.

Table I. Study case building specifications.

.Building Typology	Year	Exterior Walls	Simulated materials		
			Walls	Floor	Ceiling
	1850-1950	Masonry bricks (1-1 <sup>1/2</sup> sten, increase with 1/2 per block from the 2 <sup>nd</sup> floor)	Reflectance 80 %  Specularity 0.36%	Reflectance 30 %  Specularity 0 %	Reflectance 80 %  Specularity 0.44 %

Table II. Detail specifications of simulated systems.

Device Position	Shading System	Device	Geometry	Material	Optical properties
	System 1	Double-pane clear glazing	-	-	T <sub>vis</sub> = 82%
<i>Internal</i>	System 2	Roller blinds	-	Grey	BRDF calculation
<i>External</i>	System 3	Venetian blinds	C-shaped slat	Color 1 – White (Warema 71000)	T <sub>vis</sub> = 0.00 R = 0.78
<i>External</i>	System 4	MicroShade	-	MS-A	BRDF calculation
<i>Internal</i>	System 5	Roller blinds	-	White	BRDF calculation
<i>External</i>	System 6	Venetian blinds -45° cut off angle	-	Color 2 - Grey-Beige (Warema 71005)	T <sub>vis</sub> = 0.00 R = 0.64

### B. Shading Systems

The selected systems from the numerous solar shading devices available on the market can be seen in Table II. System 1 represents the initial façade setting, Systems 2 and 4 include internal roller blinds, which are commonly used in residential buildings due to relatively low cost, easy instalment and operation, which interfere with the architectural form of the building only in a minimal degree. However, the device has limited effect for overheating preventions. In the simulations, the roller blinds geometry was simplified to two surfaces in addition to the glazing: a single surface representing roller blind's fabric with complex optical properties in 95 mm distance from the window pane and a transmission surface to assign the light transmittance properties.

Generic C shape venetian blinds were investigated as System 3 and System 6. There are several technical specifications to consider when selecting venetian blinds such as installation and operational type but it is mainly the slat's material and colour of the venetian blinds that affect its optical properties.

The last simulated device (System 4) was MicroShade. MicroShade is a thin metal sheet with microstructure surface, which is applied on windows with two or three layers of glazing. The device is glued directly to the window pane using glue stripes.

## III. RESULTS

### A. Daylight Performance

For all the rooms listed on each floor of the building the daylight simulations in Diva for Rhino were conducted in order to assess the daylight conditions based on two daylight metrics: Daylight Factor (DF) and Daylight Autonomy (DA 150 (lx) set as threshold). Table III shows the DA results for a south facing living room on the first and fifth floors for two different neighbouring densities (with or without) and two vegetation scenarios (with or without). The results of simulations showed that the daylight levels are insufficient, with the DA reaching only 150 (lx) approx. 53.4% of the time in the rooms only on the top floor. As expected, it can be seen that the DA values decrease for lower floors and with presence of a neighbouring building and/or vegetation. Use of shading systems reduces the daylight availability throughout the year. A grey venetian blind has the worse effect compare to all the other systems and we can see that MicroShade has the lowest DA value when either a neighbouring building or vegetation shades the façade.

Table III. DA results for four neighbouring densities and the six shading systems.

DA 150 (lx)	Simulated Conditions						
	Neighbouring density (No vegetation)					Neighbouring density (with vegetation)	
	Without Floor 5	Without Floor 3	With Floor 3	Without Floor 1	With Floor 1	Without Floor 1	With Floor 1
<i>Shading systems</i>							
System 1	53.4%	50.0%	22.7%	48.1%	17.5%	47.5%	17.3%
System 2	30.5%	28.8%	9.8%	30.0%	8.2%	29.5%	8.2%
System 3	30.6%	29.2%	9.5%	35.4%	10.0%	35.4%	10.3%
System 4	31.6%	26.1%	3.6%	23.0%	1.6%	1.6%	1.7%
System 5	31.6%	29.6%	10.1%	30.3%	8.5%	30.2%	8.6%
System 6	27.4%	27.8%	8.8%	34.5%	9.6%	34.3%	9.6%

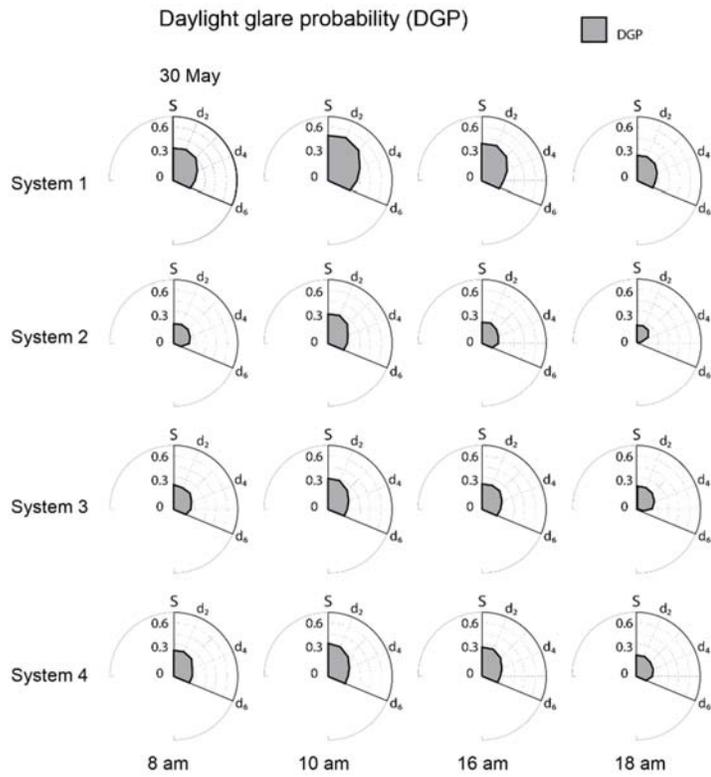


Figure 1. DGP results for Systems 1, 2, 3 and 4 for 4 time points within the occupancy hours 7 a.m. – 10 a.m. and 4 p.m. – 6 p.m.

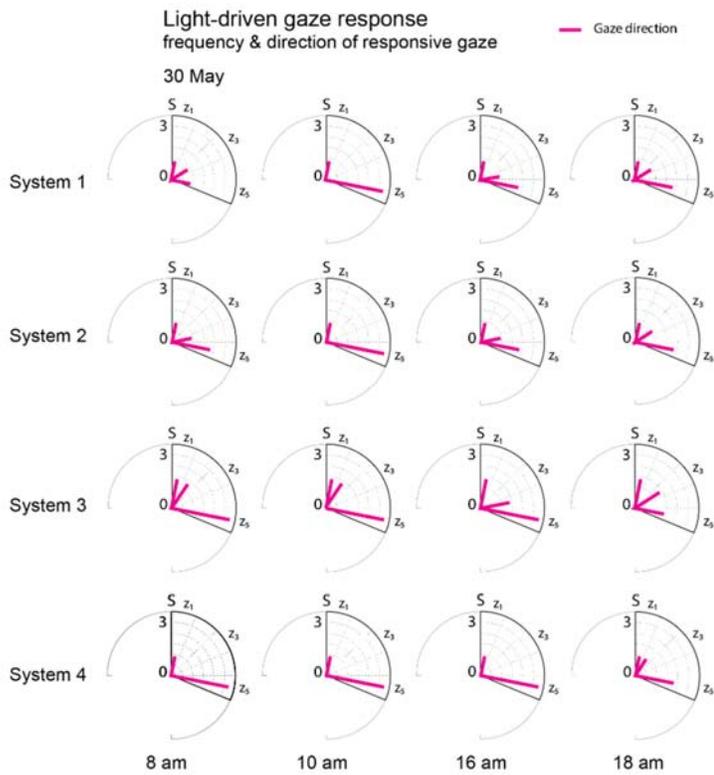


Figure 2. Responsive gaze direction predicted by  $GR_L$  for 4 time points within the occupancy hours 7 a.m. – 10 a.m. and 4 p.m. – 6 p.m..

## B. Gaze Responsiveness and Discomfort Glare

Radar graphs representing the DGP results for Systems 1, 2, 3 and 4 are shown in Fig.1. The results are reported for the  $112.5^\circ$  visual span where gaze (view) direction  $d_1$  is towards south direction and  $d_6$  at  $112.5^\circ$  inside the room from the window. In the graphs, the panorama extension of the FOV was highlighted. The DGP reduction can be observed by all the shading devices with the same trend over time. This reduction leads to DGP value equal to 0 at gaze (view) direction  $d_6$ .

The gaze shift frequency distribution is shown in Fig. 2. The graphs are angular histograms where the number of gaze directions falling in 5 bin zones ( $z_1$ - $z_5$ ) are shown. The representation of the visual span is the same as the previous graphs. The gaze (view) directions are largely corresponding to the discomfort glare predictions, which means that the highest gaze (view) directions frequencies are on zones where there is maximum discomfort glare reduction by means of the shading devices. This behaviour is consistent with roller blinds (System 2) and MicroShade (System 4) where a slight angle inside the room can assure a minimum exposure to discomfort glare. In case of venetian blinds (System 3), the general reduction of luminance levels in the room due to the  $45^\circ$  cut off angle of the slats, has created an even distribution of the gaze (view) direction frequencies. Moreover, in case of the initial case (System 1), higher glare impacts in all six view directions have shifted the gaze similarly for morning and afternoon. Whereas at 10 a.m. the gaze shift is more prominent due to the brightest glare patches in the FOV.

## IV. CONCLUSION

A combined gaze responsive visual comfort and daylight performance evaluations were conducted in order to assess various solar shading systems for residential buildings. The chosen evaluation methods allow assessing the daylight levels availability while assuring avoiding visual discomfort conditions. Daylight performance was assessed using DA. The visual comfort was then assessed for discomfort glare prediction using DGP and gaze responsiveness using  $GR_L$  evaluations methods for a selection of four shading systems. These evaluations were done for span of visual field from looking perpendicularly outside the window towards  $112.5^\circ$  inside the room where the window disappears from the FOV. The adopted three evaluation methods define different aspects of design for both façade and the interior space. This so called “trio evaluation method” will be further developed for a sensitive comparison of the shading devices. Limitations such as neglect of view attraction dependencies for visual comfort assessments are going to be addressed.

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