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Experimental and simulation analysis of daylight glare probability in offices with dynamic window shades

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ABSTRACT

This paper presents an experimental and simulation study to evaluate daylight glare probability (DGP) in office spaces with roller shades. Roller shades can be controlled in various ways and have an openness, transmitting direct and diffuse light even when fully closed. Since DGP combines the overall brightness of the visual field and the perceived contrast of the scene in one metric, the development of glare protection guidelines is complex in this case. Full-scale experiments with an HDR camera in test offices were combined with a validated, integrated daylighting and glare model. Correlations between DGP and design parameters (work plane or vertical illuminance) were developed and the applicability of DGP and DGPs for closed and controlled shades is discussed. The results show that DGPs is not an accurate metric when the sun is within the field of view – even for low openness fabrics – while the DGP equation might need a correction for such cases, due to extreme values of the solar corona's luminance influencing the luminance term. DGP and work plane illuminance are not well correlated, except for the case of perfectly diffuse fabrics. However, for all instances when the sun is not visible by the occupant, DGPs can be used to approximate daylight glare, including cases with sunlight on various surfaces in the space, for any fabric openness and control type. This enables the development of model-based, real-time glare control shading operation, with vertical illuminance being the basic parameter. Simple sunlight protection strategies cannot prevent glare, despite maximizing daylight utilization.

1. Introduction

Utilizing large glazing areas has increased daylight availability in office spaces, leading to advantages in terms of energy savings and outdoor views. However, more daylight is accompanied by increased solar gains and visual discomfort. Glare, defined as the contrast lowering effect within a visual field due to the presence of bright light sources, has been studied and quantified using several indices. Daylight Glare Probability or DGP is the most recent index used for evaluating glare from daylight, as it was extracted by human subjects' surveys in private office spaces [1]. DGP is considered part of the main climate-based daylight metrics for assessing daylight quality [2], although more research is still needed to establish appropriate criteria for acceptable luminance ratios as well as to investigate cases with direct sunlight present in the field of view.

There has been an extensive amount of literature in the last few years involving daylight glare. The majority of studies are related to simulation, usually utilizing Radiance renderings to simulate the visual field. A computational analysis of DGP and its simplified version [3], with discussion on vertical illuminance and contrast based glare, showed that the contrast term needs more detailed analysis, especially under low illuminance conditions. Mardaljevic et al. [4] conducted an initial study to relate DGP with a daylight metric such as the useful daylight illuminance [5], showing some initial potential, while Araji and Boubekri [6] linked window size with vertical illuminance and glare. Fewer studies actually involved experimental glare measurements, investigating the impact of large area sources [7], luminance variation and non-uniform luminance distributions [8,9], identifying modifications in existing glare indices [10,11], or performing case studies with translucent facades [12], anidolic daylighting systems with electric lighting operation [13] and advanced windows [14,15].

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Jakubiec and Reinhart [16,17] investigated the “adaptive” glare zones, laying the foundation for investigating the positional dependence of glare, and later combined simulation-generated DGP results with occupant surveys for three different levels of comfort in open plan spaces, to suggest that long term visual satisfaction can be described with current metrics – although more than one metric is required. As stated by Clear [18], more research is needed since evaluating glare in complex scenes may require fundamental changes to the form of glare models.

The potential effect of different window views on the subjective assessment of discomfort glare can be significant [19–22]. Suk and Schiler [23] and Suk et al. [24] used DGP measurements in two different studies to validate Radiance simulations and to initiate their approach towards developing a relative and absolute glare index. Post-occupancy studies with measurements and surveys under different sky conditions and façade configurations emphasize the complexity of assessing glare including occupant preferences [25]. Surveys and detailed glare measurements were conducted by Hirning et al. [26], to evaluate how different glare indices perform in open plan offices, and by Van den Wymelenberg et al. [27] to study the effects of luminance ratios and distribution patterns. Most of the above studies use a camera-based glare evaluation methodology, with useful details provided by Reinhart et al. [28], and also employ extensive HDR imaging research related to luminance measurement techniques [29–31].

Shading design and control play a central role in mitigating daylight glare, thus a few studies have focused on shading control strategies – mainly for venetian blinds. Wienold [32] presented his methodology for evaluating visual comfort and energy with different venetian blind controls, while Yun et al. [33] extended to more control types. Comprehensive venetian blind control strategies were presented by Chan and Tzempelikos [34], including the effects of blind material properties and an introduction to model-based glare control strategies. However, similar studies for roller shades are scarce [35], although roller shades are commonly used in perimeter offices, and glare problems have been reported due to excessive brightness or direct light transmission through the fabric. Chan et al. [36] recently proposed a systematic method to select shade properties based on glare criteria, recognizing that more research is needed in terms of utilizing a glare index extracted from simple measurable inputs.

This paper presents new experimental and modeling results for analysis of DGP in spaces with closed and controlled roller shades. Full-scale measurements with an HDR camera were conducted in test office spaces under variable sky conditions and shading control operations. The measured data were used to investigate the relative impact of contrast and overall brightness terms, and to derive potential correlations of DGP with design parameters such as indoor illuminances. The applicability of DGP and DGPs in the case of roller shades with openness and partially open windows is discussed. An advanced daylighting model, coupled with a glare prediction model, is validated and used to provide insights on the efficiency of control algorithms and potential simplified guidelines with regards to daylight glare.

2. Experimental methodology

2.1. Experimental facilities

The experiments were conducted in the Architectural Engineering laboratories of Purdue University in West Lafayette, Indiana. This research facility was particularly designed for quantifying the impact of facade design options and related controls on indoor environmental conditions and energy use. Two identical, side-by-side test office spaces with reconfigurable facades (Fig. 1) were used to compare the impact of different glazing, shading and control options under real weather conditions. The dimensions of each room are 5 m wide by 5.2 m deep by 3.4 m high, with a glass façade (60% window-to-wall ratio) facing south.

Two different glazing systems were used in this study: a SB70XL-clear high performance glazing unit with a selective low-emissivity coating (visible transmittance: $\tau_v = 65\%$ at normal incidence), as an example of modern solutions used in new buildings and a double clear glass unit ($\tau_v = 78.6\%$ at normal incidence) as a standard baseline used in existing buildings. Spectral and angular solar and optical properties were known for both glazing systems. The façade is equipped with motorized roller shades, with total visible transmittance equal to 5% (beam–beam transmittance: $\tau_{bb} = 4.2\%$ at normal incidence), exterior reflectance equal to 74.5% and interior reflectance equal to 28% (gray color). These properties were measured with an integrated sphere as described by Collins et al. [37]. The shades can be controlled automatically (through customized software) or manually, and their operation is connected to the lighting control system and to the data acquisition and monitoring system, to continuously monitor shading operation and position in parallel with other environmental variables. Several LI-COR calibrated photometers were used to measure light levels, both exterior (horizontal and vertical illuminance on the exterior wall and roof) and interior (transmitted through window on the interior surface of the glass, horizontal work plane illuminance at six points in each room, in two rows, 1.6 m and 3.30 m from the window respectively, and vertical illuminance at the eye height level at 2.20 m from the window). Illuminance sensors have a cosine correction for incidence angles up to 80°, a response time of 0.01 ms and an absolute error of 3%. Direct and diffuse portions of incident solar radiation on the façade were also measured with a vertical exterior solar pyranometer, mounted vertically on the exterior south wall. All sensors are connected to a data acquisition and control system (Agilent and Labview), accessible through remote access in order to run experiments without interfering with indoor lighting conditions. Measured data were recorded for every minute, under variable sky conditions and automatic shading operations, during fall 2013 and spring 2014. During most of the measurements, the sun was not visible from the measurement position, therefore DGP values were not affected by direct sunlight. The impact of direct sunlight is discussed separately in section 3.2. Each shading control test case was studied under variable sky conditions in the test offices, in order to observe the fluctuation of design values such as work plane illuminance with respect to discomfort glare and other daylighting metrics. Note that the double-clear glass was used as a comparative baseline and the WPP control was only used for the SB70XL glazing – a more realistic case for newer buildings.

2.2. Experimental setup for glare measurements

A calibrated Canon 550D camera, equipped with a Sigma 4.5 mm fisheye lens was used for luminance mapping and glare measurements, located at a distance of 2.20 m from the glass and 1.60 m from the western wall. The fisheye lens is recommended since it better resembles the human visual field. Hirning et al. [26] suggests a modified human visual field according to the total field of Guth [38], which is also an option in Evalglare software [39]. Although this approach is reasonable for studies involving human subjects, due to the fact that this study was focused on measurements and simulations and includes correlations with values extracted by photometers having 180° field of view, the original 180° wide visual field was used. The camera was mounted on a tripod at 1.2 m height, simulating an average seated occupant's eye level (Fig. 1), and was facing a laptop screen at a distance of 0.50 m, running typical