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Verification of simple illuminance based measures for indication of discomfort glare from windows

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ABSTRACT

Modern office buildings are often designed with highly glazed facades, with an intention of being sufficiently day lit. However, extensive daylight supply has its backside, as glare might be a considerable concern. From a building design perspective it is important to be able to make reasonable predictions of discomfort glare from windows already in the early design stage when decisions regarding the façade are taken. This study focus on verifying if simple illuminance based measures like vertical illuminance at eye level or horizontal illuminance at the desk are correlated with the perceived glare reported by 44 test subjects in a repeated measure design occupant survey and if the reported glare corresponds with the predictions from the simple Daylight Glare Probability (DGPs) model. Large individual variations were seen in the occupants' assessment of glare in the present study. Yet, the results confirm that there is a statistically significant correlation between both vertical eye illuminance and horizontal illuminance at the desk and the occupants' perception of glare in a perimeter zone office environment, which is promising evidence towards utilizing such simple measures for indication of discomfort glare in early building design. Further, the observed response indicate that the participants in the present study were more tolerant to low illuminance levels and more sensitive to high illuminance levels than the DGPs model would predict. More and larger studies are needed to confirm or enfeeble this latter finding.

1. Introduction

Daylight has been utilized as an architectonic and aesthetic concept through thousands of years to reveal form and structure and to create visual effects [1]. As for the more functional aspect, daylight was the predominant source of light through the ages, and buildings were designed to satisfy the light demands. However, after the development of artificial light and HVAC systems, architectural design developed more towards a pure art form while the use of energy demanding technical systems ensured occupant comfort [2]. With tightening of the requirements for energy use of buildings, daylight has experienced a renaissance during the last decades as architects and engineers see the value of daylight as an energy-efficient alternative to artificial lighting. Modern commercial buildings are consequently often designed with highly glazed facades, and it is a common belief that these buildings have a very high daylight supply. However, extensive daylight supply has its backside, as glare might be a considerable concern. A very common scenario in highly glazed buildings is seeing blinds down and lights on [3]. Many of these buildings could probably have been optimized by reducing the glazed area of the façade and thereby reduce the occurrence of glare and use of solar shading [3,4]. Unfortunately, the glare problems are rarely assessed in the building design which might be a result of the lack of an internationally accepted measure to evaluate glare from windows and/or solar shadings at the present time.

1.1. What is glare and how is it quantified?

Glare is commonly divided into two categories: disability glare and discomfort glare. According to the CIE vocabulary, disability glare makes a person unable to see certain objects in a scene, while discomfort glare produces discomfort without necessarily influencing visual performance and visibility [5]. Disability glare is well understood at the present time, but there is still a lack of knowledge

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Nomenclature

$L_{s,b}$	Luminance source/background in cd/m^2
Ω_s	Solid angle subtended by the glare source modified by Guth's position index
ω_s	Solid angle subtended by the glare source in sr
E_v	Vertical illuminance at the eye in lux
E_h	Horizontal illuminance in lux
P	Guth's position index

about the underlying process for discomfort glare, especially discomfort glare from daylight [6,7]. Fluctuation in pupil size [8], visual distraction [9] and hyperexcitability of visual neurons [10] have been suggested as mechanisms for causing discomfort glare. According to Vos [11], the present understanding of discomfort glare covers two fundamentally different phenomena which both produce discomfort. Vos suggests separating this concept into what he denotes as discomfort glare and dazzling glare. Vos explains that discomfort glare occurs with disturbing lights off the line of sight interfering with the foveal vision. The disturbing lights attract the eyes and work as a distraction from the visual task in the central vision. Dazzling glare, on the other hand, occurs when our eyes meet a very bright field of view which makes one screw up the eyes and show avoidance rather than attraction reactions. In a similar way of thinking, Suk et al. [12] recently introduced the terms absolute and relative glare factor.

Even though discomfort glare is a subjective sensation, several efforts have been made to objectively predict discomfort glare, which have resulted in a number of glare indexes, e.g. CIE glare index (CGI) [13], Daylight glare index (DGI) [14,15], Unified glare rating (UGR) [16], Visual comfort probability (VCP) [17] and Daylight glare probability (DGP) [18]. Most of these measures only focus on the contrast ratio between the background mean luminance and the glare source luminance, except for Daylight Glare Probability (DGP) which also incorporates vertical eye illuminance as a non-contrast-based aspect of the metric [12,19]. There is no consensus of which measure to use [7,12,20] and, in most glare studies, all indices are reported regardless of appropriateness [19]. However, only two of the aforementioned basic glare metrics are intended for evaluation of glare from daylight: DGI and DGP.

1.2. Daylight glare measures

Hopkinson [14] developed the Daylight Glare Index, see equation (1), by modifying the formula for Glare Index which had been performing satisfyingly for small glare sources. The modified formula permitted a Glare Index to be computed for glare from a bright sky seen through a window. Hopkinson emphasizes that high correlation between the predictions and the actual discomfort experienced should not be expected since discomfort glare has several side effects. Pleasant view has, for instance, been found to be an important side effect which makes the observer extend his/hers tolerance for discomfort [6,14,15,21,22]. Several researchers have proposed improvements of the formula for DGI over the years in order to obtain better correspondence with experimentally derived data or better mathematical formulation [15,21,23,24]. However, as Van Den Wymelenberg [19] points out, neither of the modifications have gained wide acceptance in practical building design and, according to Van Den Wymelenberg, DGI has surpassed its useful life.

$$DGI = 10 \cdot \log_{10} 0.48 \sum_{i=1}^{n} \left(L_s^{1.6} \Omega_s^{0.8}\right) / \left(L_b + 0.07 \omega_s^{0.5} L_s\right) \tag{1}$$

In 2003–2004, Wienold and Christoffersen [18] conducted a user assessment with 76 subjects under various real daylight conditions in Denmark and Germany. CCD camera-based luminance mapping technology was used to measure luminance within the field of view. The results from the user assessment showed poor correlations with the existing glare models DGI, CGI and UGR, which also have been confirmed in later studies [25–27]. Wienold and Christoffersen found that the general field of luminance was not suitable as a measure for the adaptation level, since the large glare sources themselves have an impact on the adaptation level. They instead suggested using vertical eye illuminance as a measure for the adaptation. Daylight glare probability (DGP) was developed, which is based on a combination of the existing CIE glare index algorithm and an empirical approach, see equation (2).

$$DGP = 5.87 \cdot 10^{-5} E_v + 9.18 \cdot 10^{-2} \log(1 + \sum_i \left(L_{s,i}^2 \omega_{s,i}\right) / \left(E_v^{1.87} P_i^2\right) + 0.16 \tag{2}$$

One major drawback with DGP, as well as most of the traditional glare metrics, is that it might be very time-consuming to carry out an annual analysis. In order to address this problem, Wienold [28] developed and validated two simplified versions of DGP: (1) DGP simplified (DGPs) based on vertical eye illuminance, see equation (3) and (2) enhanced simplified DGP based on vertical illuminance at eye in combination with a simplified image. The validation generally showed good results for the enhanced simplified DGP and reasonable results for DGPs when no peak glare sources where present.

$$DGPs = 6.22 \cdot 10^{-5} E_v + 0.184 \tag{3}$$

Some literature give recommendations [20,29,30] for the use of the DGP in assessing discomfort glare from daylight, and multiple studies show that DGP outperforms DGI [18,27,31]. However, a number of studies also indicate that DGP is not a robust glare metric [25,32], at least not as a single measure for securing visual comfort [31,33].

From a building design perspective, it would be advantageous with simple and computationally effective measures of discomfort glare from daylight that give reasonable predictions of glare for use in early building design when decisions regarding the façade are taken. These quantities should further be easily measurable in order to be able to validate the design as well as having the potential of being incorporated in building control strategies, e.g. of solar shading control.

Horizontal illuminance is the variable traditionally evaluated and referred to by engineers and architects in the daylight design community, and it is commonly used as an indicator of daylight sufficiency. However, it has also been proposed as an indicator of visual discomfort [34–36]. In 2005, Nabil and Mardaljevic [36] proposed Useful Daylight Illuminance (UDI) as a measure for annual daylight availability based on occupant preferences in daylight environments reported in the literature. At the present time, UDI is divided into four categories [37] where the category UDI exceeded (UDI-e, 3000 lux<) is associated with glare or overheating and an indication of the time when solar shading might be needed – the threshold for UDI-e was originally 2000 lux [36]. Horizontal illuminance is also considered as an indicator of visual discomfort within the recently approved method by IES [35] for annual daylight evaluations, where a threshold of 1000 lux from direct sun is proposed as an upper criteria. A few recent studies have also reported a reasonable relationship between the reported glare perception by occupants and horizontal illuminance [31,38].