Building and Environment 131 (2018) 63–73

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Subjective survey & simulation analysis of time-based visual comfort in daylit spaces

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ARTICLE INFO

Keywords:
Visual comfort
Discomfort glare
Time-based
Duration time

ABSTRACT

Based on the fundamental of instantaneous assessment of visual comfort evaluations, the novelty of this research is the idea to go beyond the instantaneous assess approach and to consider the duration time in predicting visual comfort issues, aims to explore the relationship between human discomfort perceptions and glare integral in time. Subjective survey and 6-min time interval glare metric simulations were taken place in four east-facing test rooms in Guangzhou, China. 16 volunteers participated in this survey from July 6th to Sep 3rd, 2017, all participants ranked the visual discomfort condition three times a day in morning/midday/afternoon. The metric calculation method used in this research was validated in the test room in Guangzhou. The results of this survey illustrated that enhanced simplified DGP (eDGPs) is capable to replace full-rendered DGP in predicting time-based visual comfort issues, and eDGPs has the advantage of being able to be rapid calculated in long-term survey or analysis. Moreover, there existed a strong correlation between the duration time above certain visual comfort thresholds with reported time-based visual comfort. The trigger duration time of $0.45 > \text{eDGPs} \geq 0.40$ is 12 min that occupant could evaluate the space visual intolerable and the corresponding median duration time is no less than 24 min. Meanwhile, the median duration time of $0.40 > \text{eDGPs} \geq 0.35$ is 6 min that a subject could rank the office space visual disturbing. The trigger duration time of $0.35 > \text{eDGPs} \geq 0.30$ is 6 min and the median value is 18 min that subject could probably evaluate the room space as glare perceptible.

1. Introduction

Free from glare, hence a visually comfort daylight environment has shown positive effects on health, well-being, circadian rhythms, productivity, mood, alertness, etc [1]. A widely accepted common view returning to architecture is to create comfortable and energy-efficient daylit buildings. In order to achieve this goal, the first approach may springs to one's mind is to utilize large glazing areas that could allow more daylight in perimeter building zones. However, besides increasing daylight availability in office spaces, leading to advantages in terms of energy savings and outdoor views, more daylight is always accompanied by increased solar gains and discomfort glare [2]. Discomfort glare is an underutilized parameter in contemporary architectural design due to uncertainties about how they should be well used [3]. Several metrics (e.g. DGI/DGP/vertical eye illuminance/simple luminance metrics/luminance ratios) had been proposed and/or their criteria had been studied to predict daylight glare over the past decades [4–6]. Anyway, it is a fact that the glare condition exceeded the discomfort criteria at a single instant could not equal that the building facade is failed from visual comfort design. According to common perceptions, visual discomfort couldn't be fully supposed to instantaneous, indeed, people tend to avoid glare with certain actions (e.g. close or adjust the shades) whenever they feel glare, but the response time might depend on the degree of glare. The instant response is urgency only when severe glare occurs. Discomfort glare perceptions is a temporal-related issue, hence, with respects to long-term or time-based evaluations, Jan Wienold [7] pointed that the behavior of the building's façade follows ambient weather conditions and seasonal differences dynamically. Glare condition follows the luminous condition changes. Accordingly, the sense of glare is a temporal correlated perception of an individual. In order to introduce glare into rating systems and apply more reasonably, it is therefore desirable to summarize the overall glare sensation in hours, days, months, and better, over the course of a year. So the results can be customized by the time of day, adding time as another analytical dimension in addition to space [8].

The continuous practices of dynamic daylight glare evaluation have yet to embrace a well-used rating framework of long-term visual

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https://doi.org/10.1016/j.buildenv.2018.01.007
Received 29 October 2017; Received in revised form 2 January 2018; Accepted 3 January 2018
Available online 06 January 2018
0360-1323/

comfort prediction. Early in 1998, Mardaljevic [9] noted that the prediction of high luminances in the field of view due to the visible sky on an annual basis is more straightforward. There are a number of theoretical glare formulations, any of which could be used to analyze the output from a lighting simulation. Reinhart and Wienold [10] noted that using the software tools Dasyim plus Evalglare could assess time-based or annual daylight glare probability profile. In aims of quick rendering and rapid to acquire, simplified DGP (DGPs) and enhanced simplified DGP (eDGPs) were proposed by Wienold [7] for replacing of full rendered DGP in hourly annual daylight glare simulation. Tzempelikos and Chan [11] proposed a hybrid ray-tracing and radiosity method for calculating illuminance and luminance distribution with time intervals in daylit spaces, as the algorithm combines the advantages of both methods, so the accuracy is also ensured. It has been proven very useful for faster calculation of time-based glare metrics with any fenestration system [12]. Jakubiec and Reinhart [13] proposed a concept for predicting occupants' long-term visual comfort within daylit spaces: a paired study consisting of occupant surveys and visual comfort simulations was performed. Jakubiec also noted that it is necessary to test the concept of long-term visual comfort in different buildings, use types and with more voluminous data to aid in validation of the concept.

It is therefore critical to understand how building occupants rate the time-based glare evaluations. Nowadays, most visual comfort investigations focused on the comfort of an individual at a single instant. Different from instantaneous visual comfort, time-based prediction of visual comfort is a ceaseless measure of sensation. Though the state-of-the-art rhino based analysis software tool DIVA [14] have the function of calculating discomfort glare for every hour of an entire year, but no distinct guideline existed for how often and how much discomfort glare is acceptable. Essentially, how much the frequency or duration time of the occurrence of glare metrics exceed a certain threshold would evaluate a space as 'perceptible/disturbing/intolerable' lack of assessing. This paper is, therefore, an attempt to make efforts with our endeavors in China for assessing how much time or how often the discomfort glare in a period could be adopted in evaluating the visual comfort in daylit spaces.

Subjective survey combined with daylit simulation results is an approach arose due to the need to keep the interference with the participants' usual work activities to a minimum, while still providing data suitable for meaningful analysis. According to Reinhart's study [15] that subjective evaluations by students could correlate well with daylit simulations in a studio space. This study planned to use occupant's surveys to assess visual comfort predictions in real spaces compared to simulated results.

In this research, a subjective survey was conducted from July 6th to Sep 3rd, 2017. The dynamic glare metric predictions in this research were made using the eDGPs method. Totally, 16 volunteers take participant in this survey who are ordered to work in the test room as usual. The participants were asked to finish a survey on commenting about their visual comfort sensation in the past hours. Meanwhile, an illuminance meter was installed on the back of monitor top to measure the vertical illuminance, which was used to convert to vertical eye illuminance at the subject position. Moreover, radiance based 0-ambient luminance map rendering plus on-site measured vertical eye illuminance (calculated from vertical illuminance on monitor top) were processed with Evalglare to assess the dynamic glare evaluation with computer model. Hence, the time-based visual comfort analysis is processed based on the subjects' perception survey results and the simulated eDGPs values at time intervals.

Generally, the novelty of this research are two: a) the proposed methodology allowing to simultaneously collect users' surveys and measured data, without interfering with the participants' usual work; b) the idea to go beyond the instantaneous assess approach and to consider the duration time for which some glare metric values are calculated.

2. Review of visual comfort metrics

There has been an extensive amount of separate attempts have conducted to quantitatively predict discomfort under various laboratory or field conditions. It is found that discomfort turns out to be referred to precise moments of the day and to particular weather conditions. A correspondence between daylight performance index and users' opinions is not always observed [16]. So, according to reviews of the related investigations, each discomfort metric has limitations or range of application for predicting visual discomfort. E_v and DGI, DGP are three widely used metrics to predict visual discomfort under daylight conditions, the related studies are reviewed in this section.

2.1. Vertical eye illuminance (E_v)

E_v is assumed with more light reaching the eyes, experiencing luminous environment is more likely. E_v is validated by Wymelenberg [17] to outperform than DGP & DGI in evaluating visual discomfort under no direct sunlight occasions. A study showed that the E_v measured near the facade and from the back of the room is a good measure towards monitor visual comfort under intermediate and overcast sky conditions [18]. According to Bian and Luo's investigation [19] in China, E_v has a notable correlation with occupants' visual comfort preference under various sky conditions. Moreover, it is found that E_v and DGP have a strong correlation with all shading controls [20]. It could generate that in scenes that are relatively dim due to intermediate or overcast sky patterns, E_v would yield significant results.

Based on the results of the study taken place in China, E_v above 2000 lx identifies discomfort [19]; Karlsen et al.'s research in northern Europe [21] noted that the threshold of E_v for avoiding excess glare perceptions is 1700 lx; Alstan Jakubiec [22] found that $E_v > 1500$ lx identifies 54.7% of visual discomfort; Wymelenberg and Inanici [6] reported that E_v level above 1250 lx is likely to be uncomfortable. Konstantzos, Tzempelikos and Chan [23] noted that the total vertical eye illuminance would still be used for the overall brightness term. The proposed threshold values were 2760 lx for the total vertical illuminance and 1000 lx for the direct vertical illuminance.

2.2. Glare indices (DGI, DGP)

DGI is the only and default indicator to evaluate glare under daylight environment in the present national standard of building daylighting design in China [24], which is proposed by Hopkinson [4] in 1972. Generally, in the definition of DGI, discomfort glare is treated as a phenomenon arising from high luminance contrasts in the visual field. Several studies have been implemented to examine the correlations between DGI and occupant assessments of visual comfort in multi kinds of spaces. Wienold and Christoffersen [5] noted that the correlation of DGI to users' responses is low; Painter, Fan and Mardaljevic [25] found that DGI couldn't well resolve subjective visual discomfort in dim or low-contrast luminous environment. Also, Suk et al. [23] found that DGI underestimate glare. Bian and Luo's investigation [19] under various sky conditions in China found that DGI has little to no correlations with occupants' perceptions. Nevertheless, Hirning et al. [26] also noted that contrast-based measures such as DGI works better in deep spaces than perimeter areas.

DGP is developed by Wienold and Christoffersen [5] in 2006, prior to DGI or other contrast based glare metrics, which combines the overall brightness of the visual field and the perceived contrast of the scene in one metric. DGP is considered as a recent proposed and meanwhile widely accepted index used for evaluating glare from daylight. The adaptability and threshold of DGP were studied and validated by daylighting researchers in U.S, EU, Australia and Asia. Jakubiec and Reinhart [3] showed that DGP is a robust metric and the least likely to give false comfort indications in a simulation-only study. Wymelenberg [6] noted that no matter the glare source identified by 2000 cd/m^2, 5 *