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Investigation of existing discomfort glare indices using human subject study data

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ABSTRACT

As daylighting becomes an increasingly important component of design for energy savings and views to the outside, it is necessary to take into disadvantages that windows pose including the possibility of glare. It is crucial to understand how current metrics of glare perform this task. Validation studies were performed on five glare indices including Daylight Glare Probability (DGP) and Daylight Glare Index (DGI) that have been developed specifically for daylight glare issues. A parallel human subject study has been performed to collect subjective discomfort glare evaluations of daylit conditions. In addition, high dynamic range imaging was used to capture and analyze the glare scenes that were experienced by those human subjects. More than 450 daylight glare scenes and subjective surveys were collected in a closed office setting. The collected data were processed in Evalglare to obtain glare scores, and the results were compared for statistical analysis of subjective evaluations. The results show that DGP functions best at absence of glare and presence of intolerable glare; but in between it provides disappointingly low predictions. DGI underestimates glare while Visual Comfort Probability and CIE Glare Index overestimate it. This evaluation comparison study supports the findings that the five glare indices have significant inconsistency and inaccuracy issues. The glare indices behaved differently based on the perceived glare categories: imperceptible, perceptible, disturbing, and intolerable. The existing glare score ranges are compared to the newly defined glare score ranges for further improvement.

1. Introduction

Discomfort glare occurs when the eyes have adjusted to a certain general level of brightness, and some annoying, distracting, or blinding light appears within the visual field [1–3,18]. In daylighting design, discomfort glare should be avoided to successfully achieve the benefits of utilizing natural light source in buildings. However, accurate evaluation of discomfort glare has been challenging since glare is a subjective phenomenon. Many discomfort glare indices have been developed to accurately quantify and determine perceived levels of glare. However, the existing glare indices report widely inconsistent evaluations on a same glare scene [8]. Many researchers have performed validation studies on the glare indices but there is not yet clear instruction on the correct usage of the glare indices. Extensive human subject study was performed to confirm the findings of previous research and to understand how the existing glare indices perform in evaluating glare in different daylit conditions.

Glare can be described in one of three main ways: according to the process that created the glare, according to an individual's perceived degree of glare intensity, and according to the results of the glare. Many existing glare indices including DGP (Daylight Glare Probability), DGI (Daylight Glare Index), UGR (Unified Glare Rating), VCP (Visual Comfort Probability), and CGI (CIE Glare Index) focus on evaluating perceived degree of glare intensity. DGP and DGI were specifically developed for daylight glare which needs to be treated differently from visual discomfort issue of electrical light sources. The equations of the glare indices look complex, but they use same variables with different weighting factors. Crucial values such as background mean luminance, glare source luminance, glare source position, solid angle of glare sources, vertical illuminance, and direct vertical illuminance should be obtained to calculate the following equations [5,8,10,20,21].

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$$DGP = 5.87 \cdot 10^{-5} \cdot E_v + 0.092 \cdot \log\left(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^2 \cdot P_i^2}\right) + 0.16$$

$$DGI = 10 \cdot \log\left(0.478 \sum_i \frac{L_{s,i}^{1.6} \cdot \omega_{s,i}^{0.8}}{L_b + 0.07 \cdot \omega_{s,i}^{0.5} \cdot L_{s,i}}\right)$$

$$UGR = 8 \cdot \log\left(\frac{0.25}{L_b} \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2}\right)$$

$$VCP = \left[224.4 - 46.8 \cdot \log\left(\times \sum_i \left(\frac{0.5 \cdot L_{s,i} \cdot \left(20.4 \cdot \omega_{s,i} + 1.52 \cdot \omega_{s,i}^{0.2} - 0.075\right)}{P_i \cdot L_a^{0.44}}\right)^{-0.0914}\right) \times\right] + 50$$

$$GGI = 8 \cdot \log\left(2 \cdot \frac{1 + \left(E_d / 500\right)}{E_v} \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2}\right)$$

Where,

E_v = vertical illuminance at eye level [lux], E_d = direct vertical illuminance [lux],
L_s = luminance of the source [cd/m^2], L_b = background mean luminance [cd/m^2],
L_a = average luminance of entire field of view, ω_s = solid angle of the source [sr], and P_i = Guth position index [-]

For evaluating glare in a luminous environment using High Dynamic Range (HDR) photography or simulated by daylighting software, the software program Evalglare was developed [4,5]. Evalglare analyzes a glare scene by using the five glare indices stated above and identifies potential glare sources based on a threshold value, which can be specified by the user manually as a fixed luminance value or computationally determined by a multiplier "5 times" of the mean total image luminance or the mean task area luminance [6,7]. Evalglare has been plugged into several daylighting analysis software programs making glare analysis easier, but its use has not been widely adopted in practice yet. Also, it still requires more validation studies. Based on the information taken from an image, Evalglare provides glare scores of the glare indices. The following table shows different glare score ranges of the five glare indices to categorize different levels of perceived glare from imperceptible to intolerable glare. Lower scores represent lower levels of discomfort glare except for VCP where a higher score represents better visual comfort.

Based on a study using computer simulation, Jakubiec and Reinhart claim that DGP shows the most robust results for most daylight situations among the five indices [10]. VCP is not intended to be used for daylight glare calculations, and CGI tends to overestimate glare levels. DGI and UGR can be used for daylight glare evaluation, but they work only when the direct sunlight does not enter [10]. Based on human subject study performed in a large open office space, Hirning claims that DGP and DGI were unable to provide accurate evaluations of discomfort glare experienced by the participants [2,3]. Evalglare is one of the most practical tools for studying daylight glare, but previous research has shown that the existing glare indices provide inconsistent glare evaluations for a same glare scene, which makes users suspicious of their evaluation accuracies [8]. The previous study was done entirely with software; recent research utilizing extensive human subject study data was performed to find out levels of accuracy and consistency of the five indices.

2. Methods and approach

A number of precedents shows various human subject study methodologies for discomfort glare investigations [1,2,11–17]. A human subject study using a survey and HDR photography was developed to collect accurate and consistent subjective and objective data for analysis.

2.1. Human subject study and high dynamic range photography

A human subject study was performed from February 18, 2013, to June 17, 2013. Six male and female subjects were recruited from an architecture school who fulfilled the following requirements and they were tested repeatedly in different times and dates:

- No vision-related illness
- No color blindness (established by a color blindness test using the Ishihara template)
- Age between twenty and forty years
- English speaking, reading, and writing ability
- Basic typing skill in MS Word and Adobe Acrobat (PDF)

The human subject study to assess discomfort glare issues was performed inside a closed office space in Los Angeles. The room dimension is 9′-6″ by 11′-4″ with an 11′-3″ floor to ceiling height (Fig. 1). There are no exterior visual obstructions that are closely located to the office. The room is a corner office with two 8′-6″ high clear glass windows (from task height to ceiling) facing southwest and southeast. The corner office condition was expected to provide more opportunity to experience potential glare sources. Since the office has front and side windows, it can have potential glare sources from different directions: from the left side of subject's face and in front of subject face. A desk was located adjacent to the southwest facing window.

Each subject was tested under three different lighting conditions. For each, the subjects were asked to perform three different activities: no task, typing task, and writing task. The room had both venetian blinds and roller blinds on the windows. There were three lighting conditions:

1. Fully open: both roller and venetian blinds were fully opened on both front and side windows and could not be adjusted (Fig. 1, top).
2. Roller blinds only: the subjects were able to separately adjust front and side roller blinds as they preferred. The venetian blinds were fully open and could not be adjusted (Fig. 1, middle).
3. Venetian blinds only: the subjects were able to separately adjust front and side venetian blinds as they preferred. The roller blinds were fully open and could not be adjusted. Unlike with the roller blinds, venetian blinds can also be set to different angles. This allowed the subjects to introduce more natural light into the room if they wanted higher light levels and to block incoming natural light if they wanted lower light levels (Fig. 1, bottom).

A glare scene experienced by a subject was captured by using

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