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The influence of shading control strategies on the visual comfort and energy demand of office buildings

Gyeong Yun, Kap Chun Yoon, Kang Soo Kim*

Department of Architecture, Korea University, 5-1 Anam-dong, Seongbuk-gu, Seoul 136-713, South Korea

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ABSTRACT

A lighting control strategy using daylighting is important to reduce energy consumption, and to provide occupants with visual comfort. The objective of this research is to evaluate visual comfort and building energy demand, and suggest lighting and shading control strategies for visual comfort and building energy savings. This research intends to achieve visual comfort and energy savings in an office building, by means of visual environmental control, and focuses on a quantitative criterion (illuminance), and a qualitative criterion (glare index) in daylighting. We used HDR images captured in real scene and simulation (*DIVA-for-Rhino*) for glare evaluation. The measured data from the mock-up room and the scale model were compared, to validate the simulation tool. Vertical eye illuminance (E_v) is recommended for the glare index, in place of the DGI or DGP. To prevent disturbing glare and to secure maximum daylight, control strategies of lighting and shading are suggested, related to the E_v value. In addition, the *EnergyPlus* program was used for calculation of the annual energy consumption. Building energy consumption is presented according to three building orientations, and 10 control strategies of lighting and shading. If there is no need to consider glare, a blind slat angle of 0° or dynamic shading is better in winter, regardless of the building orientation. In summer, a blind slat angle of 30° (static angle) or dynamic shading is suitable for an energy efficient and anti-glare control strategy.

1. Introduction

Buildings account for approximately 40% of the world's annual energy consumption [1]. Building energy consumption is closely related to the lighting environment, according to daylighting. Daylighting is an important factor in determining indoor visual comfort, and affects user satisfaction and productivity [2]. In addition, daylighting from windows can bring both positive and negative experience: access to view and daylight, but also glare and thermal discomfort [3–5]. Occupants use personal computers; therefore, the issue of visual comfort comes to the fore as an essential element, particularly in office buildings. Daylighting has quite a different influence on the cooling, as against the heating load. In the cooling period, daylight negatively affects the cooling load; but the complete exclusion of daylight increases electric lighting energy consumption. In the heating period, daylight has a positive influence on the heating load, but an excessive amount of daylight affects discomfort glare.

Energy performance and the indoor environment have become increasingly important in building design [6]. In office buildings, the use of glass for façade designs has increased in recent years for aesthetic reasons, and this has caused excessive energy consumption, and glare. Daylighting is an effective and sustainable development strategy for enhancing visual comfort, energy-efficiency, and green building development [7]. Therefore, it is necessary to study the relationship between the visual environment and energy savings, according to the control strategy of electric lighting and daylighting.

Electric lighting is one of the major energy consuming items, and accounts for 20–30% of the total electric energy consumption [8]. In South Korea, lighting energy consumption comprises about 30% of the total building energy consumption [9]. Therefore, we should utilize daylighting for the cost-effective management of electric lighting.

A lighting control strategy using daylighting has been proposed, in order to reduce the energy consumption of new buildings or existing buildings. In addition to energy saving, the control strategy achieves visual comfort for the occupants.

The main objective of this study is to evaluate visual comfort and building energy demand, and suggest lighting and shading control strategies for visual comfort and building energy savings. This research intends to achieve visual comfort and energy savings, by

* Corresponding author. Tel.: +82 2 3290 3744; fax: +82 2 921 7947.
E-mail addresses: poprin@korea.ac.kr (G. Yun), kapchun@korea.ac.kr (K.C. Yoon), kskim@korea.ac.kr (K.S. Kim).

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visual environmental control in an office building, and focuses on quantitative criteria (as illuminance), and qualitative criteria (as glare index), in daylighting.

The research is conducted for

(1) the indoor environment of an office building,
(2) the application of venetian blinds,
(3) Seoul, Korea,
(4) the climate condition of a whole year,
(5) three orientations: south, east and west, and
(6) during the weekday times of: 9:00 am to 6:00 pm.

2. Theory

2.1. Simulation programs

2.1.1. EnergyPlus

The *EnergyPlus* program is based on a combination of BLAST [10] and DOE-2 [11]. This program calculates with the heat balance of BLAST. The *EnergyPlus* daylighting algorithm is derived from the daylighting calculation in DOE-2.1E [12], which is described in Winkelmann [13], and Selkowitz [14]. In this research, we used the *EnergyPlus* program to predict the electric lighting energy and HVAC energy.

2.1.2. DIVA-for-Rhino

DIVA-for-Rhino is a daylighting and energy modeling plug-in for Rhinoceros. The plug-in was developed by the Graduate School of Design at Harvard University, and it is now developed by Solemma LLC [15]. *DIVA-for-Rhino* allows users to evaluate the environmental performance of buildings or urban landscapes. We can obtain radiation maps, photorealistic renderings, climate-based daylighting metrics, annual and individual time step glare analysis, LEED and CHPS daylighting compliance, and single thermal zone energy and load calculations.

Evalglare is applied to *DIVA-for-Rhino* in individual time step glare analysis, and we can obtain the HDR images for a specific point in time. The images were compared to the measured HDR images, for glare analysis, and vertical eye illuminance evaluation.

2.2. Glare indices

2.2.1. Daylight glare index (DGI)

Daylight glare index (DGI) predicts glare from a large source, such as a window. The BRE and Cornell University conducted this study [16]. The equation is expressed as follows.

$$\mathrm{DGI} = 10\log_{10} 0.48\sum_{i=1}^{n}\frac{L_s^{1.6}\Omega_s^{0.8}}{L_b + 0.07\omega_s^{0.5}L_s}$$

where L_s [cd/m^2] is the luminance of a glare source, L_b [cd/m^2] is the background luminance, ω_s [sr] is the solid angle subtended by the source, and Ω_s [sr] = ω_s/P is the solid angle subtended of the source, modified for the effect of the position of its elements in different parts of the field of view. The DGI criterion corresponding to the mean relation is as shown in Table 1.

2.2.2. Discomfort glare probability (DGP)

DGP is a glare index for the measurement of glare caused by daylight. The equation is defined as follows.

$$\mathrm{DGP} = 5.87\times10^{-5}E_v + 9.18\times10^{-2}\log\left(1+\sum_i\frac{L_{s,i}^2\omega_{s,i}}{E_v^{1.87}P_i^2}\right) + 0.16$$

E_v [lx] is the vertical eye illuminance at eye level. DGP describes the fraction of disturbed occupants under the specific daylight situation. This index is developed by Wienold et al. [18]. The higher the DGP, the higher the glare.

The DGP criterion corresponding to the mean relation is as shown in Table 2.

In the Radiance tool called *evalglare*, DGP is based on the evaluation of the full luminance distribution of a visual field. This method is not convenient for a dynamic simulation, because it demands a picture for each time. Therefore, DGPs was generated, to be used in dynamic simulation by Daysim and *DIVA-for-Rhino*.

Table 1
Glare rating of DGI [17].

Glare criterion corresponding to mean relation	DGI
Just imperceptible	16
Noticeable	18
Just acceptable	20
Acceptable	22
Just uncomfortable	24
Uncomfortable	26
Just intolerable	28
Intolerable	30

2.2.3. Simplified discomfort glare probability (DGPs)

DGPs was developed to overcome time-consuming repetitive work. Wienold and Christoffersen [17] revealed that the DGP and the vertical illuminance at eye level are interrelated. The equation is as follows.

$$\mathrm{DGPs} = 6.22\times10^{-5}\times E_v + 0.184$$

In DGPs (simplified discomfort glare probability) calculation, the influence of glare sources is neglected. Therefore, this method should not be applied, when there is direct sun or specular reflection [20].

2.3. High dynamic range imaging

Humans can see objects in moonless night or bright sunny day. This means that the human eye can adapt to a dynamic luminance range of 10,000:1 [cd/m^2]. Most displays cannot present a dark area and a bright area in the same scene. A good quality LCD display has a dynamic range of about 1000:1.

High dynamic range imaging is a method to capture a higher dynamic range between the brightest and the darkest areas of an image, than those obtained by standard digital imaging methods. In general, non-HDR cameras take pictures with limited contrast range (known as low dynamic range (LDR) images), and one exposure at once. Therefore, we can only obtain images that do not show the darkest and the brightest details.

2.4. Evalglare

The *Evalglare* program was developed by Jan Wienold at the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany. This program evaluates the glare sources with 180° fish-eye images of Radiance image format, such as .pic or .hdr. For performance reasons, the image should be smaller than 800 × 800 pixel. The program calculates the glare indices (DGI, UGR VCP, and CGI) including

Table 2
Glare rating of DGP [19].

Glare rating	DGP
Imperceptible	<0.35
Perceptible	0.35–0.40
Disturbing	0.40–0.45
Intolerable	>0.45