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Assessment of user reaction to glare with three solar shading systems

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SUMMARY

The objective of the study was to investigate the user perception of solar shading systems regarding glare by using laboratory tests with subjects, to compare the results with existing glare rating equations and to derive a new glare prediction model. The laboratory tests were conducted at the Danish Building Research Institute and at the Fraunhofer Institute for Solar Energy Systems. At each site, the study was performed in two identical experimental rooms, one with subjects, and the other with measuring equipment. A total of 105 subjects were exposed to three different window arrangements typical for today's design of windows in office buildings. To ensure variations in potential glare situations, three different solar shading devices were included, in order to assess existing glare models and to provide a reliable database for the development of a new glare prediction model - daylight glare probability DGP.

KEYWORDS

Discomfort glare, Solar shading systems, User assessments, Daylight glare probability

INTRODUCTION

Today, in a world concerned about carbon emission, global warming and sustainable design, daylit buildings are proposed as being part of the 'solution'. Daylighting is acknowledged as providing many benefits ranging from improvements of people's health and well-being to increased lighting quality (Rangi and Osterhaus, 1999). Daylight design has, however, become a complex system integration challenge. Daylight varies in intensity, colour and directions. These variations are one of the design parameters, which are difficult to cope with, since they have a great impact on both the thermal and the visual environment. Additionally, the development of glass technology and shading devices results in a wide selection of new façade solutions. Successful daylight design requires trade-offs and optimisation between competing elements of façade, space, and lighting system. It also requires reliable tools and/or descriptors for different aspects of comfort and energy demand. For many aspects reliable tools are available – but not for discomfort glare from windows. The objective of this study was to investigate the user perception of solar shading systems regarding glare by using laboratory tests with subjects, to compare the results with existing glare rating equations and to derive a new glare prediction model. In the tests typical office tasks and viewing directions were investigated in order to derive a reliable glare rating. The laboratory tests were conducted at the Danish Building Research Institute (SBi, Denmark) and at the Fraunhofer Institute for Solar Energy Systems (ISE, Germany).

METHODS

Test facilities

Both institutions carried out the experiment using the same procedure and under almost identical experimental conditions (Christoffersen and Wienold, 2004). The study was performed at each location in two identical experimental rooms, one with subjects (Test room), and the

other with measuring equipment (Reference room). Each room was equipped with one work-station (a desk, an office chair, and a computer). The work place was next to the window and subjects were seated 1.5 m away from the window. Only flat panel displays (VDT) were used.

The Danish daylight laboratory (latitude 55.86° N, longitude 12.49° E) has two south-oriented experimental rooms, which can be changed so that north and east orientations can also be studied. The rooms are orientated 7 degrees east of due south to allow maximum amounts of sunlight to fall on to the glazing, but with some outside obstructions to the west. The two rooms are characterised by identical photometrical (ρ_{wall} = 0.62, $\rho_{ceiling}$ = 0.88, ρ_{floor} =0.11) and geometrical features (3.5 m wide, 6.0 m deep, 3.0 m high). The rooms have a glass area covering the whole façade and the glazing was Low-E double-glass with a light transmission of $\tau_\perp$ = 72%, U-value of 1.1 W/m^2 °C and a total solar energy transmission of 59%. The German daylight laboratory (latitude 48.01° N, longitude 7.84° E) has two experimental rooms sited on the roof and they can be fully rotated without restrictions, which allows a wide range of sun altitude and azimuth to be studied, quite independent from the seasons. The two rooms have identical photometrical (ρ_{wall} = 0.56, $\rho_{ceiling}$ = 0.80, ρ_{floor} =0.34) and geometrical features (3.65 m wide, 4.6 m deep, 3.0 m high). The distance from floor to the suspended ceiling can be changed. The rooms have a glass area covering the whole façade and the glazing is colour-neutral sun protective double-glass with a light transmission of $\tau_\perp$ = 54%, a u-value of 1.1 W/m^2 °C, and a total solar energy transmission of 29%.
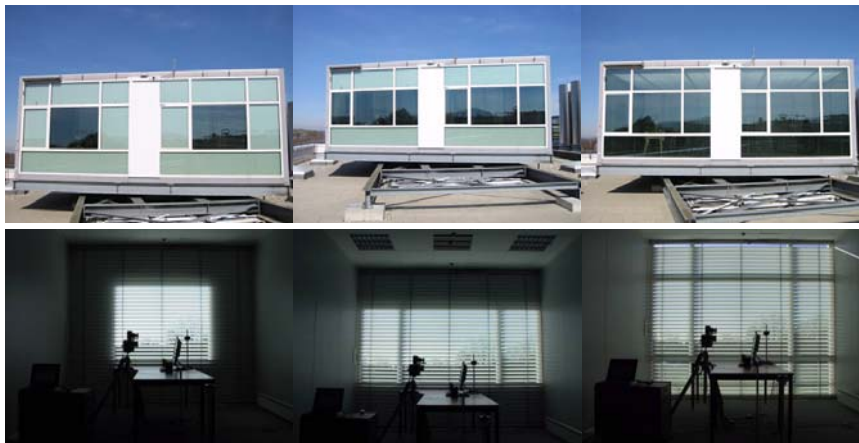

Figure 1. Top: Photographs of the ISE test facility with the three window configurations (left - small window, middle – medium window, right – large window). The rooms can be rotated fully in order to be more or less independent on seasons to set up a defined angle of incidence for the sun. Bottom: Photographs of the SBi test facility with the three window configurations seen from inside (parallel view direction).

In this study subjects were exposed, at both locations, to three different window arrangements typical for today's design of windows in office buildings. The window arrangements could be changed within 5 minutes, as the fully glazed façade could be either partially occluded (small and medium sized windows) or totally exposed (large window). These three different window sizes included a small window in the centre of the façade (sill-height at workplane, glazed area/façade area ~ 25%), a medium rectangular window covering the width of the façade (same window-height as the small window, glazed area/façade area ~ 45%) and a large window (glazed area/façade area ~ 85%) covering the whole façade (see Figure 1). Three different solar shading devices were included in the study in order to have variations in potential glare situations. The optical properties of the shading systems used in the experimental set-up were: White 80 mm, convex Venetian blinds (reflectance ρ_{vis}=84%), Top side mirror-finished 80 mm, concave Venetian blinds (reflectance ρ_{vis}=95%, lower side grey) and a transparent foil

with vertical lamellas (light transmission $\tau_\perp$ = 2%). The Venetian blind systems use special step motors connected to a LON bus to ensure the same tilt angle of the slats in both rooms.

Interior and exterior measurements

The indoor illuminance on the work plane in the reference room was monitored with five sensors at regular distances fixed on metal supports 0.85 m from the floor. To control that both rooms had the same illuminance level during the tests, two sensors in both rooms were installed at the same position; a horizontal illuminance sensor near the subject and a vertical sensor at a VDT screen facing the subject. Comparison showed that in most cases the illuminance level in the experimental rooms, at both locations, was very similar, and that there had been comparable interior lighting conditions at both locations. A vertical illuminance sensor was mounted on a tripod at a height of 1.2 m to measure the vertical illuminance (reference room) at the approximate position of the subject's eyes (see Figure 2). The illuminance measurements were made every 10 seconds at ISE and every 30 seconds at SBi.

Figure 2. Interior view of the work place with CCD camera at eye position and interior illuminance sensors in the reference room (parallel view set up) at the SBi (left) and at ISE (right).

The luminance distribution within the field of view of the subjects was measured using a calibrated, scientific-grade CCD camera with a fish-eye lens (field of view 183 degrees). The CCD camera was mounted on a tripod together with the vertical illuminance sensor measuring the eye illuminance level. The resulting digital image contained more than 1.3 million luminance values with a dynamic range varying from $3 - 1.8 \times 10^6$ cd/m^2 (ISE) and $3 - 200\ 000$ cd/m^2 (SBi). A separate exterior meteorological station located on the roof recorded global total and diffuse illuminance and irradiance measurements.

Procedure

In the Test Room, the subjects were asked about their impression and opinion of the room, the windows and occurring glare problems. The subjects performed different tasks and the task presentation order was fixed and data on user's performance (speed and errors) were recorded. The main purpose of these work tasks was that all subjects performed the same office task during the tests before answering the questionnaire, since almost all previous studies evaluated discomfort glare by directly viewing the glare source rather than focusing on a work task. The order of presentation of the three window sizes and two viewing directions (within-subject) was carefully controlled (balanced presentation order). The viewing direction was either parallel with the window (90°, only white Venetian blinds) or facing diagonally towards the window (45°, all systems). Glare assessment for each of the three different shading systems tested (between-subject) lasted for about 1 hour and 45 minutes (either morning session or afternoon). During one session, only the window size was changed, which meant that the subject evaluated three different window sizes, each lasting about 30 minutes. Subjects left the room when the window size was changed. Each time the subjects entered the test room, the venetian blinds were in a fixed position with maximum daylight coming into the room, maintaining some view to the outside, but allowing no direct sunlight to penetrate

the solar shading device ("cut-off" position). The foil system was completely closed. All tests were carried out under stable clear sky and overcast condition in order to prevent significant changes of the interior lighting conditions (see Table 1). No artificial lighting was added during the test. All collected data has been analyzed by a repeated measure ANOVA, with three levels of Window size and for white Venetian blinds we also had two levels of Direction as within-subjects factors. The shading systems (white and specular Venetian blinds, and a transparent foil) is between-subject factor.

Questionnaire on lighting conditions
The questionnaire on the lighting conditions was divided into 4 main parts. The demographic questions (part 1) considered gender, age, left or right handed, the wearing of glasses or contact lenses, and sensitivity to bright light. Questions in part 2 were related to rating the lighting conditions when reading, typing and performing letter-search tasks. The subjects described the perception of the visual lighting conditions by means of a set of line rating scales and the magnitude of glare on a 4-point scale with pre-defined glare criteria (imperceptible, noticeable, disturbing and intolerable). Part 3 was subdivided into two parts, where the first part concentrated on general lighting conditions within the room before the subjects could change the system according to their wishes, while the second part concentrated on why they had changed the initial set-up of the solar shading system. Part 4 focused on indoor climate conditions in the room.

RESULTS
Demographic characteristics of subjects and test conditions
The subjects were mainly recruited at SBI and ISE. A total (n=105) of 62 men and 43 women participated (SBI 27 men and 19 women; ISE 35 men and 24 women) ranging in age from 20 to 63 (SBI: $\underline{M}$ = 46.50, $\underline{SD}$ = 9.79, n=46; ISE: $\underline{M}$ = 25.85, $\underline{SD}$ = 3.48, n=59). Within the group 49 subjects used glasses and 8 subjects used contact lenses. Almost all the subjects (n=100) where right-handed. We also asked the subjects about which job category that best describe their job. About 50% reported they where students, while more than 30% said technician/engineers described their job best. The remaining 20% was more or less equally distributed among administrators, secretaries and managers.

Interior illuminance levels
The blind systems provided a mean desk top illuminance around 1500 lux with a small window and almost 8000 lux with a large window (see table 1). Subjective assessments of needs for supplementing interior light levels (desk lamp or general light) showed that with blind system about 80% stated no additional needs for artificial lighting. However, interior light levels of this magnitude should in general not cause needs for additional light. The transparent foil reduces the mean desk top illuminance by more than 90% compared to the blind systems (mean desk top illuminance > 350 lux), resulting in higher need for additional artificial light. Note that subjects could only state a wish for turning on the artificial light, but they could not actually turn the lights on. Illuminance ratios between the VDT screen and the desk top show that the ratio for the blind systems is within normal recommendations (<1:4), while the ratio with the foil system is a bit too high (>1:15). Recommendations for VDT work usually state that a ratio between task areas that are frequently viewed should be smaller than 1:10.

Subject's rated the light levels inside the room after each task (reading text on paper, typing text and letter search task on PC) with variables such as light on desk, light on keyboard, light on screen when typing or reading, overall light in the room and at the back on a scale of 1 (too low) to 100 (too high). Between-subject tests show the subjects rated the light level differently, except on screen when typing (all Fs(2,101)>3.73, all ps < .027). The two blind systems were rated to be almost in the middle of the scale (around 40 to 50), while the foil

system is generally rated lower. Within-subject test indicate significant window size main effect (all $F_s(2,202)>4.52$, all $ps < .012$) and no interaction, meaning light levels where rated gradually higher with increasing window size. There were only modest differences in the way subject's rated light levels for the different tasks (reading, typing). Rating of general light level within the room and rating of light level at the back of the room show more distinct difference between the three window sizes and the light level at the back of the room is rated lower than the general light level, but the relative difference is similar.

Table 1. Overall descriptive statistics for the desk top illuminance on the desk 1.5m from the window. The white Venetian blind is separated into parallel (P) and diagonal (D) view direction, while specular Venetian blind and transparent foil have only diagonal view direction. Mean desk top illuminance (lux) performing reading and VDT tasks - three window sizes (small, medium, large) and two viewing directions.

Work plane (Lux)	Weather	Mean	Standard Deviation	Median	95% Confidence Interval Lower	Upper
Small (P) – White VB	Clear	2770	1050	2920	2447	3093
Medium (P) – White VB	Clear	3977	1317	4028	3572	4382
Large (P) – White VB	Clear	5878	1884	6150	5298	6458
Small (D) – White VB	Clear	1768	984	1544	1465	2071
Medium (D) – White VB	Clear	2656	1521	2705	2188	3124
Large (D) – White VB	Clear	3879	1801	3217	3325	4433
Small (D) – Specular VB	Clear	3148	1104	3101	2670	3625
Medium (D) – Specular VB	Clear	4709	1361	4867	4120	5298
Large (D) – Specular VB	Clear	7715	2035	7773	6835	8595
Small (D) – Specular VB	Overcast	1410	2039	521	396	2424
Medium (D) – Specular VB	Overcast	1643	1771	1078	763	2524
Large (D) – Specular VB	Overcast	2841	3743	1237	980	4702
Small (D) – Foil	Clear	222	128	199	159	286
Medium (D) – Foil	Clear	286	134	245	220	353
Large (D) – Foil	Clear	348	152	341	272	424

Subjects express satisfaction with current light level by a set of line rating scales with end-points very dissatisfied (1) and very satisfied (100). The questions were similar to the previous questions about light level. Analysis related to the different tasks with different shading systems show significant shading device effect (between-subject tests) for all variables described above (all $F_s(2,101)>3.19$, all $ps < .045$). With diagonal view, the subject's satisfaction with the light level performing different tasks show the foil system is generally rated to produce more satisfying light levels for the different tasks than the two blind systems, and the white Venetian blind is rated to cause the least satisfying light levels. The two blind systems are generally rated to cause more dissatisfying lighting conditions, especially when looking horizontal working on the PC. Furthermore, some results show satisfactions with light level decrease with window size for the two blind systems, while the transparent foil system rise satisfaction level with increasing window size. These findings somewhat support measured light levels, but it also contradict the findings of how subject rated current light levels, since the two blind systems were rated to provide more sufficient light levels, while the foil system was generally rated to provide more inadequate light levels. Also, subjects evaluating the transparent foil system replied higher need for additional artificial compared with the two blind systems.

After each task we asked the subjects to decide, on a line scale, whether the lighting condition is comfortable or uncomfortable, if they have to conduct their daily work at this work place. The between-subject tests indicate significant shading system effect for reading and typing task (all $F_s(2,82)>3.43$, all $ps < .037$). All shading systems and diagonal view show that

generally the white Venetian blinds provide higher comfort than the other two systems, but working on the VDT cause the specular blind (medium and large windows) and transparent foil system (small window) to be reported to make more uncomfortable work place. This may be due the magnitude of glare from the specular blinds (see below) and the foil systems produce too low illuminances levels in the working area.

Glare from windows

Subjects rated the magnitude of glare from windows by line rating scales (1 - not at all and 100 - very much) and four-point scale with pre-defined glare criteria (imperceptible, noticeable, disturbing, and intolerable). The reported magnitude of glare was different and specular blinds were reported to caused higher magnitude of glare than the other two systems (between-subject, all $F_s(2,101)>3.29$, all $ps < .041$). Subjects also report a higher degree of glare with increasing window size (within-subject, all $F_s(2,202)>3.04$, all $ps < .05$). All systems have a clear tendency that subjects are more affected by glare looking horizontal working on VDT than looking downward reading paper on desk. Furthermore, specular blinds and large windows cause more glare problems in the lower part of the field of view, since reflections of the sun and sky on the lower slats are visible within the field of view. There is also a tendency of higher reported glare in the afternoon, when subjects are more affected by the reflected image of the sun on the slats.

Daylight glare probability

Within this project, one of the goals was to provide new insights into the impact of luminance distributions in the field of view on glare and user acceptance of daylighting systems, by use of CCD technology. We developed an innovative technique where we can transform the luminance mapping from the CCD camera, into a software format like the RADIANCE pic file format. This enables us to use the software engine to analyse many problems such as glare evaluation according to a number of daylight glare prediction models. An automatic glare evaluation program of the luminance pictures was developed (evalglare), and the program enables calculating the window luminance or existing internationally recognised glare indexes (e.g. DGI, CGI, UGR) based on the found glare sources within the scene (for more detailed information, see Wienold and Christoffersen, 2006). A new glare prediction model was developed - daylight glare probability (DGP), since current glare indices cannot reliably predict the level of discomfort glare from daylighting in a working environment with normal work activities and complex non-uniform glare sources, such as Venetian blind system. Using the vertical illuminance at the position of the subject's eyes as a predictor for the daylight glare probability showed high correlation with the users' response ($R^2 = 0.77$), but the function in this form does not take into account individual glare sources. Further investigations showed that the correlation between user reaction and DGP could be improved by taking into account the individual glare sources of each situation. Our final approach was using the vertical eye illuminance as well as using the central sum of the glare source term of CIE glare index and develop a new daylight glare probability, DGP. It is defined by following equation:

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

with E_v as the vertical illuminance at eye level [lux], L_s is the luminance of the source [cd/m²], ω_s is the solid angle of the source [sr] and P as the Guth position index [-]. Compared to existing glare models, the DGP shows a very strong correlation with the user's response regarding glare perception ($R^2 = 0.94$). Adding parameters to an equation, which are fitted to the data usually lead to higher correlations – but this does not automatically mean, that this optimised equation describes the behaviour better. The authors do not believe there are any well defined statistical tests to unambiguously determine statistical significance for this non-

linear and group changing problem. However, the standard F-test for multi-linear regression indicate (F = 11.5, p = 0.0045) that that the added parameters provide significant improvement.
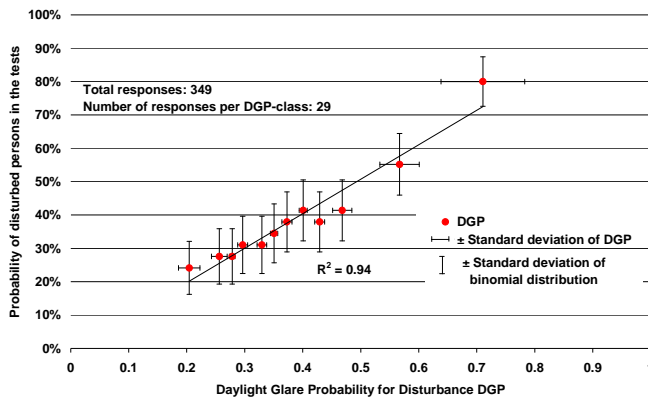

Figure 4. Correlation between the new DGP formula and the probability of disturbed persons in the tests. A DGP value higher than 0.2 approximately corresponds to a vertical eye illuminance higher than 800 lux. Subjective glare rating included in the graph consisted mostly of subjects' evaluating the white Venetian blinds (not causing severe glare sensation). As the white Venetian blinds did not cause a severe glare sensation, the majority of established classes were in the lower part of the function.

User adjustments of the shading systems

After the subject completed the rating of the lighting conditions, they could adjust the system to their preferred position for each combination of window sizes and viewing direction. For the Venetian blind system the subject were allowed to change slat angle position, but not raise the blinds. The transparent foil could be turned, which mean that subjects can open the foil system and allow sunlight to enter the room. More than 70% of the subjects stated they were either very uncomfortable or slightly uncomfortable with the initial settings and wanted to change the settings of the blinds and foil system to maintain a comfortable work place. With a blind system, almost 50% or more of the subject's state they want to change the slat angle of the initial setting, and specular blinds with large windows cause more than 80% of the subjects to wish to change the initial slat angle. Increasing window size tends to cause the subjects to close the blinds more than the initial setting. For the transparent foil system the need for opening the vertical foil decline with window size. When asked about control, subject's can accept the blind systems to be automatically controlled, as long as there is an option to override the system, when needed.

Performance

Several researchers (Osterhaus, 1996, Sivak & Flannagan, 1991) have pointed out need for attention to work tasks, as a relevant variable in the analysis of discomfort glare. We included three relevant visual tasks; a paper based reading task, a typing task (PC, from the National Research Council of Canada) and a letter search task (PC, Roufs & Boschman, 1997). Data on user's performance (speed and errors) were recorded. First indication of the performance analysis showed significant effects of Direction ($F(1,56)= 4.76$, $p = .038$)) and the interaction Direction x Window size ($F(2,56)= 3.27$, $p = .045$), and a close to significant effect of Window size ($F(2,56)= 2.90$, $p = .063$). However, controlling for reflections in the screen by entering ratings of perceived reflections separately, for the 2x3 conditions, as covariates in a repeated measures ANCOVA, abolished the significant and close to significant main effects and interactions and reduced the corresponding p-levels to .234, 147, and .734 (Direction, Window size, and Direction x Window size respectively). This reduction of significance level is a strong indicator of reflections in the screen as a mediating variable in between the independent variables Direction and Window size and the dependent variable Performance.

DISCUSSION AND CONLUSION

The use of CCD camera-based luminance mapping technology to measure luminances within the field of view, provides a great potential for improved understandings between measurements and user response. In our view, it is essential to use the CCD technology to assess, e.g. limits of acceptance for luminances and their ratios within the field of view for different sky and solar shading control conditions. The CCD technology also simplifies what was earlier a tedious measurement technique, since luminance measurements at specific 'spots' using a point-by-point measuring technique require an enormous amount of time, can only be achieved in a grid or was almost impossible to carry out. Although the CCD camera enables us to study the visual environment in detail as well as some of its parameters affecting the user, it also needs a lot of effort to extract the 'correct' values for the evaluations and to ensure high data quality.

The new evaluation tool evalglare can manage these evaluations and detect, effectively, all possible glare sources within very different lighting scenes. The tool also enables assessments of possible glare problems with simulated RADIANCE pictures, and could therefore be used at an early stage in the design of a building. Using the tool for this study, we calculated several currently available glare prediction models and found that these indices showed a weak correlation with how subjects reported discomfort glare in an experimental set-up with three different facade layouts, two different view directions and three different solar shading systems. Due to the above uncertainties with the currently available glare prediction models, we propose a new glare equation, called ''daylight glare probability (DGP)'', where we use a combination of an existing discomfort glare algorithm and an empirical approach. The evaluation of the results from the experiments shows good correlation between the DGP and the user's response. The authors rate the new DPG as a reliable tool in many office situations, but the new equation should be confirmed by additional assessments. The probability model should also be tested in conjunction with other solar shading systems. The data set provides ample opportunity for further analysis of, e.g. contrast ratios or user reactions to windows and shading devices.

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