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 daylit. 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.

Key words: discomfort glare, daylight, illuminance, visual comfort

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

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 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.

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

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.

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

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.

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

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 a upper criteria. A few recent studies have also reported a reasonable relationship between the reported glare perception by occupants and horizontal illuminance [31, 38]. However, these studies only consider perimeter zones and, according to a study by Konis [26], the occupants report visual discomfort in the core zones of a side-lit office building even when the horizontal illuminance at the workstation is low – significantly lower than 2000 lux. Therefore, Konis suggests that the relation between horizontal illuminance and subjective assessment of discomfort may be context specific related to the distance of the observer to the façade as well as interior surface reflections.

As the study by Wienold and Christoffersen [18] and the development of DGP demonstrate, vertical illuminance at eye level might be a reasonable, simple indicator for discomfort glare. A number of other studies have also reported correlation between vertical illuminance and perceived glare by occupants [26, 31, 39-41]. Konis [26] reports that E_v performs in the same range or better than glare indices like CGI, DGI and UGR in core zones of a side-lit open-plan office in San Francisco, US. Contrary, Hirning et al. [32] report that these glare indices in addition to DGP and VCP performed better than E_v in open-plan offices in Brisbane, Australia. Yet, the coefficient of determination was not significantly different statistically among the glare indices and E_v. Van Den Wymelenberg and Inanici [31] recently carried out a repeated measure designed occupant survey with 48 participants in a private office laboratory environment in order to review existing visual comfort metrics. The results showed that vertical illuminance and simple luminance metrics with respect to mean and standard deviation of scene luminance outperformed more complex metrics such as DGI and DGP as well as horizontal illuminance. Therefore, they conclude that establishing reliable design criteria for E_v which can be used in the design stage should lead to improved occupant satisfaction with the visual environment. Based on the results from the study, a threshold for E_v measured close to the occupants' view point should be in the range of 1000-1500 lux. Konstantzos et al. [42] also suggest that successful control of vertical illuminance is a key factor towards achieving visual comfort.

Based on the findings in the literature, this study will investigate if the simple and easily measurable quantities of vertical eye illuminance and horizontal illuminance at a desk are correlated in a statistically significant way with the perceived glare reported by 44 test subjects in a repeated measure design and if the reported glare corresponds with the predictions from the simple DGPs model. The results from the study will be useful with respect to supporting if these simple measures are reliable for use as indicators of glare in the building design and as variables incorporated into building control strategies. The study is restricted to evaluate the luminous conditions close to the façade in an experimental cell-office type room located in Aalborg, Denmark.

2 Method

2.1 Facility

The survey was carried out in the Cube, a test facility at Aalborg University (latitude 57.02°N, longitude 10.0°E). The Cube has a south-oriented experimental room, which is 2.76 m wide, 3.6 m deep and 2.70 m high. Figure 1 presents a photo of the south façade of the Cube and gives an illustration of the layout of the experimental room. The façade wall is equipped with a double layer glazing (2.76 m × 1.60 m) with a U-value of 1.2 W/m^2K, g-value of 0.36, direct solar transmission of 0.31 and a visible light transmission at normal incidence of 0.65. The window is equipped with both an internal and external white 65 mm convex venetian blind. The blind systems use a motor connected to a National Instrument Chassi controller to control the slats according to desired angles.

All internal surfaces in the experimental room are kept in light colours with reflectivity of 0.73, 0.32 and 0.94 for walls, floor and ceiling respectively. For more detailed description of the test facility, see [43, 44].

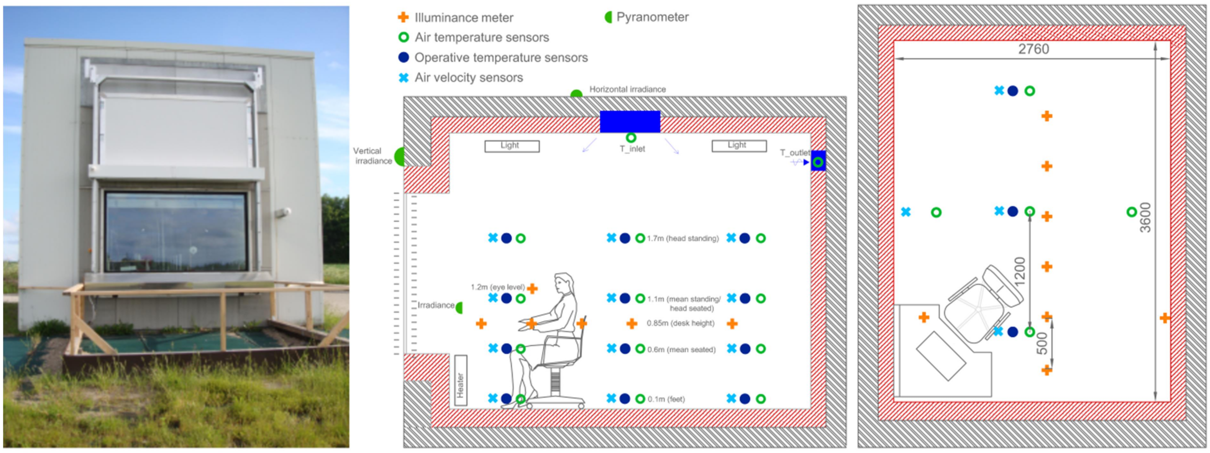

Figure 1: Photo of the south façade of the Cube and section and plan view of the experimental room and placement of sensors in the experimental room.

2.2 Measurements

2.2.1 Indoor environment

Indoor horizontal illuminance at the work plane was monitored with six illuminance sensors in the centre line of the room, 0.85 m above the floor. Additionally, one illuminance sensor was placed horizontally at the work desk; see the location of the sensors in Figure 1. An illuminance sensor was placed vertically on a wood stand at a height of 1.2 m close to the test subject in order to measure the vertical illuminance at the eye level, and one illuminance sensor was placed vertically on the east wall behind the work station at a height of 1.2 m, see Figure 1. All sensors were cosine corrected of type Hagner SD1/SD2 detectors connected to a Hagner MCA-1600 Multi-Channel Amplifier (basic accuracy +/- 3 %). The illuminances were recorded every 10 ms.

Measurements of temperatures and air velocities were made to make sure that the thermal environment was kept within comfortable ranges, see Figure 1.

2.3 Procedure

2.3.1 Participants

Forty-six subjects took part in the study during May–June 2014. Responses from 44 of these test subjects were usable for assessment of glare in relation to vertical eye illuminance or horizontal illuminance at the desk; the subjects counted 26 males and 18 females. The participants were mainly university students, researchers or office workers in the age range of 20-62 years old (mean 28.5 years, median 26 years, SD 8.1). The subjects were instructed to wear lenses or glasses if these were normally worn in office work situations.

2.3.2 Introduction to the test and test facility

In order to reduce biases caused by the test persons having or not having experience with the test room from previous visits, the test subjects conducted a pre-test up to 10 days before the main test. In the pre-test, the subjects were thoroughly introduced to the test and the experimental room, they got familiar with the concepts of glare and the definitions of the scales they would use in the test to rate the glare sensation. Additionally, they answered some personal questions regarding gender, age and occupation. In total, the pre-test lasted for approximately 20-30 minutes.

As illustrated in Figure 1, the test subjects were facing diagonally towards the window, which is assessed as a worst-case situation with respect to daylight glare probability in an office work situation. A line of sight directly towards the window could presumably cause higher probability of glare; however, this viewing direction is assessed as less common in an office environment. The subjects had the opportunity to adjust the height of the office chair, but were instructed not to adjust the computer screen in order to secure the same pre-set viewing direction for all test subjects.

2.3.3 Control of indoor environment

The main test was a repeated measure design where all the subjects were exposed to two blind control strategies: (1) a simple control where the blinds were activated and slats completely closed at vertical irradiance of 100 W/m^2 at the external façade, simulating the simplified way blinds commonly are treated within building design and energy calculations (2) a more detailed control where the blinds were activated if vertical illuminance at the eye level exceeded 2000 lux or if vertical external irradiance exceeded 150 W/m^2 and there was a cooling demand. In the detailed control strategy, the slats were adjusted to the cut-off angle or a minimum tilt angle of 15˚ to avoid penetration of direct sun as well as avoiding negative cut-off angles in situations with large solar altitude angles. For more details regarding the blind control, see [44] which assess the occupants' preference towards the solar shading strategies. When a test subject entered the experimental room, one of the control strategies was activated. Yet, the solar shading was only activated if needed, according to the criteria given in the two solar shading strategies.

The temperature set points for heating and cooling were 21˚C and 24.5 ˚C respectively in all the tests. If daylight alone could supply 300 lux minimum at the horizontal work plane 1.5 m into the room, no artificial lighting was added. If not, general artificial lighting from the ceiling was added to maintain an illuminance of 500 lux at the work plane.

2.3.4 Questionnaire and test procedure

Test subjects were asked for their subjective feedback by completing a web-based questionnaire constructed in SurveyXact [45]. The questionnaire was made with categorical scales with verbal labelling. Providing a word label over each point ensured that everyone interpreted the points similarly and thus reducing measurement error.

In order to evaluate the visual comfort and glare, the basic questions and surveying procedure given by Christoffersen and Wienold [46] were used. This procedure entails that the occupants perform different visual tasks like reading from a paper, reading on a computer screen and writing on a computer while their performance is recorded, see Figure 2. In this way, the occupants will perceive the visual environment in a similar manner as in a normal working situation [47]. This procedure is in line with recommendations given in the international project IEA SHC task 21 [48].

The occupants were asked to rate the perceived glare according to the four-point scale: *imperceptible, noticeable, disturbing and intolerable*. In the pre-test, the participants were presented with the definition of the scale according to [46], where the borderline between *imperceptible* and *noticeable* should correspond to the changeover point where glare discomfort would first be noticed. The criterion *noticeable* would then be equivalent to a very slight experience of discomfort that could be tolerated for approximately one day if one for instance were to be placed at someone else's workstation. The borderline between *noticeable* and *disturbing* glare is defined as a discomfort experience that would be just disturbing and which could be tolerated for approximately 15 to 30 minutes, but that would require a change in lighting conditions for any longer period. The borderline between *disturbing* and *intolerable* glare is defined as the turning point where the lighting conditions could no longer be tolerated.

The occupants rated the glare twice under each solar shading control strategy, once after reading on paper and once after doing computer work respectively. Three full tests were carried out per day; morning (08.00-10.30), noon (11.00-13.30) and after noon (14.00-16.30). The order of exposure to the different solar shading strategies was randomised and balanced between the test subjects and time of day.

2.4 Data analysis

The occupants' responses of the visual and thermal environment were combined with physical measurements. Measurements of horizontal and vertical illuminance used in the data analysis were averaged over the 15-20 last minutes before the occupants answered questions regarding the light environment and perception of glare.

Statistical analysis were carried out to identify significant correlations between predictor variables and the reported sensation of discomfort glare and to evaluate model fits. Occupants' response of glare from the two solar shading strategies were mixed together and a reasonable illuminance range which frequently occurs in an office environment is thereby represented in the data. All statistical analysis were conducted by use of the statistical software package R version 3.1.2 [49].

2.4.1 Vertical and horizontal illuminance

In order to evaluate the correlation between vertical eye illuminance or horizontal illuminance at the desk and the perceived glare, logistic regression was used. For the logistic regression technique applied in this analysis, the response variable of glare is assumed to be a binominal response, i.e. disturbed by glare or not disturbed by glare. The four-point glare scale was, therefore, simplified to a binary form; responses of *imperceptible* and *noticeable* were regarded as “not disturbed” while *disturbed* and *intolerable* were regarded as “disturbed”. Logistic models were generated using the generalized linear function glm, family=binomial and the function lrm in R.

Unlike the ordinary linear regression where predictors often are ranked by R^2, there is less consensus regarding how to evaluate predictors in logistic regression [50] and various measures are often used, e.g. Aikaike information criterion (AIC), Bayesian information criterion (BIC), p-value of Wald chi-square test, pseudo R^2, Brier score and c-statistics [50-52]. In this study, AIC and BIC are used to compare the non-nested logistic regression models, the p-value of the Wald chi-square test is used to indicate the strength of the evidence that there is some association between the predictor variables and the reported perceived glare. The overall performance of the logistic regression models are evaluated with Nagelkerke’s pseudo R^2 [53] and Brier score [54], while the c-statistic is used to indicate the discriminative ability of the logistic regression model. The reader should be aware that the pseudo R^2 is not equivalent to the traditional R^2 referred to in OLS regression and rather low pseudo R^2 is common for logistic regression. The Nagelkerke’s pseudo R^2 can be interpreted as improvement from null-model to fitted model.

2.4.2 DGPs

DGPs is based on the probability of whether a person is disturbed by glare. With this approach the glare scale is also reduced to a binominal response – “disturbed” and “not disturbed” – similar to the division for the logistic regression. The probability is established by grouping equal sample sizes of the total number of responses and evaluating the percentage of subjects disturbed in each of these groups. The groups are established by sorting the data according to vertical illuminance at eye level. In the study by Wienold and Christoffersen [18], they studied 349 responses in total which were arranged into 12 groups with a sample size of 29 responses in each group.

When averaging over individual data, this of course reduces the information in the dataset and requires a substantially large database. Using all available data from all users, tasks and tests in the present study gives in total 176 responses of glare sensation. However, the validity of the equation for DGP values ranges between 0.2 and 0.8 and a minimum vertical eye illuminance of 380 lux [38]. When extracting glare responses at vertical eye illuminance below 380 lux, the total available responses of glare is 144 for the current study.

Due to the restricted amount of data, the correlation seen between the vertical eye illuminance and the percentage of persons disturbed by glare might be sensitive to the grouping of the data. Hirning et al. [32] have criticised Wienold and Christoffersen [18] for grouping the data in a way that overdetermines the correlation. According to Hirning et al. [32], an ideal method of grouping data is to have as many response levels as there are observations in each level. In this way, the group size should be $\sqrt{m}$, where m is the total number of observations being analysed. However, the grouping size according to Hirning et al. is only suitable for large datasets, since in a grouping size of e.g. 10 observations, one response of discomfort more or less will have a significant influence on the response variable. This influence will decrease with an increasing group size, and information gained from large group sizes might, therefore, be considered as more reliable. This study uses two approaches of grouping; one analogue approach to the one used by Wienold and Christoffersen where the group sizes are as large as practical in order to avoid large sensitivity depending on the grouping while, at the same time, having a sufficient amount of groups, and another approach according to the recommendations of Hirning et al. [32]. Due to smaller amount of data in the present study compared to the study by Wienold and Christoffersen [18], the grouping size has been reduced to 24 for the present case which leaves us with six groups.

3 Results and discussion

In the following section, the subjects' glare rating within the occupant survey is compared with measures of vertical eye illuminance, horizontal illuminance at the desk and predictions with DGPs.

3.1 Limitations of the experimental set-up

Wienold and Christoffersen [18, 46] propose using two identical test rooms: one room for control measurements and one for occupant surveys. The facilities in the present survey only have one test room, meaning that all measurements are conducted in the same room as the occupants stay in, see Figure 2. During some of the tests, this was a challenge with respect to measurements of vertical eye illuminance and horizontal illuminance at the desk since there were times when the occupant him or herself shaded the vertical illuminance sensor or when the occupant unconsciously shaded the illuminance meter on the desk with papers used in the test. Both measured illuminance levels and photos taken in the test room during the test were evaluated to uncover the occurrence of these problems. For times when shading situations occurred, the vertical illuminance measured on the east wall behind the occupant and/or the horizontal illuminance measured at the second lux meter position from the window were used in combinations with the equations given in Figure 3. The reader should be aware that the correlations reported in Figure 3 are reasonable for the experiment period, but cannot be considered as general correlations especially not for winter time when the sun is low on the sky and where the sunlight might hit one sensor without hitting the other.

Figure 2: Illustration of the set-up around the occupant. (a) and (c) picture from the front and back for computer work. (b) and (d) picture from the front and back for paper work.

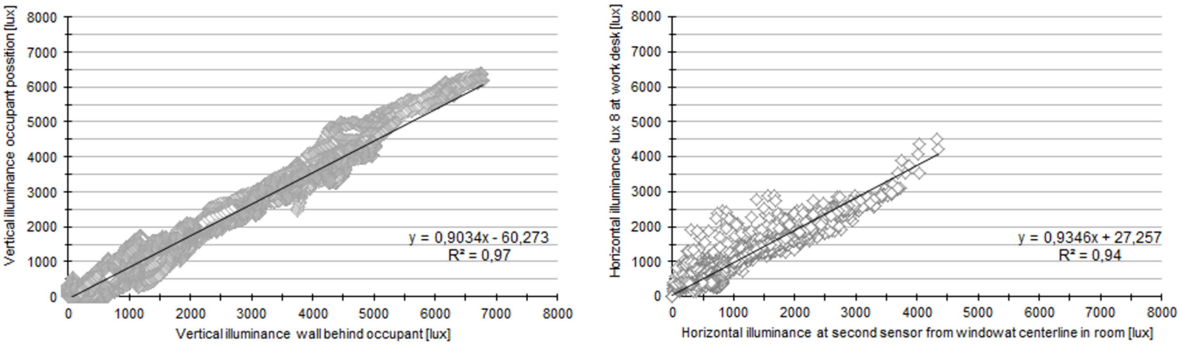

Figure 3: Left: Correlation between vertical eye illuminance measured at occupant position and vertical illuminance measured at height 1.2 m at the east wall behind the occupant. Right: Correlation between horizontal illuminance at the desk and horizontal illuminance measured at second illuminance meter from the window in the centreline of the room. All the measurements used to make the correlation are taken without the occupant in the room.

Some studies have reported that sub factors like e.g. sex, age and time of day may influence the individual glare sensitivity [55-57]. Wienold [58] has reported a weak but statistically significant improvement of the correlation between user perception of glare and DGP when age is accounted for. Hirning et al. [32] did not, however, find age, eye correction or view interest to play any statistically significant role in predicting discomfort glare. Bargary et al. [59] did not find any main statistically effect of age and sex on discomfort glare thresholds either, nor did Osterhaus [6] find age to be related to glare experienced by participants in an real day lit offices. Due to a relatively homogeneous age group in the present study and relatively few participants reporting eye correction, analysing the diversity in individual preferences due to such sub-factors where unfeasible, and all responses are treated in the same manner.

3.2 Vertical eye illuminance

Figure 4 shows the frequency of participants reporting glare on the four-point glare scale in relation to vertical eye illuminance. Similar to what has been reported in earlier literature [14, 26, 31, 40], large variations in rating of discomfort glare were present in this study when comparing individual subjects, see Figure 4. Even though there are large individual variations, Figure 4 still shows some tendencies. If we regard the responses in the two upper parts of the glare scale as disturbing glare, which is reasonable according to the definitions of the scale, two relatively distinct groups can be seen. Some people reported disturbing glare in the low light environment, while a severe part of those reporting disturbing glare were exposed to a relatively high vertical eye illuminance above 1500 lux.

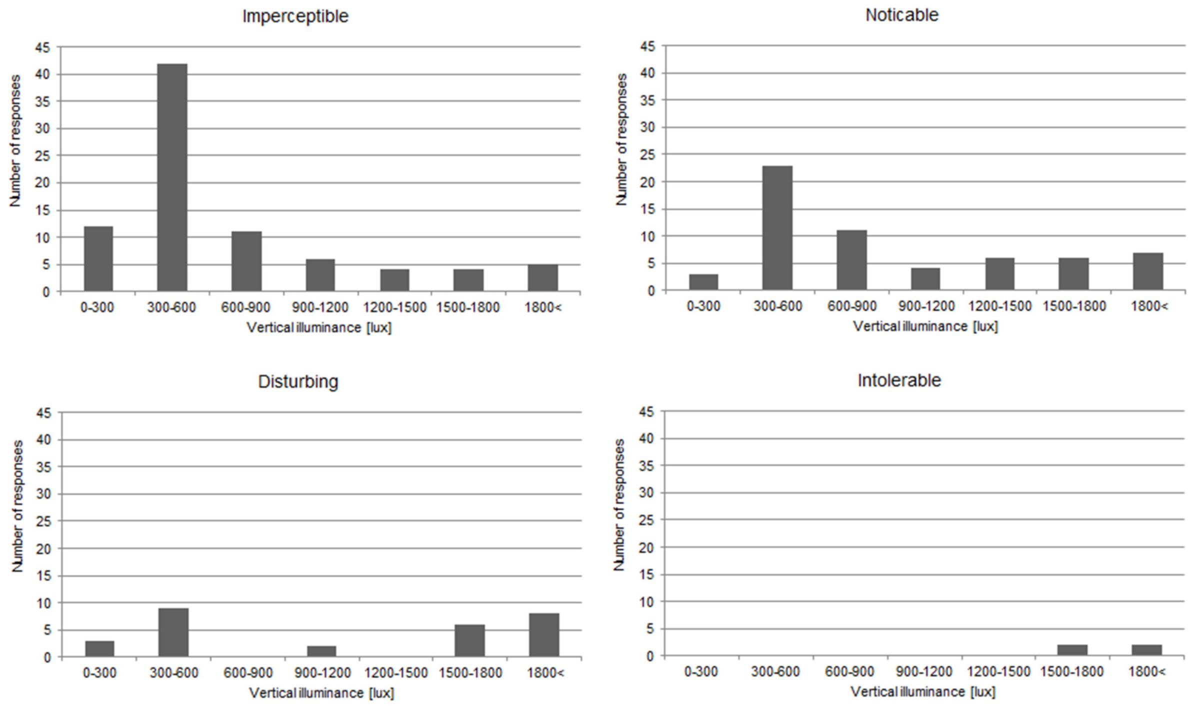

Figure 4: Reported sensation of glare on a four-point scale with respect to vertical eye illuminance (n=176).

It might seems like a contradiction that subjects report glare in the low light environment; however, it is important to remember that contrast-based glare might be a considerable concern in low light environments [32, 60]. One of the limitations with vertical eye illuminance as an indicator of glare is that it can never account for contrast-based glare, unless the contrast itself contributes to a significant increase in the vertical illuminance [38, 60]. It should be noted that all responses of disturbing glare in the low illuminance range are reported under the simple solar shading control strategy when the lamellas are fully closed. Additionally, 10 out of 12 of those responses are given during computer work when the line of sight is relatively horizontal towards the computer screen where parts of the window behind the screen also occupy sections of the subjects' central vision. The external solar shading was installed with a distance to the window of approximately 20 cm and, consequently, a vertical stripe of light from the side of the solar shading and a horizontal stripe of light at the bottom of the solar shading occurred in closed position. When the lamellas are closed, the luminance ratio between the vertical/horizontal light stripe and the surrounding surfaces might be significant, especially for sunny weather conditions (see Figure 5), and the light stripes might act as a distraction to the occupants' eyes.

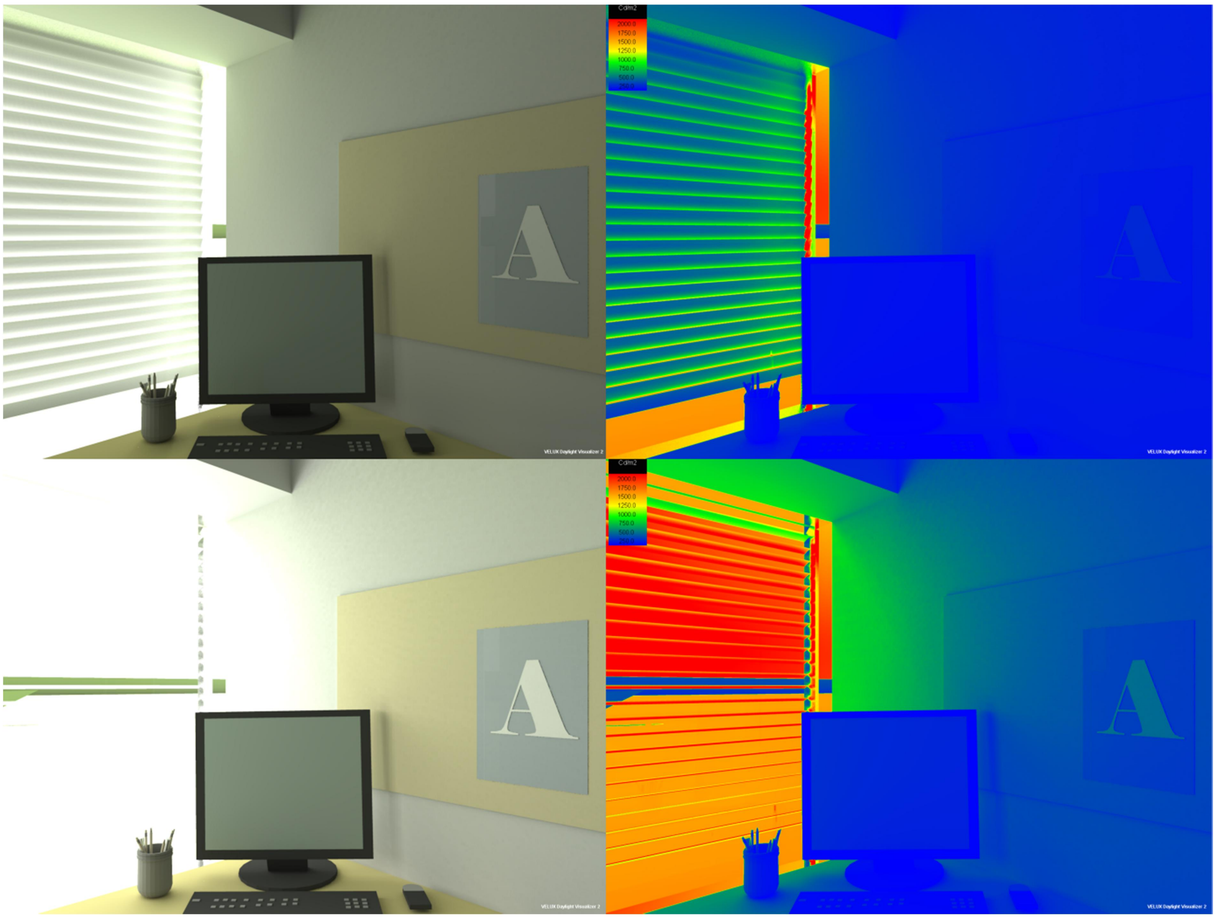

Figure 5: Rendering of the luminance in the test room for the two solar shading control strategies, upper row = simple, lower row = detailed. The luminance values are represented with a false color scale where red indicates values equal to or above 2000 cd/m^2 (for interpretation of the references to colour, the reader is referred to the web version of this article). The rendering is done by use of Velux Daylight Visualizer [61] for sunny sky conditions on May 21th at 10.00 AM.

Van Den Wymelenberg and Inanici [31] used plots with data of occupant responses regarding most and least perferred luminous environment sorted according to the investigated metric in order to recommend preliminary performance criteria based on the borderline between comfort and discomfort (BCD) approch proposed by Luckiesh and Guth [62]. They found that E_v measured in the participants' viewing direction from the top of the computer monitor correctly differentiated beyween *most preferred* and *just uncomfortable* luminouse scenes for most cases. Scenes with E_v>1600 lux were especially regarded as uncomfortable, whereas it was already likely to be uncomfortable at E_v levels above 1250 lux. Figure 6 shows the ordered results of vertical eye illuminance colour-coded by the reported response of perceived glare for the present study. The dotted line in the graph markes the turnover point at E_v>1700 lux for where the responses in this study indicate that it is more likely to be disturbed by glare than not being disturbed by glare when assessing the glare response as an binominal response. This turnover point is higher than that reported by Van Den Wymelenberg and Inanici [31] of 1250 lux; however, it is important to remember that the questions asked were different. The turnover point reported by Van Den Wymelenberg and Inanici represents the change from “most perferred” to “just uncomfortable” scenes, wheras the turnover point in this study represents the change from imperceptible or noticable glare to disturbing or intolerable glare.

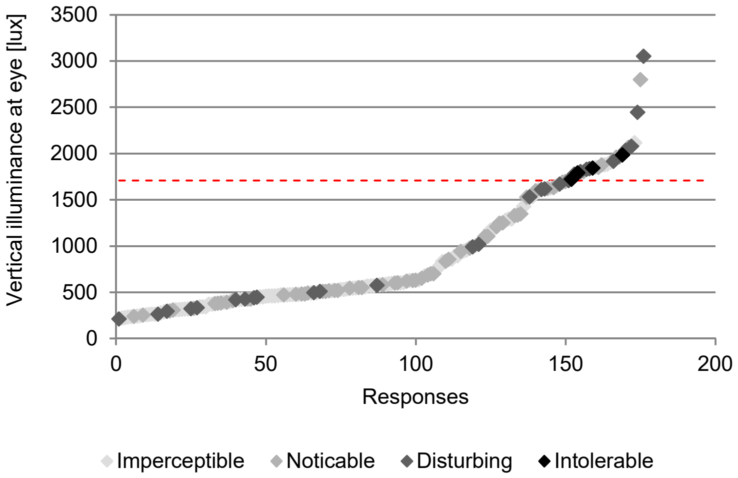

Figure 6: Results ordered according to vertical eye illuminance (E_v) and colour-coded by response to perceived glare. The dotted line represents the turnover point where it is more likely to be disturbed by glare than not to be disturbed by glare at values above this.

Figure 7a shows the logistic regression model of the probability of being disturbed by glare as a function of vertical illuminance at eye level, Figure 7b shows the distribution of the fitted values of non-disturbed (y=0) and fitted values of disturbed (y=1) by glare and Table 1 gives a summary of statistical measures for the logistic regression model. The resulting p-value from the Wald test for E_v from the logistic regression is equal to 1.17e-4, suggesting that E_v is connected to the probability of being disturbed by glare in a statistically significant way. The residual deviance of the model when taking E_v into consideration is 158.28 on 174 degrees of freedom (p=0.78), suggesting that it is plausible that the data emanates from a logistic regression model that includes E_v. Table 1 also shows that computing the chi square difference between the model with only an intercept and the model where E_v is added gives us a p-value of 7.74 e-5, suggesting that only adding E_v significantly improve the prediction of disturbance by glare. Further, Table 1 gives us the c-statistic of the model of 0.66 indicating that the model has an acceptable but rather weak discriminative ability. This is also supported by the parallel histograms given in Figure 7b which have an apparent overlap of the distributions, which according to Tjur [63] indicates that the model does not have much explanatory power. A good model is evidenced by strong separation of these two distributions [63]. The lack of explanatory power of the model might be attributed to limited data as well as to a restricted number of occupants reporting disturbance by glare in the present study.

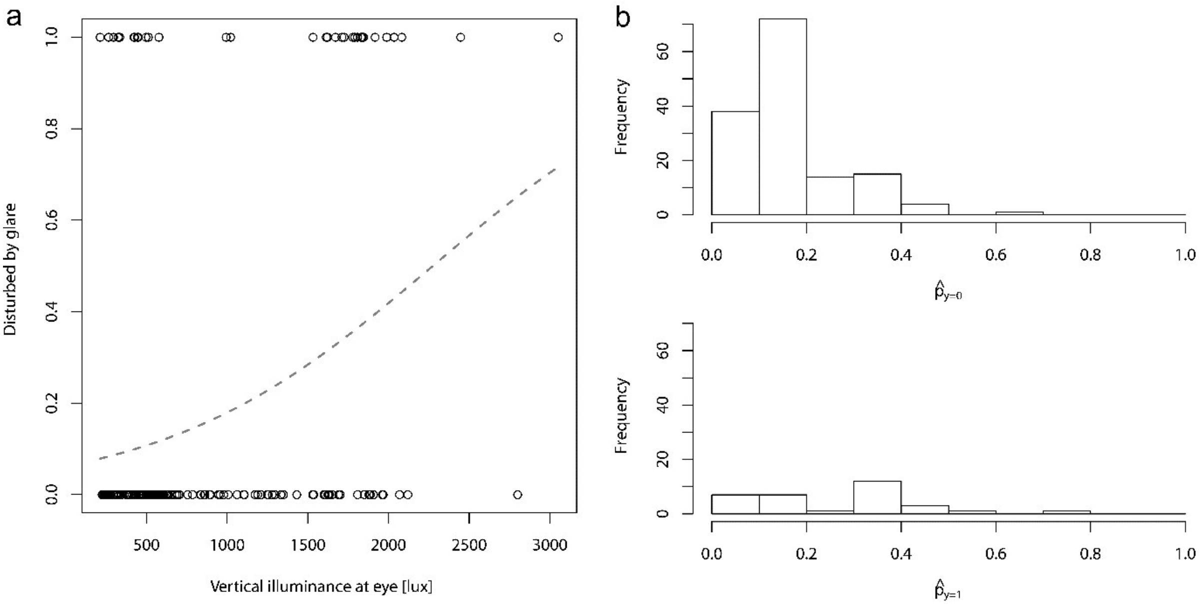

Figure 7: (a) The dotted line visualizes the logistic regression model predicting the probability of disturbance by glare as a function of vertical eye illuminance. The circular markers indicate the reported response of glare 0=not disturbed, 1=disturbed. (b) The two parallel histograms show the distribution of fitted values of failure (y=0) and fitted values of success (y=1) for the logistic regression model.

Table 1: Summary of statistical measures for the logistic models with E_v and E_h as predictor variables.

	α	β	AIC	BIC	Nagelkerke's pseudo R^2	Brier score	c-statistic	p-value predictor variable	p-value likelihood ratio test
E_v	-2.71	0.001	155.28	161.62	0.14	0.13	0.66	1.17 e-4	7.74 e-5
E_h	-3.28	0.001	150.60	156.94	0.18	0.13	0.67	1.24 e-5	6.62 e-6

3.3 Horizontal illuminance at the desk

Figure 8 shows the frequency of participants reporting glare on the four-point glare scale in relation to horizontal illuminance at the desk. Compared to Figure 4, the horizontal illuminance is generally higher than the vertical illuminance under the test conditions.

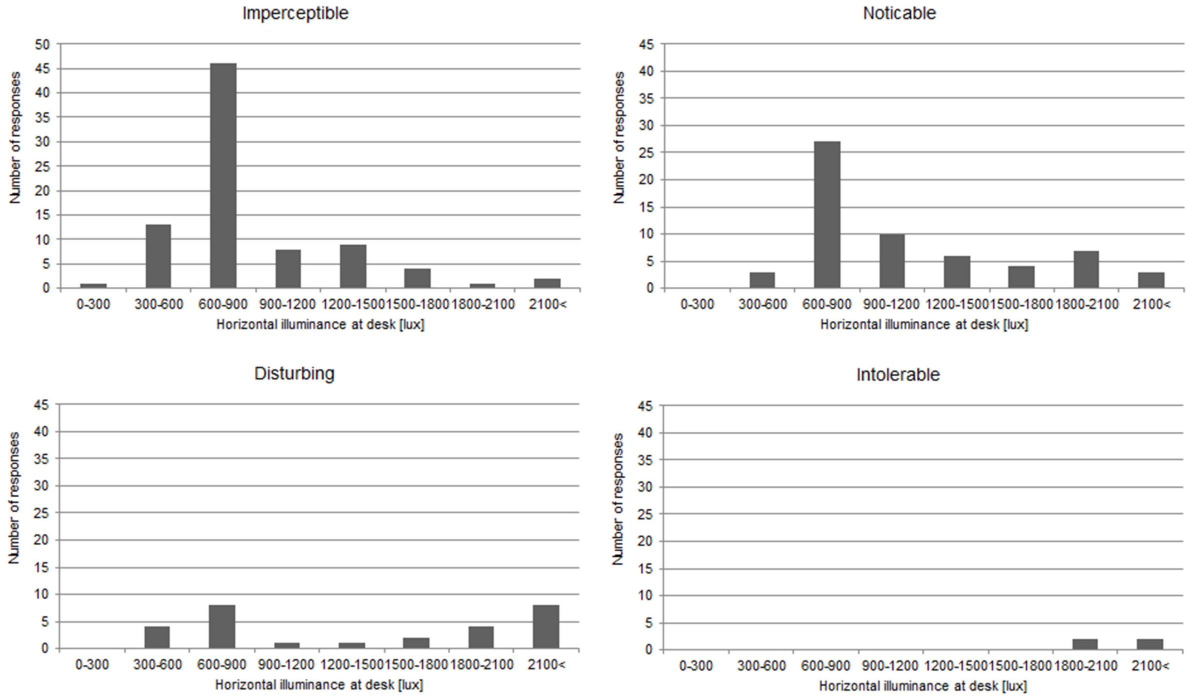

Figure 8: Reported sensation of glare on a four-point scale with respect to horizontal illuminance at the desk (n=176).

Figure 9 shows the ordered results of horizontal illuminance at the desk colour-coded by the reported response of perceived glare. This graphic reveils three preliminary thresholds: if $E_h < 1900$ lux, it is likely that the occupants are not disturbed by glare; if 1900 lux $< E_h <$ 2100 lux, the probability of being desturbed/not disturbed by glare is 50/50; while if $E_h > 2100$, it is likely that the occupants are disturbed by glare. This upper threshold corresponds well with the upper threshold of the bounded-BCD approach reported by Van Den Wymelenberg and Inanici [31] of 2000 lux as well as the original threshold of UDI-e of 2000 lux [36].

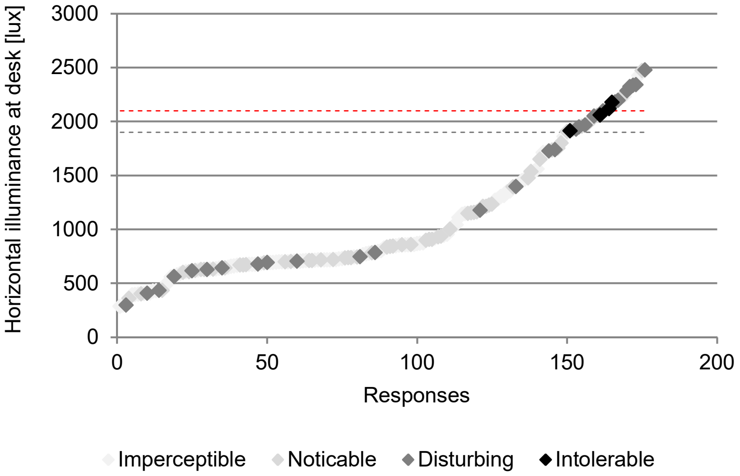

Figure 9: Results ordered according to horizontal illuminance (E_h) and colour-coded by response to perceived glare. The dotted lines show the bounded BCD, where the upper line represents the turnover point where it is more likely to be disturbed by glare than not be disturbed by glare at values above this.

Figure 10a shows the logistic regression model of the probability of being disturbed by glare as a function of horizontal illuminance at the desk, Figure 10b shows the distribution of the fitted values of non-disturbed (y=0) and fitted values of disturbed (y=1) by glare and Table 1 presents a summary of statistical measures for the logistic regression model. Similar to what was seen for vertical illuminance, the resulting p-value for E_h from the logistic regression (p=1.24e-5) suggests that E_h is connected to the probability of being disturbed by glare in a statistically significant way. The residual deviance of the model when taking E_h into consideration is 146.6 on 174 degrees of freedom (p=0.94), suggesting that it is reasonable that the data emanates from a logistic regression model that includes E_h. Table 1 also shows that conducting a likelihood ratio test between the model with only an intercept and the model where E_h is added results in a p-value of 6.62e-6, suggesting that only adding E_h significantly improves the prediction of disturbance by glare. Similar to what was seen for E_v, the c-statistic of the logistic regression model of 0.67 suggests that the model with E_h also has an acceptable but rather weak discriminative ability.

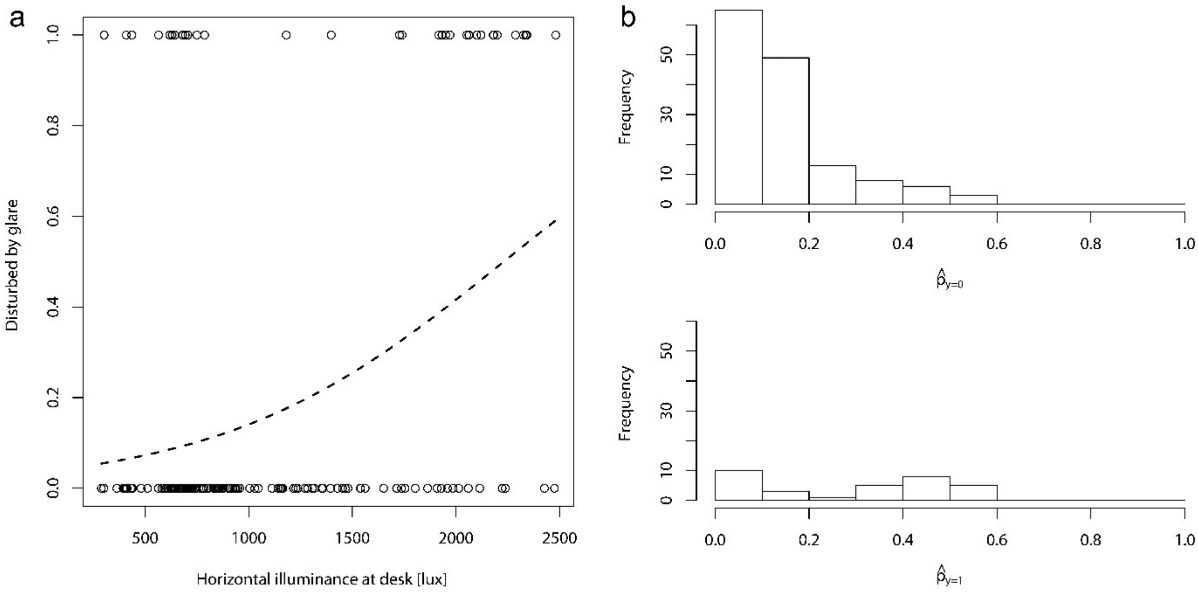

Figure 10: (a) The dotted line visualizes the logistic regression model predicting the probability of disturbance by glare as a function of horizontal illuminance at the desk. (b) The circular markers indicate the reported response of glare 0=not disturbed, 1=disturbed.

Comparing the AIC, BIC and R^2 presented in Table 1 for the two logistic models gives indications that the logistic regression model with E_h performs slightly better than the logistic regression model with E_v in this study. However, the difference of BIC between the models is < 6 which, according to Raftery [64], only gives a positive but not statistically strong evidence that the logistic model for E_h performs better than the logistic model for E_v. The same Brier score of 0.13 for the two models also indicates similar overall performance of the models.

It should be emphasised that use of horizontal illuminance as an indication of glare might be position dependent as suggested by Konis [26] as well as having the same limitation as E_v of not being able to adequately represent contrast-based glare environments. Additionally, as Wienold [38] points out, horizontal illuminance cannot take the spatial light distribution into account. However, this study strengthens the evidence that horizontal illuminance at the desk might be an applicable and promising indicator of glare for perimeter office environments, especially for use in early building design before settling work position and occupant viewing direction. While vertical illuminance, which possess the ability of taking the spatial light distribution into account, might be favourable at a later design stage when the location of the occupant is decided as well as for incorporation as control parameter for building control strategies. As placement of sensors for building control strategies close to the occupants' position is not practically feasible, correlations between the occupant position and the sensor location like those illustrated in Figure 3 can be made, and this has been done in [65]. It is though important that the users have the opportunity to over-rule the control, since it might occur that the sunlight hit the occupant position without hitting the sensor, this is especially true for times with low solar altitude.

3.4 DGPs

Figure 11 shows the comparison of the percentage of persons disturbed by glare for the observed data and the predictions according to DGPs for both of the grouping of the data described in section 2.4.2. The dotted lines indicate the confidence interval for the regression lines of the observed data from the current study.

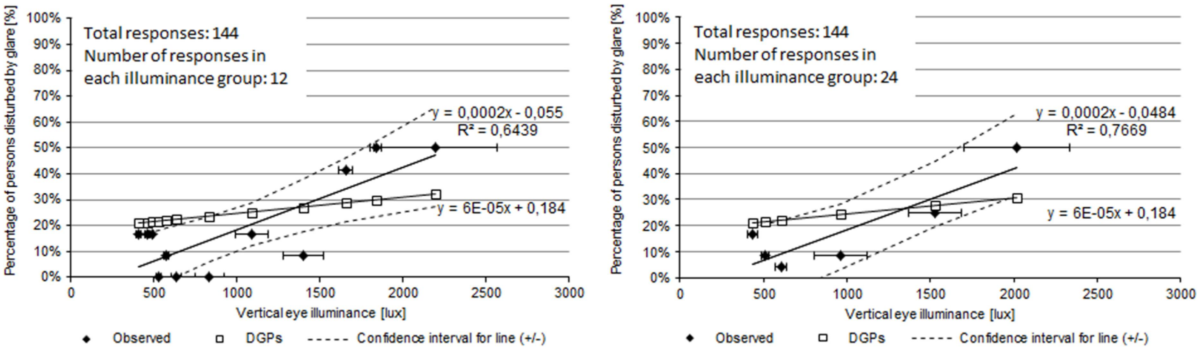

Figure 11: The daylight glare probability as a function of vertical illuminance at the position of the subject's eyes (E_V) both for the observed data in the current survey and for the predictions based on DGPs according to two group divisions. The dotted lines represent the confidence intervals for the regression lines of the observed data.

Similar to what was observed in the study by Wienold and Christoffersen [18], reasonable correlations are seen between the vertical eye illuminance and the perceived glare within the validity range of DGP for both of the group divisions, see Figure 11. The coefficients of determination are 0.77 (group of 24 responses) and 0.65 (group of 12 responses), and this might support the argument by Hirning et al. [32] suggesting that the group division by Wienold and Christoffersen [18] over determine the correlation. Still, the linear regressions gives an F-statistic of 13.16 at four degrees of freedom and a p-value = 0.02 for the division with 24 responses in each group and a F-statistic of

18.08 at ten degrees of freedom and a p-value = 1.7e-3 for the division with 12 responses in each group, which indicate that the linear models are good approximations for the data and that a relation does exist between reported glare sensation and the vertical eye illuminance for both of the group divisions.

However, when comparing the reported glare sensation in this study with the predictions done according to DGPs, the regression lines for the observed data have steeper slopes than the ones for DGPs for both groupings. It seems like the participants in the present study are more tolerant to low illuminance levels than what is predicted with DGPs, whereas they are more sensitive to illuminances higher than approximately 1400-1500 lux than predictions with DGPs indicate. This observation is confirmed by an analysis of variance, which suggests that there are statistically significant differences both between the intercept (p=0.015 (group of 24 responses), p=1.7e-3 (group of 12 responses)) and the slope (p=0.029 (group of 24 responses), p=5.0e-3 (group of 12 responses)) of the lines for the observed data and the line for the prediction according to DGPs. This is in accordance with the observations from Figure 11 that illustrates that the lines of DGPs predictions cross the confidence interval of the regression lines for the observed data for both the division of 12 and 24 responses in each group. It should be noted that the illuminance levels in the present study are generally lower than most of the levels reported in the study by Wienold and Christoffersen [18], which might be an explanatory factor for the differences seen. However, the tendency of being more sensitive to relatively high vertical illuminance levels then the DGPs predict are also supported by the recent studies by Van Den Wymelenberg and Inanici [31] who report the upper bound of BCD to correspond to E_v of 1250 lux, and Konis [26] who predicts the threshold of 50 % of the occupants to be disturbed by glare to be at E_v of 1600 lux.

4 Conclusion

The present study has used reported glare sensations from 44 subjects in an occupant survey conducted in an office like room in an attempt to validate the use of simplified measures like vertical eye illuminance, horizontal illuminance at the desk and DGPs as indicators and models for prediction of discomfort glare. The results are restricted to office environments where the occupant is facing diagonally towards the window. Position and view direction dependency is an issue which should be investigated further in the future.

Similar to earlier reported research, large individual variations were seen in the occupants' assessment of glare. This strongly suggests that the users should have the opportunity to control or overrule the glare control within an office environment in order to be able to maintain an acceptable visual environment. It is important that the designers arrange for such possibilities.

The results from this study 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. This finding is promising as it supports that such simple measures might be applied in annual analysis in the building design in order to obtain a design basis which arranges for satisfying visual comfort. Based on the result from this study, 1700 lux vertical eye illuminance at the occupant position and 1900-2100 lux horizontal at the desk seem like reasonable thresholds for avoiding excess glare perceptions in perimeter zones. However, as neither vertical nor horizontal illuminance can represent contrast-based glare, especially under low-light environment, more detailed analysis is needed in case of low-light dominating environments.

This study was not able to reproduce the results of Wienold and Christoffersen [18] with respect to DGPs. 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. The idea of being able to predict the percentage of people being disturbed by glare is advantageous as it may allow differentiating between different levels of quality of a design as proposed by Wienold [38] and it also addresses the participant variability to glare. However, more and larger scale studies are needed to either confirm the suitability of the DGPs model or to confirm the findings in the present study that suggest that the DGPs equation should be renewed.

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