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Predicting Visual Comfort in Side-lit Open-Plan Core Zones: Results of a Field Study Pairing High Dynamic Range Images with Subjective Responses

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Abstract

Transmitting sufficient daylight to core zones while maintaining a visually comfortable work environment is critical for the effective use of daylight to reduce lighting energy and enhance indoor environmental quality. Although a range of indicators exists to predict visual comfort from windows, data comparing indicators with occupant subjective data collected from the core zones of daylit buildings are limited. This paper presents results from a study conducted in the core zones of a side-lit office building located in San Francisco, California. Subjective measurements of visual comfort were collected using a repeated-measures study design involving (N=14) participants over two weeks under clear sky conditions. Desktop polling devices were used to pair subjective data with concurrent luminance measurements acquired from High Dynamic Range (HDR) imaging cameras, resulting in a total of 523 observations. Single-variable logistic regression models generated from paired physical and subjective data were used to examine and rank 15 indicators of visual discomfort. Discomfort indicators based on luminance contrast ratios and absolute measures were found to be more effective than glare metrics or the more basic measures of vertical or horizontal illuminance. Results are compared and discussed in context with existing guidance for measuring and assessing discomfort glare.

KEYWORDS: Glare, High Dynamic Range Imaging, Post Occupancy Evaluation, Daylighting, High-performance Buildings

1. Introduction

The transmission of sufficient daylight to reduce electrical lighting energy consumption and enhance indoor environmental quality (IEQ) is a common goal for U.S. office buildings designed to address energy or sustainable building objectives. For the U.S. commercial building sector, lighting is estimated to account for 3.69 quad (quadrillion = 10^{15} Btu) of which, 2.21 quad is estimated to be associated with electric lighting use in perimeter zones located 0-12.2m (0-40 ft) from the building facade during typical daytime work hours¹ (8:00-18:00) [1]. In addition to the potential of daylighting for energy reduction, designers are motivated by green building rating system daylighting compliance criteria (e.g. LEED Daylighting Credit), which require a large percentage (e.g. 75%) of the occupied area to achieve minimum daylight illuminance criteria [2].

The central challenge to effective daylighting is the balance of daylight transmission with occupant visual comfort in both core and perimeter zones. Unlike daylight perimeter zones, defined in this paper as zones located a distance of 0-6m (0-20 ft.) from the facade, where the visual environment consists primarily of a window view and brightly lit interior surfaces, occupants in core zones (6-12m, 20-40 ft.) experience greater contrast in luminance between interior surfaces and the facade, which may lead to the more frequent perception of glare. Moreover, where perimeter zone occupants typically have control over facade shading devices to control visual comfort, core zone occupants typically have no access to shading devices. Consequently, visual conditions that occasionally produce discomfort may, over time, lead to the constant shading (or retrofit) of the upper daylight aperture due to complaints from the core zone [3]. Understanding how occupants in core zones respond to the visual conditions produced by the facade is critical to improving daylighting design practices as well as for refining existing approaches to assessing daylighting performance during design. Although a range of indicators exists to predict visual discomfort, evidence validating existing indicators with occupant subjective data collected from core zones is extremely limited. The primary objective of this study was to compare the outcomes of existing visual discomfort indicators with occupant subjective

¹ Excluding non-applicable floor space such as religious worship or vacant space.

assessments collected in the field and develop preliminary probabilistic discomfort models to improve guidance in early-stage design.

1.1. Definition of visual discomfort

In most indoor environments, visual discomfort is produced from two sources: 1) excess non-uniformity (illuminance ratios) between visual tasks and 2) discomfort glare. Unlike disability glare: the disabling of the visual system to some extent by light scattering in the eye [4], there is no well-understood mechanism for the cause of discomfort glare, although fluctuation in pupil size [5] as well as distraction [6] have been suggested. Discomfort glare is defined by the IEA SHC Task 21 as: a sensation of annoyance caused by high or non-uniform distributions of brightness in the field of view [7]. The Commission Internationale de l'Éclairage defines discomfort glare as: “glare that causes discomfort without necessarily impairing the vision of objects” [8].

1.2. Visual discomfort assessment in daylight spaces

Subjective and physical measures of visual discomfort in daylight spaces present a number of challenges. In contrast to the relatively small, uniform, and stationary glare sources with constant brightness produced by electric lighting, discomfort glare produced by windows varies in brightness, is constantly changing in size and position, and is usually distributed non-uniformly across a large area (e.g. a window or facade). Visual discomfort calculations for daylight spaces are inherently difficult to perform because they depend not only on the locations and brightnesses of light sources, but also on the apparent size of the light sources as seen from a particular viewpoint [9]. This presents a difficult measurement problem to researchers using conventional sensors (e.g. luminance meters, masked illuminance sensors) because the observer's entire field of view must be sampled in order to capture the luminance, position, and size of the glare source(s) present. In addition, due to the non-uniform lighting distributions common in daylight spaces, the boundary of the glare source is more difficult to define. In this research, indicators based on pre-defined glare sources (e.g. windows) and glare sources detected automatically from High Dynamic Range (HDR) images were analyzed (section 3).

1.3. High dynamic range imaging and visual comfort

High dynamic range images, by acquiring scene luminance data on a “per-pixel” scale, provide the ability to record the size, position and luminance of an arbitrary number of potential glare sources in the field of view, potentially enabling greater accuracy in the detection of dynamic glare sources common in daylight spaces. However, a question emerges for how to reliably relate physical measures of scene luminance with occupant subjective assessments of visual discomfort to ensure that indicators used in design lead to visually comfortable environments from the perspective of building occupants.

Relatively few studies have been implemented to examine the relationship between scene luminance and occupant assessments of visual comfort using HDR images. In a controlled laboratory study conducted in two daylit test facilities (Copenhagen and Freiburg) with matching configurations, Wienold and Christoffersen [10,11] collected subjective data from 76 study participants to compare user assessments to various lighting conditions measured using HDR images, resulting in 349 cases. Results showed that the correlation of existing glare prediction models to user responses was low (for example, a squared correlation factor of 0.12 for window luminance and 0.56 for DGI). Consequently, the study dataset was used as a basis to develop a new glare model entitled Daylight Glare Probability (DGP), which uses the probability that a person is disturbed instead of the glare magnitude as a glare measure. This metric was found to perform substantially better compared with existing metrics (squared correlation factor of 0.94).

In 2010, Van Den Wymelenberg et al. [12] conducted a controlled study involving 18 participants and two test conditions (36 cases total) in a daylit single-occupancy office on a university campus to examine the applicability of 150 predictors of visual discomfort. Participants occupied the room for a short time interval and were instructed to adjust the daylighting in the office to create ‘preferred’ and ‘just disturbing’ lighting. The study showed that the most effective predictor was the mean luminance of the glare sources (where the glare sources were identified as 7-times the mean luminance of the task position). The authors caution that due to the small sample size and context of the study

(single-occupancy office), the results cannot be directly applied to open-plan office environments.

To better understand user visual comfort response in daylit buildings in use, Painter et al., [13,14] developed a field-based data collection method pairing user assessments with concurrent luminance measurements derived from HDR images with an effort to minimize disturbance to study participants. A total of five (5) perimeter zone workstations in an academic building were monitored in a study involving six (6) people (one workstation was used by two people). In total, nearly 4800 subjective assessments of glare were collected over a 12-month monitoring interval. Results showed weak correlations between subjective responses and existing glare prediction models. The authors attribute this outcome to the large range of model predictions that were assessed as “no glare” by study participants. Basic parameters derived from the HDR images (specifically, global vertical illuminance measured at eye-level) were found to have a stronger correlation with subjective assessments than existing glare prediction models. The authors note the importance of layout-specific parameters and the need to collect data from a wide range of conditions / environments for the development of daylight glare assessment methods.

In 2013, Hirning et al., [15] used an approach where data was collected at workstations in five buildings in Brisbane Australia. A subjective survey was filled out by office workers while an HDR image of their primary task view was acquired by a researcher. This “nomadic” approach enabled the researchers to collect 493 surveys paired with HDR images acquired from office workers, however each workstation was surveyed only once at seemingly arbitrary times over varying seasonal conditions. Data were collected sporadically over 14 days from February to October 2012, covering autumn, winter and spring. The benefit of this approach is that it resulted in subjective feedback from a larger number of study participants. However, as daylit environments are highly dynamic, and vary in response to daily and seasonal changes in sun and sky conditions, the approach presents a number of limitations for relating subjective outcomes with measured data. For example, luminance measurements may be acquired during overcast sky conditions or a

period of the day when sun is not incident on the facade adjacent to the workstation, however the participant's subjective response may still rate the space as glary due to past experience of an expectation for glare later in the day.

A review of the existing studies pairing user response with HDR images shows that nearly all data was collected in daylight perimeter zone environments, often over short monitoring time intervals. In order to examine the applicability of existing indicators across a broader range of conditions and environments, field-based approaches are needed that are capable of monitoring changes in subjective assessments in response to dynamic daylighting conditions. In comparison to controlled laboratory studies, the primary advantage of field-based research is the potential for longer monitoring intervals and the ability to survey occupants who are performing real work tasks under dynamic lighting conditions. Field studies present the additional benefit of enabling a broader range of interior space configurations to be considered. In particular, deep (>20ft, 6.1m) open-plan office environments, a condition difficult to accommodate within the geometry of existing daylight test facilities. The methodological objective of the present research was to extend the applicability of long-term (e.g. multi-week to annual intervals) field monitoring of user response to glare through the development of 15 relatively low-cost HDR acquisition systems (that do not require a PC) paired with 15 desktop polling devices that are continually accessible for recording subjective assessments without disruption to screen-based work tasks. Additional research objectives are outlined in the following section.

1.4. Aims

Although the development of models to predict visual discomfort in daylight spaces remains an active research topic, there is currently no agreed-upon method to accurately predict discomfort glare in daylight environments [16]. In addition, data collected from buildings in use for validating existing models are extremely limited, particularly in the central core zones. To address this need, the study had the following aims:

1. Compare the outcomes of existing indicators recommended for measuring and assessing visual discomfort with occupant subjective responses collected in a daylight core zone where study participants are performing real working tasks.
2. Develop and examine the applicability of field-based probabilistic discomfort models. If models can be developed from field data, determine what variables best predict visual discomfort and characterize the level of accuracy.
3. Demonstrate the application of a “nomadic” set of low-cost Post Occupancy Evaluation (POE) tools for field-based evaluation of visual comfort.

2. Methodology

2.1. Overview of the test site

The study was conducted on the upper floors (15 and 16) of an 18-story office building located in San Francisco, California (latitude: 37.8, longitude: -122.4). During design of the building a number of decisions were made, at least in part, with the objective of daylighting the core zones of the floor plate. First, the building form is long and narrow, with a 20.8m (68.24 ft) deep floor plate and, on the floors studied, large sections of open-plan office workspaces with low, 1m (3.5 ft.) and 1.2m (4 ft.) partition heights, enabling occupants in the core zone to have largely unobstructed views to the facade. The ceiling height is 4m (13 ft.), higher than conventional U.S. office construction, and the facade is floor-to-ceiling high Visible Light Transmittance (VLT) window-wall glazing (VLT = 0.67). Figure 1 shows a generic floor plan. Figure 2 shows a cross-section view of a typical open-plan core zone. Workstations in the core zone resulted in occupants seated at distances from the facade ranging from approximately 5m (16 ft.) to 10m (33 ft.).

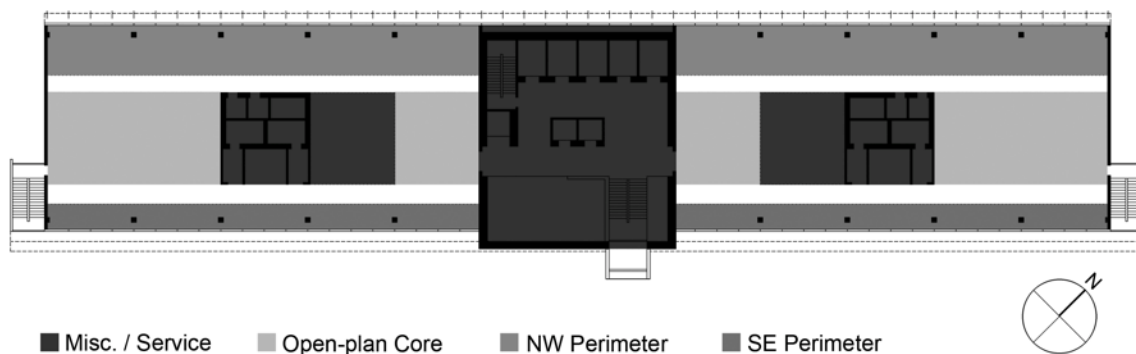


Fig. 1. Example floor plan.

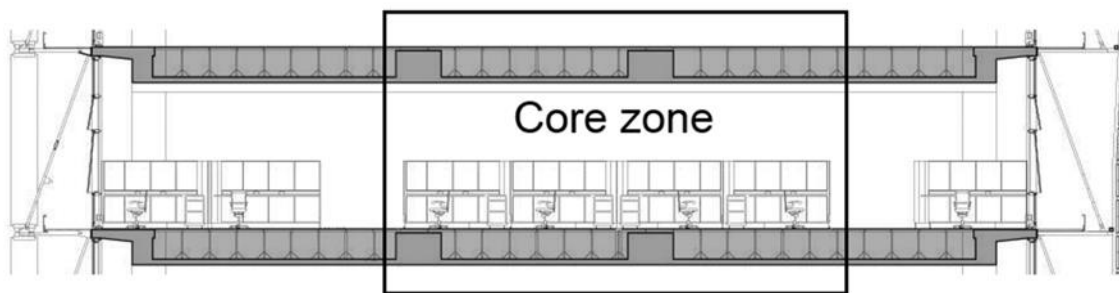


Fig. 2. Example cross-section showing open-plan core zone sections.

2.2. Study participants

Data were collected at the workspaces of 14 participants (36% male, 64% female). Forty-three percent (43%) of participants were between the ages of 30-40, (43%) were between the ages of 40 and 50, and the remainder were above 50 (14%). The work tasks for all participants were the same and involved viewing a computer Visual Display Terminal (VDT) for the majority of work hours.

2.3. Research design

Subjective measurements of visual discomfort were collected using a repeated-measures study design conducted over two weeks under clear sky conditions near the fall equinox (10/4/2010 – 10/15/2010). The objective of the research design was to collect subjective measures from participants with minimal intervention to typical patterns of office work. Therefore, the study was conducted “in-situ,” with no modifications to participant location, schedule, or environment beyond the introduction of instrumentation and repeated prompts needed to acquire subjective and physical measurements.

2.4. Field-based HDR imaging

A total of 14 digital cameras with firmware modified to enable HDR imaging were installed in the core zone. It is important to note that locating cameras sufficiently close to seated occupant’s eye position to capture task views appropriately is simply not practical in real world office applications [17]. In this study, one camera was installed at each participant location by secure attachment to the top of an adjacent 1m (40 in.) high workstation partition (Figure 3), resulting in camera positions nominally 1-1.5m (3.3-4.9 ft.) horizontally from participant viewpoints. The secure bracket attachment was necessary to ensure that the camera view position did not shift over the two-week study interval. Each camera was oriented to align with the participant’s primary view direction. Figure 4 provides an example view resulting from a typical configuration. The digital cameras used are Canon PowerShot A570 CCD cameras with a fish-eye lens converter. Features of the camera were controlled automatically using on-board scripting to control

the acquisition of exposure-bracketed sets of JPEG images. At the end of the study, sets of JPEG images were composited into HDR images using the software program hdrngen [18] and post-processed using Radiance to apply a correction for lens vignetting following the approach documented in [19]. Prior to the field study, a procedure was developed [20] using a room within a daylight testbed facility to compare the time-series HDR data (acquired at 5-minute intervals) to readings from a calibrated shielded illuminance sensor. The shielded illuminance sensor was masked to measure the average luminance of the window region of the test cell. A camera was located adjacent to the shielded illuminance sensor and a bitmap mask was created and used in a Radiance post-process to calculate the average luminance of the identical window region as viewed from the camera. Images were then calibrated by scaling the exposure value in the image file header by a coefficient uniquely determined for each camera to minimize absolute error between the camera measurements and illuminance sensor measurements over a daily set of data. Individual images calibrated using this technique were found to report luminance conditions with a measurement error of +/- 10% or less.



Fig. 3. HDR-enabled digital CCD camera mounted to workstation partition.

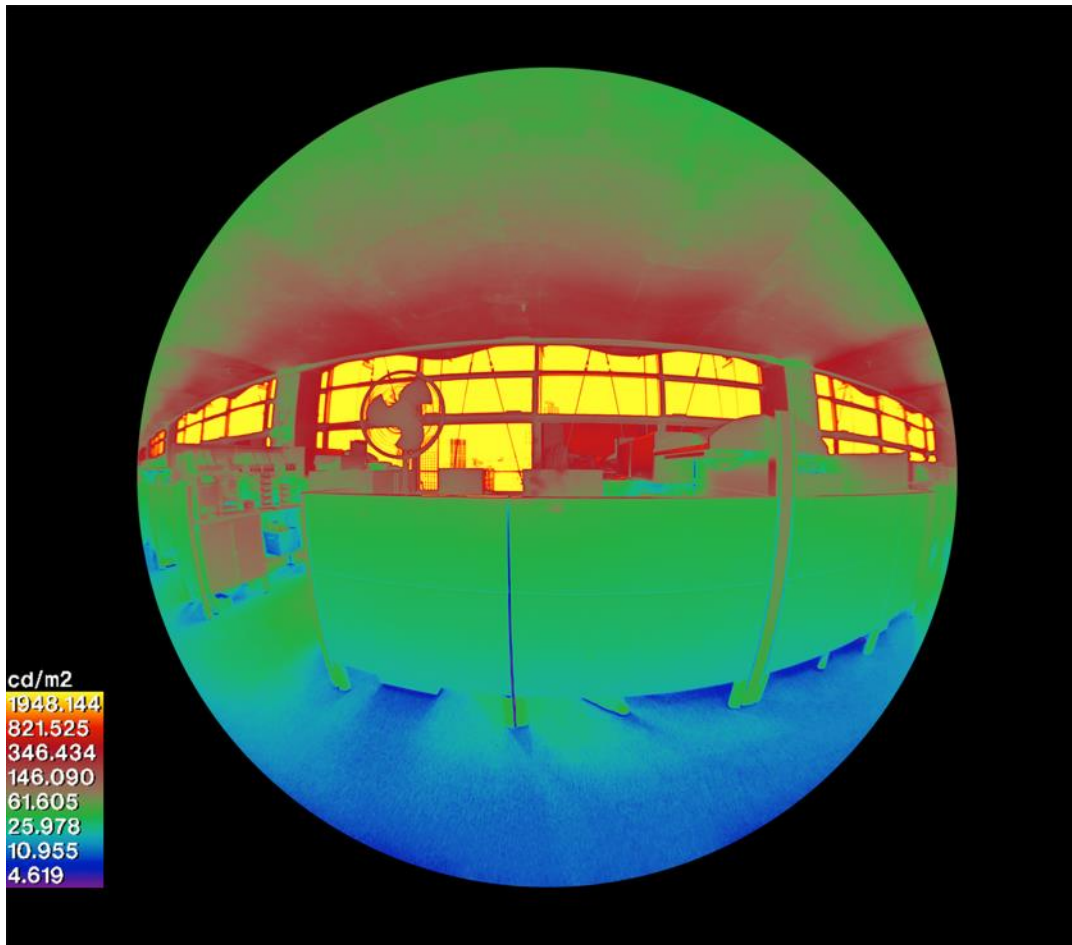


Fig. 4. Example view from HDR camera installed in field with falsecolor tone-mapping using a log scale.

2.5. Desktop polling stations

Novel desktop polling station devices designed and built for this research were located on each participant's desk and served as an interface for participants to record subjective assessments repeatedly over daily changes in visual conditions. A detailed description of the development and applicability of the polling stations for human factors field research is documented in [21,22]. Participants were instructed to use the polling station to input subjective feedback at any time throughout the day and were prompted with visual and audible cues if no response was recorded for more than two hours. Participants interacted with the polling station by pressing the button and then recording their response to the question displayed on the device's LCD screen using the horizontal slide potentiometer (figure 6) which was mapped to a four-point semantic scale of "no discomfort," "slightly

uncomfortable,” “moderately uncomfortable,” and “very uncomfortable.” The four-point scale enabled participants to indicate a range of discomfort sensations, however response data was later assigned a binary classification (“discomfort” or “no discomfort”) for binary logistic regression analysis. This approach is described in section 3. Each polling station is also equipped with two onboard physical sensors, a cosine-corrected LI-COR photometric sensor (type = LI-210, nominal accuracy = 3%) and an operative temperature sensor (not used in the scope of this study). The LI-COR was used to acquire continuous measurements of global horizontal illuminance adjacent to the participant.

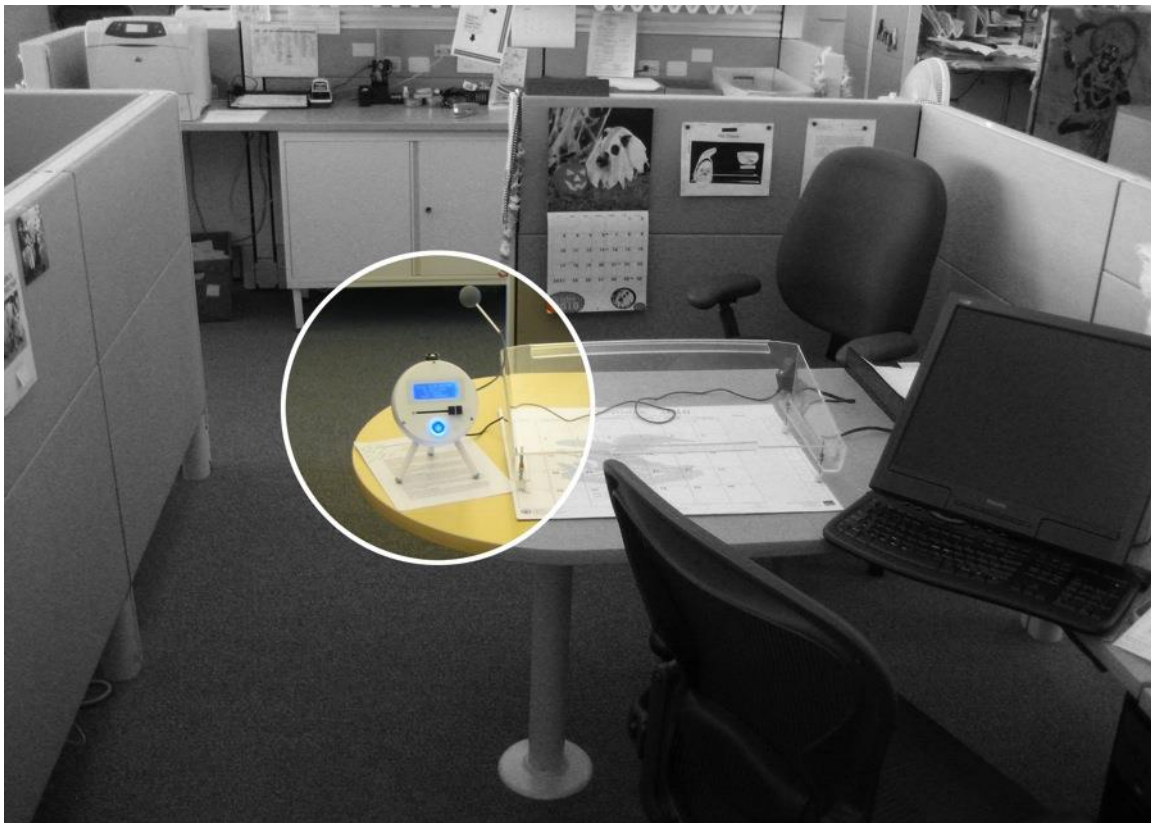


Fig. 5. Desktop polling station installed at participant workstation.



Fig. 6. Desktop polling station.

3. Data Analysis

3.1 Subjective response data

The field study resulted in a total of 523 subjective assessments of visual discomfort among all (N=14) participants. Analysis showed that, on average, participants responded 3.7 times each day. Table 1 presents the frequency and magnitude of the subjective response data.

Table 1
Frequency and magnitude of subjective responses.

Subjective response	N responses	% of total
No discomfort	180	34
Slightly uncomfortable	221	42
Moderately uncomfortable	70	13
Very uncomfortable	52	10

3.2. Selection of independent variables

To model the physical lighting conditions associated with visual discomfort, a set of candidate predictor variables was selected. Variables were selected from review of prior research and current lighting design guidance and encompass 1) luminance contrast ratio limits, 2) absolute luminance thresholds, 3) glare metrics, and 4) interior global horizontal and vertical illuminance.

3.2.1. Luminance contrast ratios

The Illuminating Engineering Society of North America (IESNA) recommends luminance contrast ratio limits of (1:10) between primary task and far field surfaces (e.g. windows) to maintain visual comfort [23]. In the context of the core-zone views of this study, the far field surfaces consisted of direct views of perimeter window-wall glazing partially occluded by interior workspace partitions. Therefore, variables were defined to express the ratio between a primary visual task and regions of window-wall glazing in the field of view. The window region was defined for each camera view through a custom mask creating during post processing of the HDR data and analyzed to produce four ratios (R_{CPU} , R_{CPUmax} , R_{win} and R_{winMax}). The first, (R_{CPU}), is defined as the ratio of the

average luminance of the window region to a hypothetical visual task of 200 cd/m^2 . In addition to the practical constraint mentioned earlier, monitoring of actual visual tasks (visual display terminals) was discouraged due to concerns for privacy. Therefore, an approximation of screen luminance was determined from measurements taken with a handheld luminance meter, where 200 cd/m^2 closely approximates the luminance of the white pixels of a word processing document. The second, (R_{CPUmax}) represents the ratio of the maximum window luminance to the visual task. Similarly, variables were defined to express the ratio between the window region and the remaining interior surfaces (R_{win} , R_{winMax}). Figure 7, presents an example of the HDR image mask technique used for calculation of luminance contrast ratios.



Fig. 7. Window region boundary (in white) defined through custom HDR imagemask for calculation of luminance contrast ratios, for example camera viewpoint.

3.2.2. Absolute luminance thresholds

In addition to luminance ratios, absolute luminance thresholds were included. Absolute luminance thresholds have been proposed as a practical approach for assessment of visual

discomfort [12, 24]. The average luminance (L_{upWin}) and maximum luminance (L_{upMax}) of the upper two rows of windows were calculated to characterize the potential discomfort produced from the clerestory zone windows (figure 8, left) by comparison of measured values to established threshold criteria. For example, in the commissioning and verification procedures for the automated roller shade system at the New York Times headquarters. Lee et al. defined glare in terms of regions of window luminance that exceeded a luminance threshold of 2000 cd/m^2 [24]. The average luminance, (L_{lwWin}), and maximum luminance, (L_{lwMax}), of the lower rows of windows were also included to isolate the luminance of the partially occluded view zone (figure 8, right).



Fig. 8. Upper daylight zone (left) and lower vision zone (right) window region boundaries defined for calculation of absolute luminance thresholds (example from one cameraviewpoint).

3.2.3. Glare metrics

Glare metrics were selected based on recommendations from existing performance measurement protocols for the measurement of visual discomfort from large area sources (e.g. windows). First, the Daylight Glare Index (DGI) was included [25]. The DGI is recommended by the International Energy Agency Solar Heating and Cooling (SHC) Program Task 21 daylighting performance monitoring procedures to assess visual comfort in daylit spaces [7]. Because the position, number, and boundaries of glare

sources are constantly changing in a daylit scene, glare calculations require the user to specify a threshold luminance to determine what areas of the field of view constitute a glare source. To address this ambiguity, two separate indicators were defined and examined for the DGI calculation. The first was to define a glare source as any luminance value seven times greater than the average scene luminance (DGI_{7x}). This approach is the default detection criterion used by the Radiance program *findglare*. The glare sources detected using this threshold are presented in figure 9. The second approach was to define glare as any source greater than 2000 cd/m^2 , (DGI_{2000}) after the approach taken by [24], where 2000 cd/m^2 indicates a luminance contrast of [10:1] between the source and a hypothetical 200 cd/m^2 visual task. The glare sources detected using the 2000 cd/m^2 threshold are presented in figure 10. Second, the Unified Glare Rating (UGR) was included. The UGR is recommended by the ASHRAE Performance Measurement Protocols (PMP) for commercial buildings [26]. The ASHRAE PMP recommends that the UGR not exceed 19 in an office environment. Thirdly, the CIE glare index (CGI), developed by Einhorn [27,28] was included. Finally, interior global vertical illuminance ($Illum_{intVert}$), recommended by prior studies [29,30,31] was included as a more basic metric for comparison. Vertical illuminance is more readily calculated through lighting software simulation tools and more easily obtained through physical measurements. However, it reduces the variation in scene luminances to a single illuminance value. Therefore, glare metrics and luminance data from HDR images offer the potential benefit of greater level of granularity in identifying and characterizing potential sources of visual discomfort.

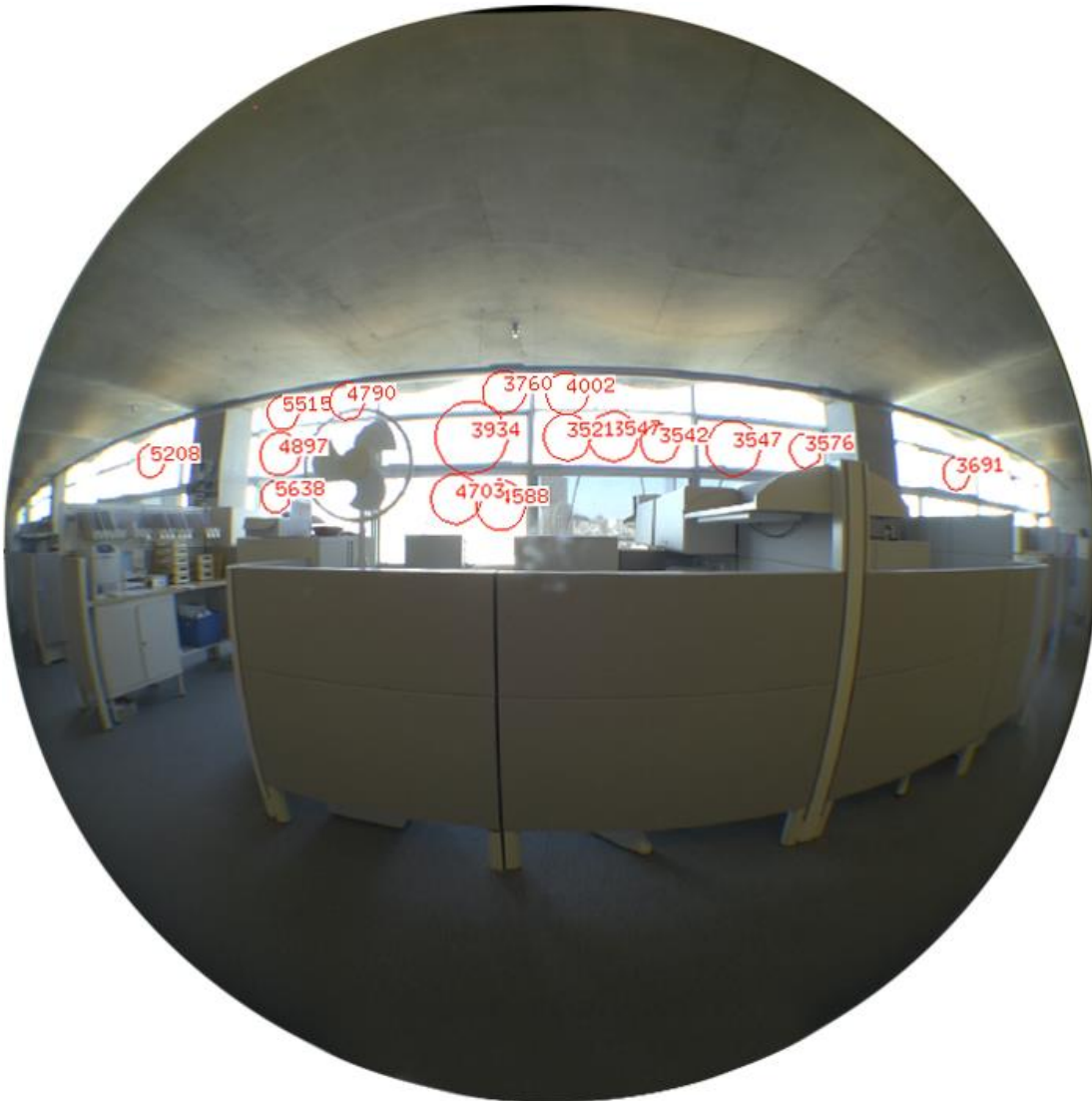


Fig. 9. Glare sources detected using the findglare default detection criterion.



Fig. 10. Glare sources detected using a 2000 cd/m² threshold criterion.

3.2.4. Interior global horizontal illuminance

In addition to the ratios and absolute values of pre-defined regions in the field of view, global horizontal daylight illuminance² ($I_{\text{ill,dH}}$) measured at each polling station, was included as an additional predictor variable. Global horizontal illuminance is used as an indicator of daylight sufficiency and is also proposed as an indicator of visual discomfort

² Because the ambient electrical lighting system did not dim in response to daylight and was never switched off during daylight hours, horizontal daylight illuminance could easily be derived by subtracting the known contribution of the electrical lighting system (measured after sunset) for the illuminance measurements acquired during the study.

when a threshold lux level is exceeded. For example, the Useful Daylight Illuminance (UDI) metric considers daylight illuminances in excess of 2000 lux as an indicator of lighting conditions likely to cause visual discomfort [32]. Threshold criteria associated with the magnitude of interior horizontal daylight illuminance are also included in the metrics Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), recently approved by the IES [33]. Finally, the daylight factor (DF) was included to examine its applicability in predicting visual comfort. The DF has primarily been used to assess daylight sufficiency [34], but is also recommended as an indicator of excessive daylight transmission ($DF > 5\%$) that can lead to visual discomfort [35].

3.3. Description of independent variables

All independent variables selected for the visual discomfort analysis are shown in table 2 along with descriptive statistics. The descriptive statistics were calculated from the set of physical measures acquired concurrent with subjective responses.

Table 2

Descriptive statistics for core zone independent variables associated with subjective responses from polling stations.

Variable	Unit	Median	SD	Min.	Max.
<i>N</i> = 14 participants (523 observations)					
Illum _{dit}	Lux	53	32	1	180
Illum _{inVert}	Lux	905	323	79	1289
DF (%)	–	0.13	0.25	0	2.56
<i>L</i> _{upWin}	cd/m ²	2673	1047	9	4917
<i>L</i> _{maxUpWin}	cd/m ²	6196	3125	46	16056
<i>L</i> _{lwWin}	cd/m ²	161	115	2	419
<i>L</i> _{maxLwWin}	cd/m ²	1461	795	9	2428
<i>R</i> _{win}	–	22	14	0	60
<i>R</i> _{winMax}	–	138	22	0	208
<i>R</i> _{CPU}	–	13	5	0	25
<i>R</i> _{CPUmax}	–	31	15	0	80
DGI ₂₀₀₀	–	25	9	0	28
DGI _{7x}	–	23	6	0	25
CGI	–	28	10	0	31
UGR	–	26	9	0	29

3.4. Scaling of independent variables

The physiological sensation of brightness, like many other physiological sensations (e.g. smell, sound, touch), increases proportionally to the logarithm of the stimulus intensity (i.e. luminance) [36]. Therefore, all variables (with the exception of the glare indices and the luminance ratios) were scaled using a log transform prior to using statistical methods to relate subjective responses to stimulus intensity.

3.5. Binary classification of subjective assessments

For the logistic regression technique used in this analysis, the response variable is assumed to be one of two possible disjoint outcomes (e.g. visual discomfort, or the absence of visual discomfort), where the probability of the outcome is related to an

explanatory variable. Because the subjective scale used to record ratings of visual discomfort included multiple discrete steps (e.g. “slightly,” “moderately,” “very uncomfortable”) to register varying magnitudes of discomfort, a classification was required to simplify the subjective responses to a binary form. For analysis, responses of “no discomfort” and “slight discomfort” were binned as acceptable and “moderately uncomfortable” and “very uncomfortable” were binned as discomfort. For each candidate independent variable, logistic models were then generated with the software program R using the generalized linear model function (`glm, family = binomial`) for the binary division of the data.

3.6. Ranking of single-variable logistic regression models

Using stepwise logistic regression (with forward selection), candidate logistic models were ranked based on the Akaike Information Criterion (AIC) [37]. Although the AIC provides a tool for model selection among a set of candidate models, the AIC does not explain how well a model fits the data in an absolute sense. For example, the AIC will not indicate if all candidate models fit poorly. Therefore, as an indicator of goodness of fit, the percent of correct responses (%-cor.) was used. The percent of correct responses was found by applying the model to the original data and comparing the predicted outcome from each model to the occupant subjective response recorded.

4. Results and discussion

This section presents and discusses the rank-order of the field-based probabilistic models developed from fifteen (15) predictor variables of visual discomfort. Predictor variables, models and associated discomfort thresholds are discussed in terms of their applicability for predicting visual discomfort reported by study participants. Outcomes are compared to existing criteria and guidance for predicting visual discomfort in daylight spaces. The section concludes by demonstrating an example application of one of the field-based models developed through this research.

The rank-order of discomfort models is presented in table 3. Table 3 additionally lists the goodness of fit for each model (AIC) and the percent of correct responses (%-Cor.), as

well as the thresholds for 20%, 50%, and 80% probability of discomfort. Overall, models developed from discomfort indicators based on luminance contrast ratio limits and from absolute measures of vertical luminance were found to be the most accurate in predicting discomfort responses. However, contrast ratios based on maximum values of a region were more effective compared with ratios based on averages luminances, which in some cases ranked poorly. All glare metrics examined were found to yield similar levels of accuracy, but were no more effective than the more basic measure of vertical illuminance. Finally, horizontal daylight illuminance and the daylight factor were found to be two of the least effective predictors for visual discomfort. Outcomes are discussed in further detail and compared to previous research findings in the follow sections.

4.1. Luminance contrast ratio limits

As shown in table 3, the highest-ranked model was found to be the ratio of maximum window luminance to a vertical visual task of 200 cd/m^2 (R_{CPUmax}). Figure 11 shows the logistic model of R_{CPUmax} (solid black curve). Logistic models predict the probability of discomfort on a scale from zero (no chance of discomfort) to one (100% chance of discomfort) in response to the stimulus intensity of the discomfort indicator. The ratio of average window luminance to task luminance, R_{CPU} , was also found to be highly ranked (4th, table 3) and is shown on the same figure (dashed grey curve). For R_{CPUmax} , data was acquired for ratios between 1:1 and 1:80. For R_{CPU} , data was acquired for ratios between 1:1 and 1:25 (table 2). Individual data points corresponding to the binned data (0 = no discomfort, 1 = discomfort) are plotted for each model in the upper and lower regions of the figure. A small random adjustment (“jitter”) is made to each point in the y-direction to better visualize clustered data. The model R_{CPUmax} was the most accurate, predicting 77.4% of measured subjective assessments of visual discomfort correctly. This outcome supports the result found in the controlled study by Van Den Wymelenberg et al. [12] where basic parameters relating task and scene luminance were the most accurate predictors of subjective assessments of glare among over 150 different illuminance and luminance metrics evaluated. Models derived from discomfort indicators based on ratios of maximum or average window luminance to interior vertical illuminance (R_{winMax} , R_{win}) were found to be among the least accurate.

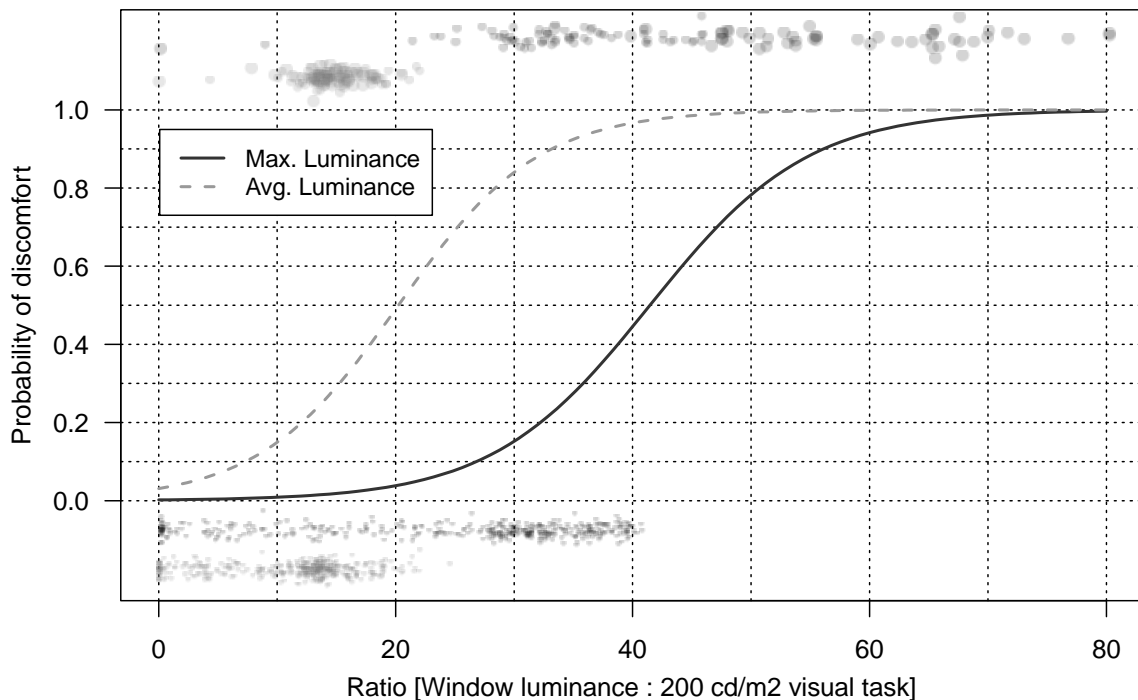


Fig. 11. Probability of discomfort as a function of luminance contrast ratio: maximum window luminance (solid line) and average window luminance (dashed line) to a 200 cd/m² visual task.

The IESNA recommends a maximum luminance ratio of [1:3:10] between primary task, near field, and far field surfaces (IESNA, 2005). However, guidance is ambiguous for surfaces with non-uniform luminance, such as windows or interior surfaces in daylight perimeter zones. The models show that occupants were tolerant of ratios between task and far field surfaces of up to [1:32], where “tolerance” is defined as a 20% probability of discomfort when the maximum luminance of the far field surface is considered ($R_{CPU_{max}}$) and up to [1:12] when the average luminance is used (table 2). Comparison between the two models presented in figure 11 illustrates the significant variation in the relationship between the contrast ratio and subjective assessment of discomfort depending on whether the ratio is computed from the average or maximum window luminance. Where far field surfaces are predominately uniform, these results support control of surfaces luminances to a limit of 12-times the task luminance (e.g. 2400 cd/m² for a 200 cd/m² visual task) as a relatively conservative criteria for maintaining visual comfort conditions in the core

zones. As window surfaces are rarely uniform, a designer may alternatively allow for variation in surface luminance while implementing design elements to limit the maximum surface luminance to below 32-times the luminance of the visual task (e.g. 6400 cd/m² for a 200 cd/m² visual task).

4.2. Absolute window luminance

Absolute measures of window luminance for the upper rows of windows ($L_{\max\text{UprWin}}$, L_{UprWin}) were also found to be highly ranked (2nd and 5th respectively). Figure 12 compares logistic models of visual discomfort generated from measures of maximum and average window luminance for the upper daylight zone windows. The y-axis of the figure is a logarithmic scale. An additional scale showing the original units is drawn at the top of the figure.

This outcome contrasts with the result found in the controlled study by Wienold et al. [10,11] where absolute window luminance (expressed as average window luminance) was found to have a weak relationship with subjective assessments of glare. There are several differences between the two study environments that are relevant to discuss related two findings. First, the present study was conducted in the core zone of a large open-plan space where the upper clerestory row of windows was typically unshaded (and the lower vision windows were typically shaded), leading to the clerestory windows serving as a the most consistent and dominant source of glare. In addition, the open-plan space lacked interior dividing walls where redirected light or direct sun could cause additional glare sources. In this context, the glare source boundary could be easily identified and a pre-determined mask was generated for each occupant's camera view during analysis. One can speculate that this pre-definition of the glare source improved the metric's performance over a more flexible, automated glare source detection process such as the method implemented in *findglare* [9] or *evalglare* [11].

As facade side-lighting strategies commonly subdivide the facade into a lower view zone and an upper daylight zone to improve daylight transmission to the core, the acceptance of core-zone occupants to the luminances produced by upper daylight zone windows is a

critical concern. The models support the conclusion that occupants tolerate ($p < 0.2$) maximum window luminances for the upper two rows of windows that remain below 6100 cd/m^2 , and average luminances that remain below 2700 cd/m^2 . The pre-defined mask approach used in this study is less likely to be applicable in perimeter zone applications and for complex fenestration, where glare source patterns are more spatially dynamic.

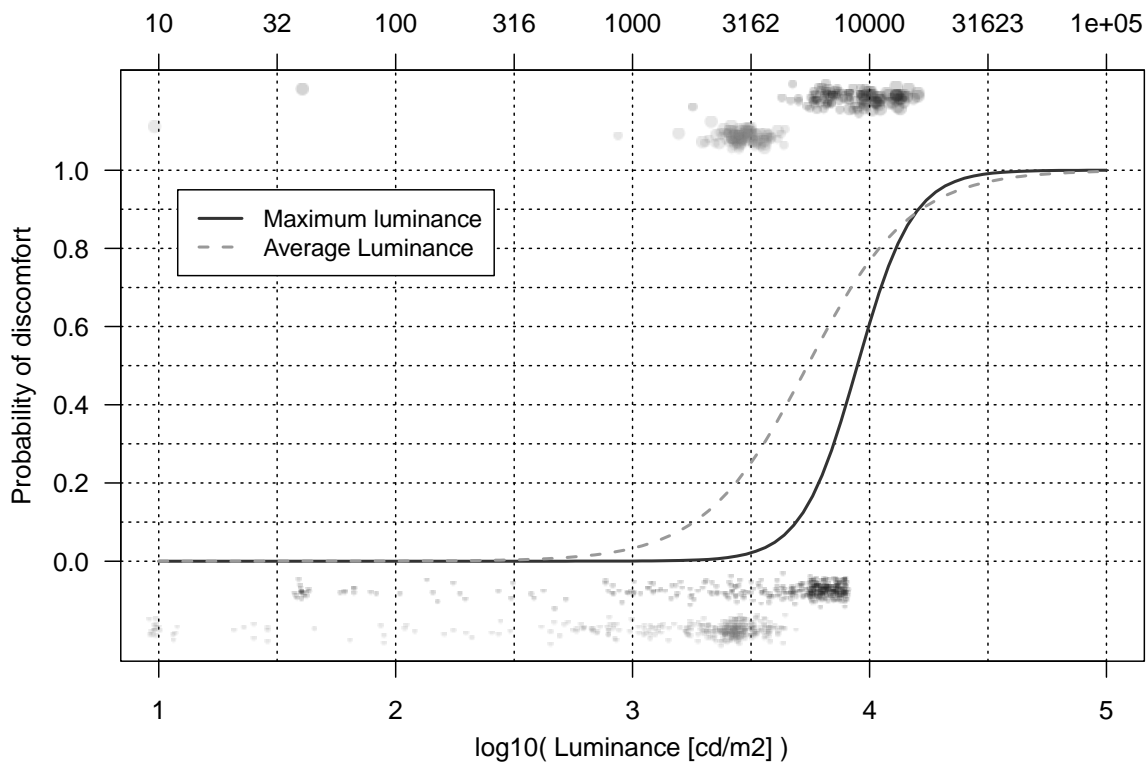


Fig. 12. Probability of discomfort as a function of absolute measures of upper window luminance.

4.3. Glare metrics

Overall, logistic regression models of visual discomfort utilizing existing glare metrics (DGI_{7x} , DGI_{2000} , UGR, CGI) were generally less accurate than more basic discomfort indicators. For example, no glare metric produced a model more accurate than the model based on interior vertical illuminance ($Illum_{inVert}$). This finding supports the results from controlled laboratory studies by Wienold and Christoffersen [11] and Van Den Wymelenberg et al., [12] that found the traditionally used glare metrics (DGI, UGR, and

CGI) to be poorly applicable for predicting subjective assessments of glare and extends this result to a core zone context. The finding additionally supports the result from the repeated measures field-study performed by Painter et al., [14] where no strong correlations were found between the traditionally used glare metrics (DGI, UGR, and CGI) and occupant subjective assessments of glare. There was little variation between glare metrics in accuracy, with less than a one-percent difference overall between the most accurate model (CGI) and the least accurate (DGI_{7x}), table 3.

In addition to finding glare metrics to have relatively weak predictive power, the relationship between the probability of discomfort and the glare index semantic thresholds was in some cases found to be incongruent. For example, the predictive model based on the Unified Glare Rating (UGR) is plotted in figure 13. Vertical black lines indicate the semantic criteria for judging UGR calculations: *just perceptible* = 10, *just acceptable* = 16, *just uncomfortable* = 22, *just intolerable* = 28. In addition to these criteria, the IESNA and the ASHRAE Performance Measurement Protocols (PMP) for office spaces [26] recommend a maximum UGR rating of 19 for office space types. In comparison to this guidance, figure 13 shows that nearly all subjective discomfort responses were recorded within the semantic range between *uncomfortable* and *intolerable*, however the model shows only a 30% probability of discomfort at the intolerable threshold, with 20% probability of discomfort at a UGR of 24 (table 3). Although the subjective responses generally aligned with the existing semantic thresholds, the result from field data suggests that the limit of 19 may be overly conservative for a daylight core zone. Consequently, the findings suggest that the UGR is applicable for predicting discomfort, but interpretation may need to be calibrated to specific daylight zones.

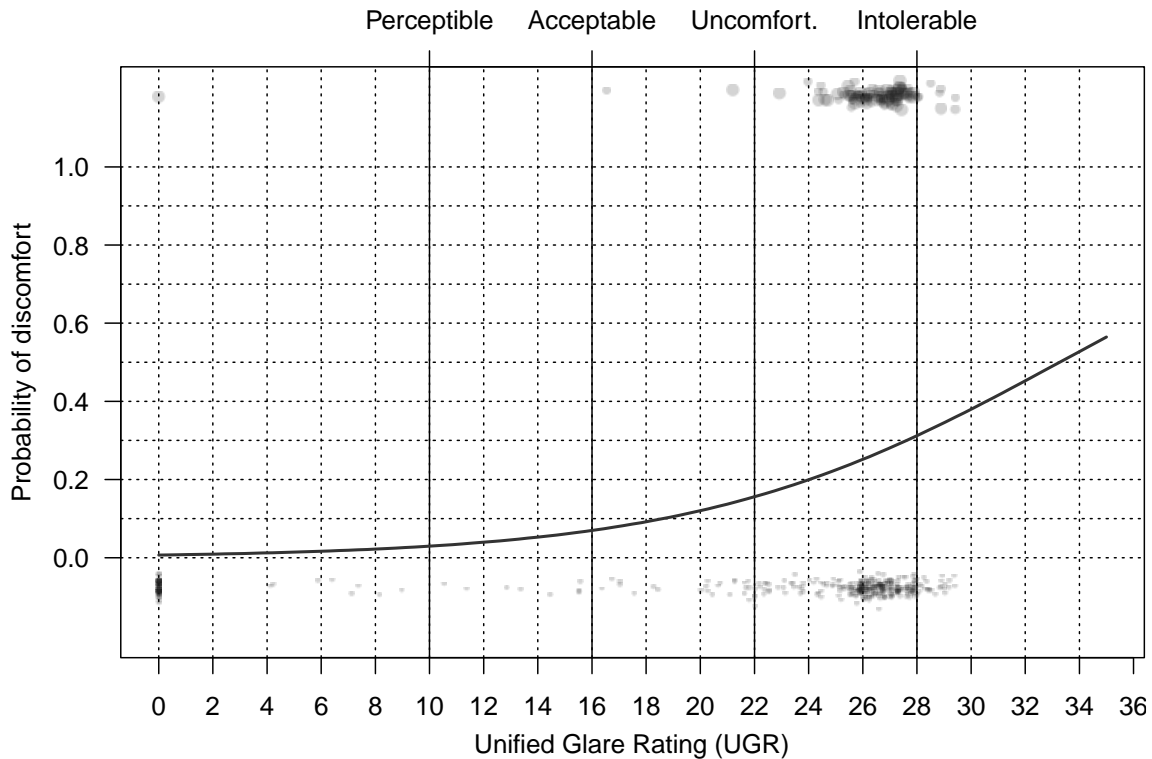


Fig. 13. Probability of discomfort as a function of absolute measures of upper window luminance.

4.4. Interior global horizontal daylight illuminance metrics

Models based on interior global horizontal daylight illuminance ($I_{lum_{dlt}}$) and the daylight factor (DF) were found to be among the least accurate predictors of visual discomfort, ranking 12th and 15th respectively. This outcome is important to consider in the context of emerging annualized daylighting metrics (UDI, SDA) that rely on global horizontal daylight illuminance as a measure on which threshold criteria are established to identify visual discomfort conditions (in addition to daylight sufficiency). Table 3 presents a number of predictive models that can be implemented in annualized simulations to establish additional indicators for assessing of visual discomfort in core zones. At the most basic level, the model rankings show that a vertical measure of daylight illuminance is more likely to predict discomfort compared with a horizontal measure (66.9% vs. 65% respectively). In addition, the field data shows that discomfort responses occur in daylight illuminances significantly below the threshold of 2000 lux. As shown in table 3, the $I_{lum_{dlt}}$ model predicts discomfort with probabilities of ($p=0.2$,

0.5, and 0.8) at (130, 450, and 1600 lux) respectively.

4.5. Model implementation

The probability of visual discomfort can be approximated by applying the regression coefficients from a model provided in table 3 to the following equation:

$$P(X) = \frac{1}{1 + e^{-z}} \quad \text{Equation 1: Probability of visual discomfort.}$$

where $z = \alpha + \beta X$

$P(X)$ Probability of visual discomfort

α, β Estimated regression coefficients

As an example, the probability of visual discomfort reaches 0.5 at a maximum upper window luminance of 8900 cd/m² (table 3). These thresholds provide important guidance for designers in regard to the luminance conditions likely to cause visual discomfort. The predictive models can also be implemented directly in software simulation workflows to place quantitative data in context with subjective outcomes. Finally, the models can be used to inform automated façade shading control algorithms to operate appropriately in response the probability of occupant discomfort. Figure 14 provides an example of the application of discomfort thresholds to measured field data of maximum upper window luminance to identify the periods of the day when the daylight zone windows are a source of discomfort.

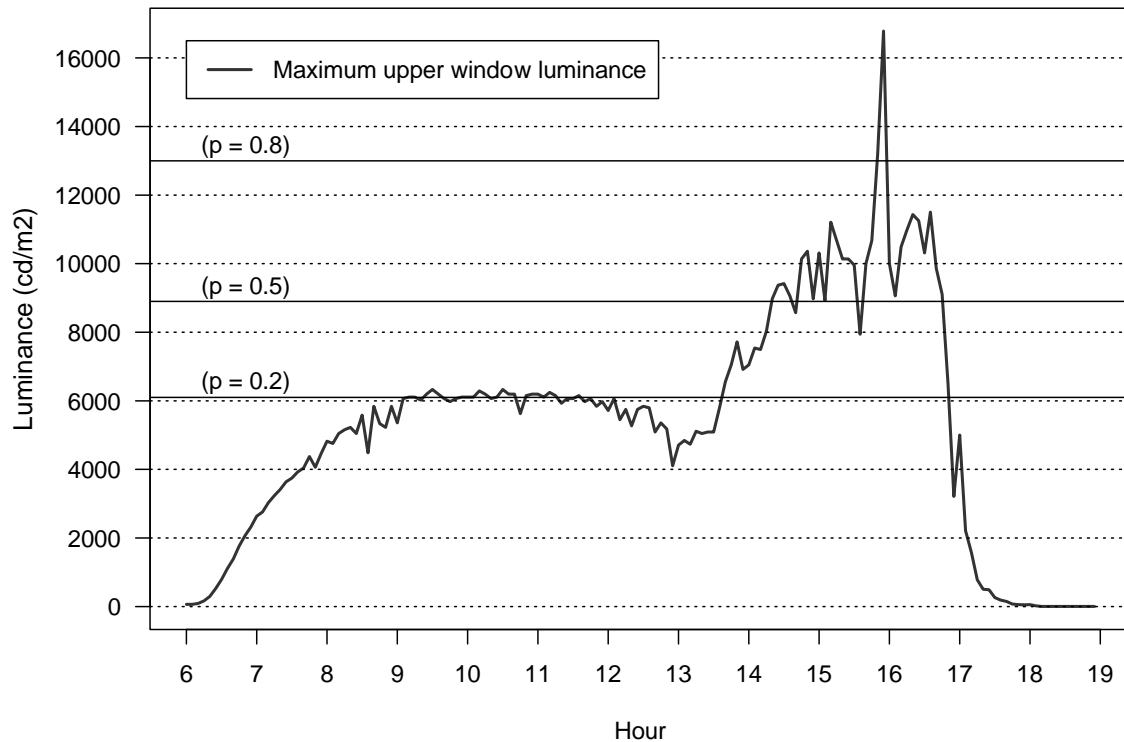


Fig. 14. Maximum upper window luminance for an example day (clear sky conditions) showing application of estimated discomfort thresholds ($p = 0.2$, $p = 0.5$, and $p = 0.8$).

5. Conclusions

A field-based technique of HDR cameras paired with desktop polling stations was used to collect 523 subjective evaluations of visual comfort among ($N=14$) participants in the core zone of a daylit office building in San Francisco, CA over a period of two work weeks. Single variable logistic regression models generated from paired physical and subjective data were found to be capable of modeling the subjective response of study participants in response to variable stimulus with a reasonable level of accuracy (64.3 - 77.4%). The technique proved effective for examining the applicability of 15 indicators of visual discomfort through model rankings and presents a promising supplement to controlled laboratory settings for conducting human-factors research on daylighting and visual comfort.

Discomfort models based on luminance contrast ratios and absolute measures of window luminance were found to have the highest probability of correctly predicting occupant

subjective responses and were more effective than the glare metrics or the more basic measures of vertical or horizontal illuminance.

Overall, the existing glare metric semantic thresholds were found to align with relatively low probabilities of visual discomfort. As one example, the UGR range of 22 – 28 (uncomfortable to intolerable) was found to align with a 15-to-30% probability of discomfort. There is currently no consensus recommendation for what an acceptable probability of discomfort in a daylit office should be over daily and seasonal changes in sun and sky conditions. However, the result showing that the majority of participants were able to work comfortably in the range defined as (uncomfortable to intolerable) suggests that the UGR may overestimate the sensitivity of occupants when applied to daylit core zones.

Occupants were found to report visual discomfort when horizontal daylight illuminances at the workstation were significantly below 2000 lux. This outcome can be attributed to the chosen location of the study in the core zone of a side-lit open-plan office space, with occupants located at a distance of approximately 20ft (6.1m) to 30ft (9.14m) from the facade. In this context, although horizontal daylight illuminance levels were one (or sometimes two) orders of magnitude lower than simultaneous measures in perimeter zones, occupants in the core retained views with relatively high average (median $L_{upWin} = 2673 \text{ cd/m}^2$, max $L_{upWin} = 4917 \text{ cd/m}^2$) and maximum (median $L_{maxUpWin} = 6196 \text{ cd/m}^2$, max $L_{maxUpWin} = 16056 \text{ cd/m}^2$) window luminances for the upper clerestory windows (median and maximum values refer to statistical summary values of variables associated with subjective responses from polling stations, Table 2). Consequently, this finding (and predictive model) relating subjective assessments of discomfort with measured horizontal daylight illuminances is considered to be context specific. For example, one can speculate that the probability of discomfort for a given illuminance value may be related to the distance of the observer normal to the facade as well as interior surface reflectances which may reduce ambient daylight transmission to the core while increasing the luminance contrast of window views from core zones. It is recommended that designers implement luminance-based indicators of visual comfort to supplement horizontal

illuminance criteria when assessing annual daylighting performance in core zones where occupants have views of unshaded windows. This condition is increasingly common as designers seek to subdivide the facade into an upper daylight zone (often intended to remain unshaded) and a lower view zone with manually controlled shading (intended to provide greater control over visual comfort conditions to perimeter zone occupants).

This paper provides 15 single-variable probabilistic visual discomfort models that can be implemented in software simulation workflows to place quantitative data in context with subjective outcomes. The models can also be implemented directly into automated facade shading control algorithms to inform shade operation in response to the probability of occupant discomfort. These models, and the outcomes reported in this paper, are developed from analysis of a relatively small (N=14) sample of core zone occupants in a single daylit office building collected over predominantly clear sky conditions. Field data from additional building populations and climates is needed to validate and refine the probabilistic models developed through this research.

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