TOWARDS AN INTEGRATED FRAMEWORK FOR PREDICTING VISUAL COMFORT CONDITIONS FROM LUMINANCE-BASED METRICS IN PERIMETER DAYLIT SPACES

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ABSTRACT

The authors test 168 luminance-calibrated high dynamic range photographs with associated subjective user data against a set of plausible visual comfort metrics and identify metric thresholds at which discomfort can be consistently identified with minimal false-positives. Correlations were identified with vertical eye illuminance, DGI, DGP $5 * L_{task}$, max. window luminance and max. workplane luminance. These five metrics in combination, tested against a separate evaluation dataset consisting of 584 measurements, identify 65.2% of discomfort during periods where direct sunlight may enter the test room. The discussion identifies necessary aspects of future work in varied space types and consideration of the view of occupants.

INTRODUCTION

It is desirable to improve access to natural daylight and views in buildings. The presence of daylight in architectural spaces is thought to improve health, awareness and feelings of well-being; however, there may also be unintended consequences of increased daylight – visual discomfort. The research community has been attempting to quantify visual comfort issues for over eighty years with limited success, but the relatively recent ability to produce high quality luminance photographic measurements and renderings of spaces has led to promising developments in new visual metrics (Wienold and Christofferson, 2006; Moghbell, 2012; Jakubiec and Reinhart, 2014; Konis, 2014; Van Den Wymelenberg and Inanici, 2014).

Independent verifications of typical metrics used in research and practice are sparse (Painter, Fan and Mardaljevic, 2009; Jakubiec and Reinhart, 2012; Hirning, et al., 2013; Van Den Wymelenberg and Inanici, 2014). Most of these studies use a single comfort metric in their analysis. Van Den Wymelenberg (2012) found that using several metrics in a multiple regression model predicted subjective visual discomfort better than a single metric alone. Jakubiec and Reinhart (2013) noted, in a long-term survey and simulation study, that by investigating multiple visual comfort metrics, they were able to better resolve reported comfort compared to using a single metric.

Following those works, this paper analyses the ability of a range of comfort metrics to predict discomfort using a high quality dataset including luminance-calibrated High Dynamic Range (HDR) photographs, measured illuminance data and detailed subjective occupant evaluations from a sidelit perimeter space. The authors propose standardized methods for deriving the metrics. In the results section, threshold values of individual metrics are established in their ability to consistently identify negative subjective evaluations using a training dataset of 168 photographs. These thresholds are tested using a separate evaluation dataset of 584 measures.

METHODOLOGY

Data Source and Subjective Evaluations

A series of luminance-calibrated HDR photographs collected by Van Den Wymelenberg and Inanici (2014) are reanalysed in this paper. Two nearly identical side-by-side test office rooms located in Boise, Idaho, USA were used for the experiment. In one test room, detailed occupant surveys were carried out while the adjacent room contained instrumentation for capturing HDR photos, illuminance and luminance measurements from the point of view of the occupant in the first test room. Each HDR photograph was calibrated using a luminance measurement taken from a neutral grey card in the scene and has an accompanying measurement of vertical eye illuminance for secondary validation or calibration. The photographs were taken using a 180 degree fisheye camera lens. Vignetting correction was applied to each photograph in accordance with best practice, correcting photographic darkening further from the centre of the camera's view. The process of converting a series of photographs to measured HDR luminance images used in the collection is covered well by Inanici (2006). A typical HDR photographic capture is displayed in Figure 1.

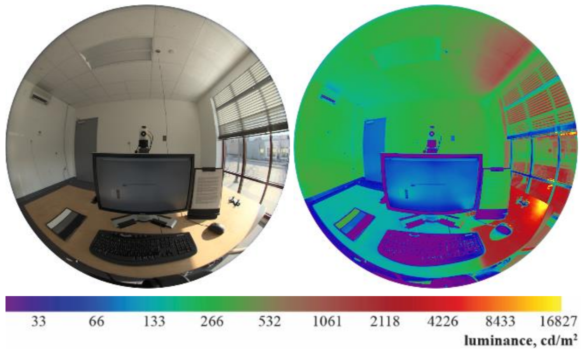


Figure 1 Example HDR luminance photograph captured in the instrumentation test room

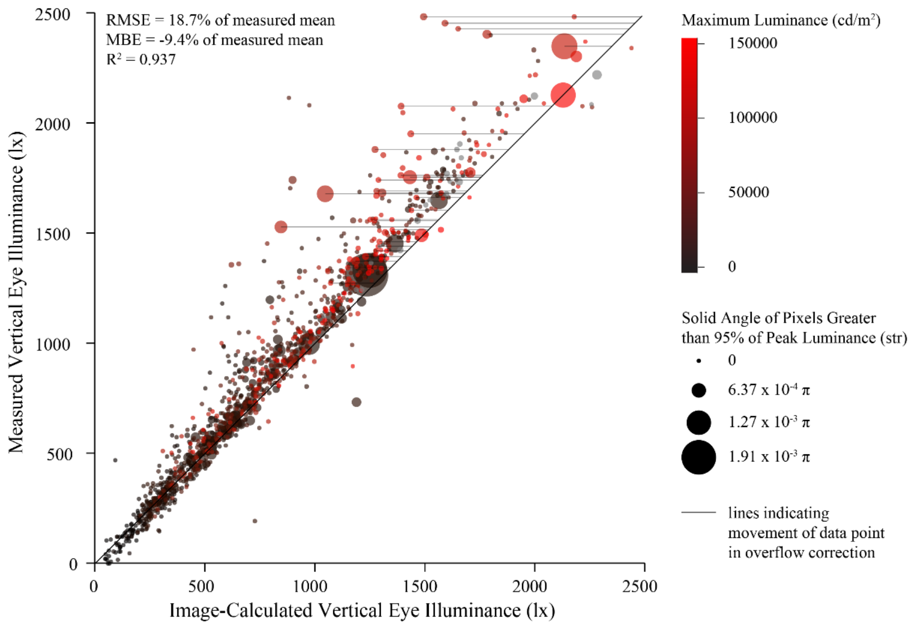


Figure 2 Measured and image-calculated vertical eye illuminances portrayed with identifying factors for luminous overflow

Forty-eight individuals participated in the experiment, which took place from June to December 2011. Each participant spent two days, one in summer and fall, evaluating 16 separate daylit conditions. Subjective statements regarding visual comfort were ranked by each occupant while experiencing each lighting condition. The authors are concerned with the subjective responses to the first statement, referred to as QU1 throughout the paper: "This is a visually comfortable environment for office work." This statement was rated on a seven point Likert scale where, **7** means Very Strongly Agree, **6** means Strongly Agree, **5** means Agree, **4** means Neither Agree nor Disagree, **3** means Disagree, **2** means Strongly Disagree, and finally **1** means Very Strongly Disagree (Van Den Wymelenberg and Inanici, 2014).

Measurement Accuracy and Correction

When capturing HDR photographs in daylit areas, it is likely for small but highly intense luminous peaks to emerge caused by direct capture of the sun or strong specular reflections. These peaks may be orders of magnitude higher than typical values for interior surfaces (~1-1000 cd/m^2) or large light sources such as diffuse portions of sky and luminaires (~3,500 cd/m^2). Considering that the sun may have a luminance of over a billion cd/m^2 on a clear day (Grondzik, et al., 2006), it is easy to imagine a condition where exposures cannot be taken 'fast' enough to accurately resolve these peaks. This inability to measure high luminances is known as luminous overflow – a condition where the dynamic range of the HDR photograph is not great enough to capture the true luminous range of the visual reality.

While the concept of luminous overflow is being studied further in a simultaneous effort, for this manuscript images with pixels having a luminance of at least 10,000 cd/m^2 that constitutes over 6.37 x 10^{-4} π str (~15 pixels) were considered to have the potential to experience overflow. If illuminances calculated from the hemispherical image are significantly lower than those measured by the illuminance sensor, then an image likely experiences overflow. Such images were corrected by adjusting pixels 95% and greater of the maximum photographically captured luminance bound to a higher value of luminance until the sensor-measured and image-calculated illuminance is equal. A manual review process was employed to ensure that only highly intense specular reflections and direct solar sources were corrected for overflow. Only 4.1 % of images analysed were found to be unambiguously in need of overflow correction.

It is reasonable to ask, how accurate are the original luminance-calibrated images? Figure 2 plots vertical eye illuminance calculated from the hemispherical image against measured vertical eye illuminance, which is used as a measurement validation. The colour of the points indicates the maximum original pixel brightness and the size of the points indicates the solid angle of pixels within the 95% overflow threshold. Horizontal lines indicate the movement of data points corrected for luminous overflow. Statistical measures describe photographs before overflow correction, excluding 8 extreme outliers. Overall the correlation between image-calculated and measured vertical eye illuminance is strong (R^2 = 0.937) with a RMSE of 18.8% of the mean measured illuminance. The image-calculated vertical eye illuminance values tend to be on average less than the measured value, especially at high vertical eye illuminances (MBE = -9.4% of the mean). This is consistent with the discussion regarding luminous overflow presented in this section.

Image-based Analysis Metrics

Sensor-measured vertical eye illuminance, discomfort glare calculations, the brightness of direct sunlight on the eye, the brightness of reflections from horizontal working planes and monitor contrast ratio, causes of visual discomfort, were collected.

Vertical Eye Illuminance (E_v, lx)

Vertical eye illuminance is measured directly from an independent sensor. The assumption in utilizing vertical eye illuminance is that with more light reaching the eye, experiencing discomfort is more likely.

Discomfort Glare (DGI, DGP 5 ∗ L_{task})

Discomfort glare is physical discomfort caused by extreme brightness, contrast or both. Contrast is defined as the weighted ratio of the size, location and brightness of glaring light sources in a field of vision when compared to a reference or task luminance. In this analysis, the Daylight Glare Index (DGI) (Hopkinson, 1972) and Daylight Glare Probability (DGP) (Wienold and Christoffersen, 2006) metrics are utilized to evaluate discomfort glare. Multiple studies have found (Painter, Fan and Mardaljevic, 2009; Hirning, et al., 2013) that in dim situations neither DGP nor DGI can resolve subjective visual discomfort, although Hirning also notes that contrast-based measures such as DGI work best in deep spaces (Hirning, et al., 2014). However, Van Den Wymelenberg et al. (2010, 2014) note that DGP consistently performs better than DGI in a perimeter space. Furthermore, Jakubiec and Reinhart (2012) showed that DGP is a robust metric and the least likely to give false comfort indications in a simulation-only study. The specific calculations of DGP and DGI are described in the above references. Essentially DGI is an assessment of pure contrast while DGP adds total brightness at the eye in order to work better in bright, perimeter spaces. Values of DGI and DGP greater than 24 and 0.40 respectively can be considered disturbing. In the calculation of DGP, glare sources are identified as being greater than five times the mean task luminance, and the result is denoted DGP 5 ∗ L_{task}. Figure 3 illustrates the task location used for this calculation.

Figure 3 Location and size of task position (in ***blue****)*

Direct Sunlight

Direct sunlight falling on the workplane or the eye directly is likely to cause discomfort. IES standard LM-83-12 states that horizontal illuminance from direct solar exposure over 1000 lux, as derived by running a simulation accounting for the direct solar beam alone, is a good indicator for visual discomfort (IESNA, 2012). Experience also shows that viewing the sun directly is uncomfortable. Using HDR photographs, luminance and therefore the intensity of direct light, can be directly measured. For this purpose, image masks are employed to collect maximum luminances originating from either the window (Figure 4A) or a horizontal working plane (Figure 4B).

Monitor Screen Visibility

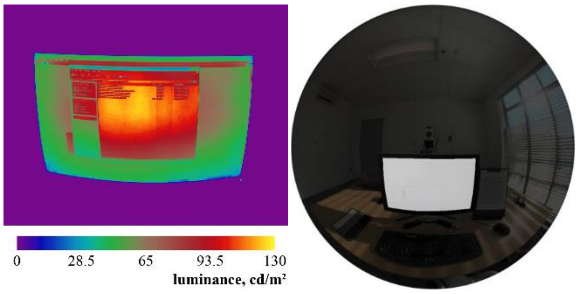
When light reflects from a monitor screen, the observable contrast between pixels is lowered. For specular screens, this problem is exasperated by veiling glare, when light sources are reflected in the monitor. The observable contrast ratio between bright (high state) and dark (low state) pixels can be calculated based on the amount of light reflected from a monitor as shown in Equation 1,

$$CR = \frac{L_H + L_r}{L_L + L_r} \qquad (1)$$

where L_H is the high state luminance, L_L is the low state luminance and L_r is the amount of reflected light. According to ISO standard 9241-3:1992 (ISO, 1992), contrast ratios above three are necessary to preserve readability. Later standards (ISO, 2008) suggest contrast ratios as high as four are necessary. In this study, L_H and L_L were measured from a HDR photograph taken in an otherwise dark test room with the monitor turned on and a screen of text displayed, shown in Figure 5A. L_r was estimated for each HDR image by subtracting L_H from the maximum observed pixel brightness within the monitor mask (5B).

A. Window mask **B**. Workplane mask

Figure 4 Image masks employed for direct sunlight analysis



A. HDR photograph **B**. Monitor mask

Figure 5 Luminance measurement and image mask used in monitor contrast ratio calculations

RESULTS

In this section, the individual comfort metrics for specific daylit test conditions (conditions C8 and C10) are tested against the QU1 subjective responses in order to identify measurable values at which reported discomfort is discernible. These results are then validated against the remaining test conditions where participants were asked to adjust shading systems to achieve a preferable or just uncomfortable lighting condition (conditions C1, C4, C5, C7, C11, C13, C14).

Establishing Probable Discomfort Thresholds

Of the sixteen conditions in Van Den Wymelenberg and Inanici's original dataset, four tasked the participants to adjust window shades in order to find a subjective 'just uncomfortable' lighting condition, and during five conditions participants were asked to create a 'most preferable' lighting condition. In separating the data into two halves for training and evaluating purposes, the authors utilize conditions C8 (most preferable) and C10 (just uncomfortable), which take place in the afternoon while direct sunlight may enter the test room. Neither condition utilizes electric lighting. Figure 6 plots a single objective parameter against each of the 168 C8 or C10 subjective responses to Likert question QU1. Recall that QU1 states, "This is a visually comfortable environment for office work." A subjective response of 7 is from a very comfortable individual capable of performing office tasks while a response of 1 is the opposite, one from an individual whose lighting conditions are uncomfortable enough to cause displeasure and negatively impact the ability to perform tasks. Therefore Figure 6 shows whether each measure is capable of resolving visual discomfort as experienced by study participants. Green points represent times where participants adjusted the blinds to achieve 'most preferable' conditions (C8). Red points represent times where blinds were adjusted to achieve 'just uncomfortable' conditions (C10). Black lines on the DGI, DGP $5 * L_{task}$ and maximum window luminance plots indicate changes in values that occurred in photographs adjusted for luminous overflow (14/168, 8.4 %).

Higher values of vertical eye illuminance contribute to a greater likelihood of discomfort (R^2 = 0.196). Van Den Wymelenberg and Inanici (2014) noticed, in an independent analysis of the dataset, that vertical eye iIlluminances below 1000 lx indicate comfortable subjective evaluations, while those over 1500 lx grow increasingly uncomfortable. This study notices the same, and illuminances between these two thresholds contain the entire subjective range of discomfort reported by occupants. No correlation was found between monitor contrast ratio as calculated and subjective comfort. The glare indices DGI and DGP $5 * L_{task}$ both notably correlate with reported comfort with R^2 values of 0.212 and 0.151 respectively. In the case of DGI, very few data points are above the metric-defined threshold of 24, indicating disturbing discomfort, and those that are have been adjusted for luminous overflow. The DGP results show a similar trend; the only data points above the defined threshold of 0.40 for disturbing discomfort have been adjusted for luminous overflow. This suggests that the DGI and DGP $5 * L_{task}$ metrics indicate discomfort for this scene primarily when direct sunlight or strong specular reflections are present and that their thresholds for detecting discomfort may be too high. Maximum window luminance, a proxy for direct sunlight on the eye, has a weak correlation with subjective discomfort in this case (R^2 = 0.093), and only overflow-corrected images clearly demarcate a discomfort threshold at 10^6 cd/m^2. Finally maximum luminance on the workplane, a proxy for direct sunlight, also correlates noticeably with subjective discomfort (R^2 = 0.208). For the typical range of vertical eye illuminances observed in this study (~500 to 2500 lx), workplane luminances greater than 1000 cd/m^2 consistently identify reported subjective discomfort. In the case of maximum workplane and window luminances, an analysis of the solid angle of the size of the sources over 1000 and 10^6 cd/m^2 respectively was performed in order to identify potential conditions where small solid angles of brightness give a false positive. There was no obvious threshold at which small sources caused false positives.

Overall, Figure 6 illustrates that no individual measure in this study fully explains subjective human comfort as each only identifies a subset of the reported discomfort. Vertical eye illuminances between 1000 and 1500 lx, which contain the entire range of reported discomfort, identifies a subjective range where some participants feel comfortable or uncomfortable at similar lighting levels. It seems likely that specific measures occurring within this range such as task visibility, discomfort glare or the presence of direct sunlight may aid the identification of uncomfortable scenes.

Testing Subjective Thresholds with Separate Data

The thresholds defined in the preceding section were identified using 168 HDR images during conditions C8 and C10, which always takes place in the afternoon when direct sunlight may enter the test room. These thresholds are now tested against other conditions (584 data points) in which participants were asked to find their 'just uncomfortable' or 'most preferable' lighting conditions. As the immediate goal of such analysis is to determine whether specific lighting conditions are comfortable or uncomfortable, the authors propose to split the subjective evaluations into two categories: those classified as negative (uncomfortable) with subjective responses < 4, or neutral to positive (comfortable) with responses ≥ 4. Figure 7 portrays the percentage of correct uncomfortable evaluations using each separate metric and threshold identified with the training data (Ev > 1500 lx, Max. Window Lum. > 10^6 cd/m^2, Max. Workplane Lum. > 1000 cd/m^2) or by previous research (DGI > 24, DGP $5 * L_{task}$ > 0.40). The data is portrayed across three time windows: the morning when the space is primarily lit by diffuse daylight, the afternoons when direct sunlight may be incident on the test room façade, and a total accounting of morning and afternoon conditions. In evaluating the results of Figure 7, it is useful to note that using the C8 and C10 condition calibration data from Figure 6,

- E_v > 1500 lx identifies 54.7 % of discomfort,
- DGI > 24 identifies 12 %,
- DGP $5 * L_{task}$ > 0.40 identifies 14.7 %,
- Max. Window > 10^6 cd/m^2 identifies 17.3 %,
- Max. Workplane > 1000 cd/m^2 identifies 44.0 %,
- and all metrics combined identify 61.3 %.

It is apparent that the identified metrics are not often able to identify reported subjective discomfort during the morning hours, with only 10 % of uncomfortable reports being correctly identified using vertical eye illuminance. However during afternoon periods where direct sunlight may enter the space, individual metrics combine to identify 65.2 % of reported discomfort. Vertical eye illuminance is most successful at identifying afternoon discomfort (55.1 %) followed by direct sunlight present on the workplane (34.8 %), direct visibility of the sun (20.4 %), DGI (10.1 %) and DGP 5 ∗ Ltask (8.7 %). These afternoon successes are in line with the training data values reported above.

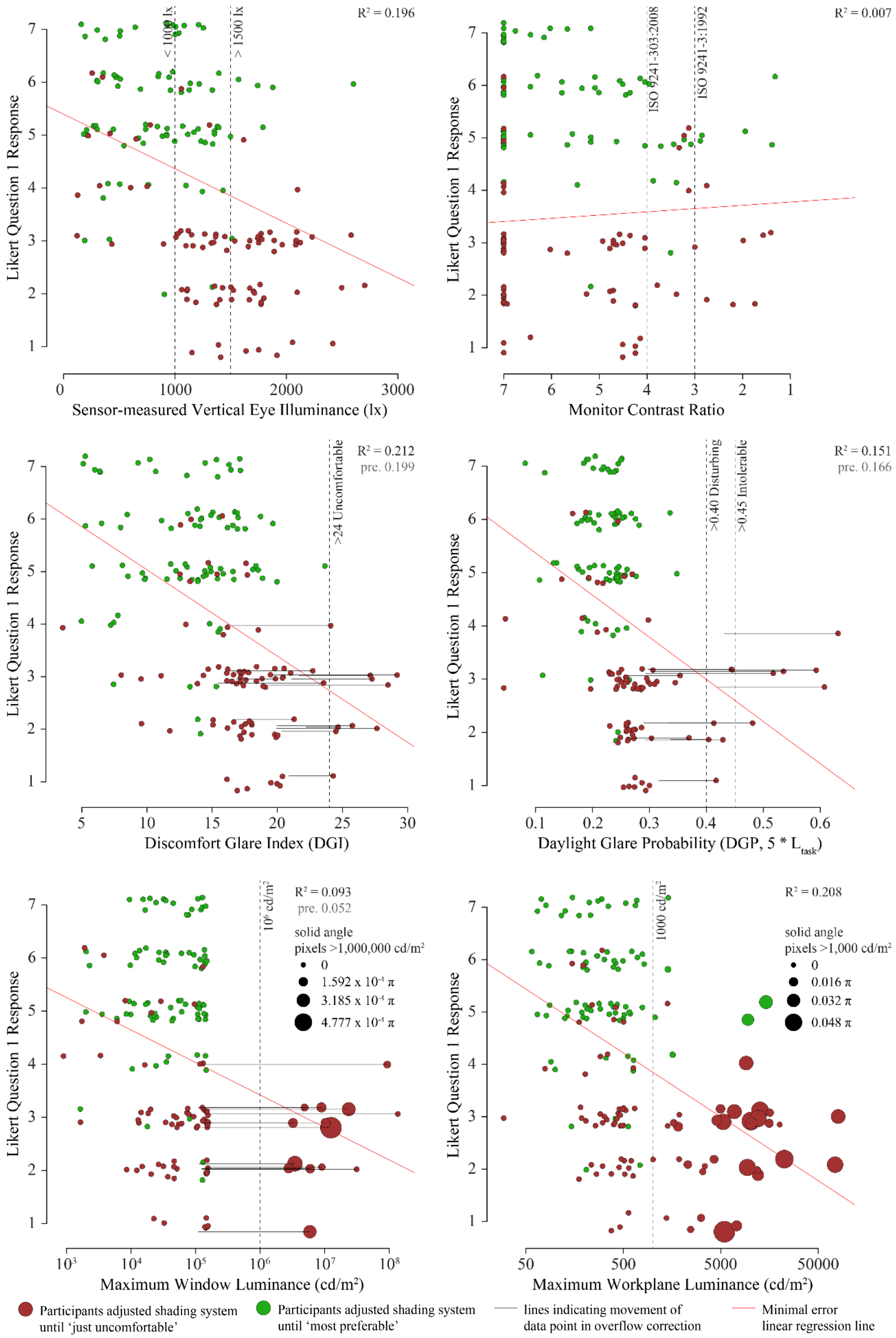


Figure 6 Single analysis metrics related to participant comfort evaluations for conditions C8 and C10 (training data set)

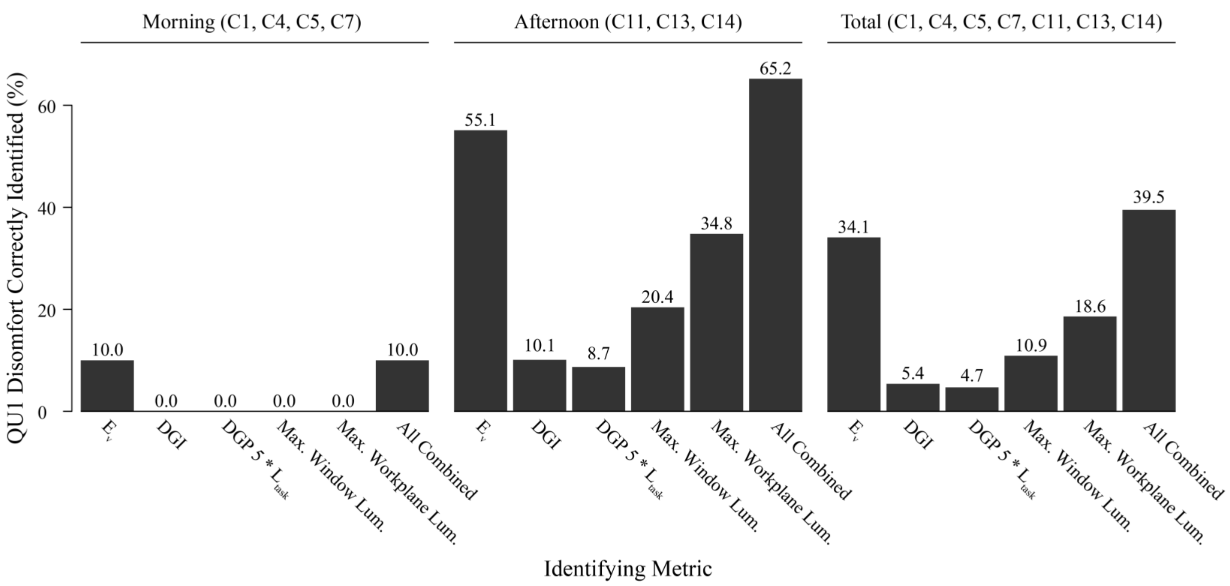


Figure 7 Percent of discomfort correctly identified in evaluation dataset

DISCUSSION

Many of the comfort thresholds investigated were meant to identify direct sunlight (maximum workplane luminance and maximum window luminance). Another metric, DGP, was derived using measurements during the two hours before and after the sun is perpendicular to the building façade under clear sky conditions (Wienold and Christofferson, 2006). One would also expect vertical eye illuminance to positively correlate with the presence of direct sunlight. It is hardly surprising that these measures identify discomfort more thoroughly in the afternoon data rather than the morning data. Experiencing visual discomfort is also more likely during these times. Unfortunately, employing morning data as the training set does not help to identify simple causes of the discomfort reported by participants during morning conditions.

What does this mean for the results of this study and for the ability to differentiate discomfort from comfort in both real and simulated environments? Brusquely, the simple measures tested in this study are not capable of resolving discomfort during diffusely lit morning periods. 60 % of participants experiencing morning discomfort indicated that they had trouble with legibility or veiling reflections on the computer screen. Clearly this is an aspect of visual comfort that the current analysis cannot resolve well. Reflections from a monitor are highly dependent on context: a human is not present behind the monitor in the measurements. They are also view-dependent: is the relationship between the camera in the instrumentation test room and the human in the other test room identical? These two issues make measuring monitor contrast somewhat difficult.

On the other hand, vertical eye illuminance, DGI, DGP, and strong luminances from the window and workplane are shown to be useful in identifying uncomfortable luminous circumstances in perimeter spaces. Most importantly, these discomfort indicators do not strictly occur at the same time as indicated by the results in Figure 7. In other words, discomfort may be caused by seeing the sun separately from luminous conditions that lead to unpleasant contrast. The identified metrics and thresholds have a broader application than to HDR photographic assessment of existing spaces. Many software platforms are capable of accurately simulating renderings with associated luminance information. The renderings from such programs are functionally identical to calibrated HDR photographs and can be analysed in the same manner. By applying the identified subjective thresholds to simulated spaces, it is possible to identify likely uncomfortable conditions in daylit spaces throughout the year and to address them before construction, potentially without the use of operable shading devices.

Coefficient of determination (R^2) values for single discomfort measures predicting subjective evaluations do not exceed 0.212, a low value; however, this result is in line with other studies (Van Den Wymelenberg and Inanici, 2013-14; Karlsen, et al., 2015). This is for several reasons. Because comfort is a personal and subjective criterion, there is a high degree of difference between participants leading to scatter. The authors have therefore sought thresholds where all participants were consistently uncomfortable rather than a correlation that identifies the extent of discomfort ranked between 1 and 7 on a Likert scale, which may only be achievable for a given, single individual. To predict ‘comfort’ or ‘discomfort’ in this Boolean manner seems within reach using this dataset and is a first step towards more nuanced results. Another reason for low R^2 values is that a single metric may not be suitable to identify all causes of discomfort. For example, high E_v values correlate with discomfort, but contrast-based glare is still likely to occur at lower illuminance levels.

Pursuit of a Single Visual Comfort Model

A goal shared by many researchers is to find a single model to explain subjective visual comfort. While discomfort glare indices such as DGI and DGP aim to achieve this, their results in evaluation studies are mixed, as noted in the introduction and methodology sections of this manuscript. The authors aim to understand how well a multiple linear regression model consisting of the calculated measures in Figure 6 may explain subjective evaluations during afternoon, brightly lit, conditions. The measures employed are: vertical eye illuminance, DGI, DGP $5 * L_{task}$, maximum window luminance and maximum workplane luminance. Contrast ratio was not included as it had no correlation with subjective reported discomfort. All afternoon data was included in producing and evaluating the regression model. Figure 8 plots the multiple linear regression model predictions against actual subjective responses, and Table 1 communicates the results and statistical significance of the regression. All metrics are statistically significant in the model – p-values are all below 0.001 or 0.01; however, DGP has a suspiciously positive model estimate when it is expected for higher values to be negatively correlated with reported comfort, that likely occurs because other model parameters (E_v, DGI) are strongly related to DGP. The R^2 coefficient for the regression is 0.279, higher than the single-parameter correlations portrayed in Figure 6.

The result of this model, despite its increased correlation, is however not necessarily better than treating individual metrics separately. For example, DGI (contrast) and vertical eye illuminance (brightness) can both cause discomfort, but weighing them together is not necessarily a benefit as each may occur independantly of the other. As a result, the regression model, even when setup and evaluated using the same dataset, can only identify 59.7 % of reported afternoon discomfort when setting the 'uncomfortable' threshold to a predictive value of <4 compared to 65.2 % using separate metrics. These results are little better than using vertical eye illuminance as the sole predictor of discomfort in this case. The regression model also minimizes predictive error by moving estimates closer to a neutral subjective value (4). Issues of personal subjectivity and scatter discussed previously with regards to R^2 values apply to this multiple-regression analysis as well.

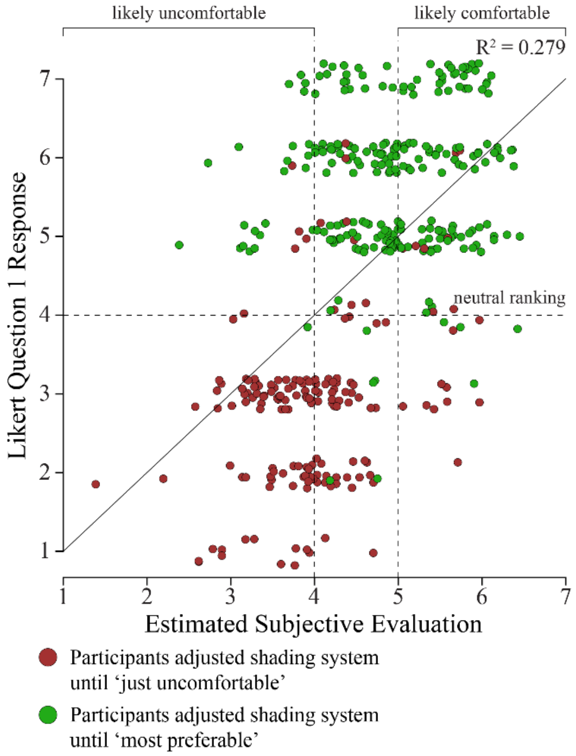


Figure 8 Regression model predictions compared to actual subjective responses for all afternoon data

Table 1
Multiple linear regression model coefficients

Name	Estimate	Std. Err.	t-value	Pr(>|t|)
Intercept	8.6978	0.6120	14.211	$< 2x10^{-16}$
Ev	-0.0008	0.0002	-3.469	$5.78x10^{-4}$
DGI	-0.1206	0.0274	-4.394	$1.42x10^{-5}$
DGP	11.3273	3.0965	3.658	$2.87x10^{-4}$
log_{10}(Max. Window)	-0.6346	0.1768	-3.590	$3.71x10^{-4}$
log_{10}(Max. Workplane)	-0.4538	0.1727	-2.627	$8.94x10^{-3}$

CONCLUSION

This paper uses a set of plausible metrics from practice and research to analyse a set of 168 HDR photographs of daylit interior office scenes with associated subjective user survey data and identify thresholds at which discomfort occurs. The results identify several subjective thresholds that indicate discomfort in the participant study:

- $E_v > 1500$ lx,
- Max. Window > 10^6 cd/m^2,
- and Max. Workplane > 1000 cd/m^2.

Furthermore, two more thresholds were extrapolated from existing research:

- DGI > 24,
- and DGP $5 * L_{task} > 0.40$.

Monitor contrast ratio as calculated did not correlate with subjective evaluations. Combined, the five thresholds correctly identify 65.2 % of subjective evaluations using a separate evaluation dataset of 584 measures when classified as negative (score < 4) or positive (score ≥ 4) on a seven point scale. The establishment of the above thresholds and proposed methods of image processing helps to evaluate instantaneous subjective visual comfort from HDR photographs as well as physically-based luminance renderings.

Future Outlook

This study is based on data from a sidelit space with the view direction parallel to the window while DGP was derived with view directions either perpindicular with the window or facing diagonally towards the window at a 45 degree angle. Multiple studies have found that neither DGI nor DGP are able to resolve occupant-reported subjective visual discomfort at least at typical 'disturbing' glare thresholds as defined by the individual metrics (Fan, Painter and Mardaljevic 2009; Hirning et al. 2013). Later, Hirning and colleagues concluded that DGI and other similar contrast-based discomfort glare measures (UGR) are the most correlated with subjective discomfort in open floorplans where vertical eye illuminance is relatively low compared to the conditions under which DGP was derived (Hirning, Isoardi and Cowling 2014). Konis (2014) found that simple contrast ratios predicted discomfort best in 'core' zones of buildings further than 6 m from the façade. These results suggest that occupants in interior spaces, close to the building façade, may experience visual discomfort dominated by total brightness and vertical eye illuminance while in less-bright areas contrast-based discomfort dominates. For these reasons, the authors suggest that similar studies in varied space types may prove useful. It is likely that full applicability for certain visual comfort measures may not be well understood until a more diverse variety of space types are investigated.

Beyond the desire to apply similar research methods to a variety of spatial types, consideration of view in visual comfort analysis is another important factor. Jakubiec and Reinhart (2012) noted that within a space, small changes in view can have a large effect on visual comfort metrics. Sarey Khanie and colleagues (2013) note that space occupants focus on different areas depending on task and lighting quality in a space, which influences discomfort glare metrics. Using the same dataset as this paper, Van Den Wymelenberg and Inanici (2014) found that the perceived brightness of a view towards the window rather than parallel to it correlated better with other subjective measures, leading them to propose an 'inverse adaptive zone' where the least comfortable view might be the most useful to consider when evaluating a design. In light of these studies, it seems necessary to consider view in both future research and simulation of visual environments.

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