

# THE EFFECT OF LUMINANCE DISTRIBUTION PATTERNS ON OCCUPANT PREFERENCE IN A DAYLIT OFFICE ENVIRONMENT

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**ABSTRACT:** *New research in daylighting metrics and developments in validated digital High Dynamic Range (HDR) photography techniques suggest that luminance based lighting controls have the potential to provide occupant satisfaction and energy saving improvements over traditional illuminance based lighting controls. This paper studies occupant preference and acceptance of patterns of luminance using HDR imaging and a repeated measures design methodology in a daylight office environment. Three existing luminance threshold analysis methods [method1) predetermined absolute luminance threshold (e.g. 2000 cd/m<sup>2</sup>), method2) scene based mean luminance threshold, and method3) task based mean luminance threshold] were studied along with additional candidate metrics for their ability to explain luminance variability of 18 participant assessments of 'preferred' and 'just disturbing' scenes under daylighting conditions. Per-pixel luminance data from each scene were used to calculate Daylighting Glare Probability (DGP), Daylight Glare Index (DGI), and other candidate metrics using these three luminance threshold analysis methods. Of the established methods, the most consistent and effective metrics to explain variability in subjective responses were found to be; mean luminance of the task (using method3;  $adjr^2 = 0.59$ ), mean luminance of the entire scene (using method2;  $adjr^2 = 0.44$ ), and DGP using 2000 cd/m<sup>2</sup> as a glare source identifier (using method1;  $adjr^2 = 0.41$ ). Of the 150 candidate metrics tested, the most effective was the 'mean luminance of the glare sources', where the glare sources were identified as 7\* the mean luminance of the task position ( $adjr^2 = 0.64$ ). Furthermore, DGP consistently performed better than DGI, confirming previous findings. 'Preferred' scenes never had more than ~10% of the field of view that exceeded 2000 cd/m<sup>2</sup>. Standard deviation of the entire scene luminance also proved to be a good predictor of satisfaction with general visual appearance.*

**KEYWORDS:** *daylight metrics, luminance based lighting controls, discomfort glare, occupant preference, high dynamic range.*

## **1 INTRODUCTION**

Successful daylight designs of office buildings can provide significant energy savings when properly integrated with daylight sensing electric lighting control systems. However, previous research shows that spaces [excepting large volume toplit spaces (McHugh et al., 2004)] designed to integrate daylight with electric lighting controls rarely produce the energy savings purported during design stages (Heschong et al., 2005). Discrepancies in realized savings are attributed to complicated specification, installation, and commissioning (Rubinstein et al., 1997; 1998), and are compounded by operational issues associated with suboptimal manual blind (or shade fabric) operation and user dissatisfaction, resulting in systems being disabled (Heschong et al., 2005). In fact, users that intentionally disable daylight harvesting systems account for over 70% of non-functional systems (Heschong, et al., 2005).

Commercially available electric lighting control systems are exclusively based upon illuminance, often measured at the ceiling plane looking toward the work plane as a proxy for desktop illumination. In general, illuminance-based metrics drive lighting design decisions and control system technology due to their predominance in professional standards (Rea, 2000), and the historic measurement limitations (including cost and accuracy) associated with luminance measurement. However, a literature survey on determinants of lighting quality (Veitch and Newsham, 1996) indicates that illuminance is important for visual performance only at extremely low levels; and it does not significantly affect the task performance over a wide range of illuminance levels and varieties of tasks. On the other hand, visual performance studies (Blackwell, 1959; Boyce, 1973; Rea and Ouelette, 1991) and visual comfort metrics such as Daylight Glare Index (DGI) (Hopkinson, 1972; Chauvel et al., 1982) and Daylight Glare Probability (DGP) (Wienold and Christoffersen, 2006) establish a relationship between luminance, comfort, and visibility. Contemporary office occupants spend a significant amount of time working on vertical tasks (computer monitors) rather than paper-based horizontal tasks. Therefore, it stands to reason that occupant preferences in office settings can be better predicted by patterns of luminance in the vertical visual field than by horizontal illumination. As a result, luminance-based lighting and shading control systems can potentially improve user satisfaction over traditional illuminance-based systems while also increasing energy savings. Unfortunately, there is not enough information available about human acceptance and preference with regard to luminance metrics in daylight settings.

With the developments in digital High Dynamic Range (HDR) photography (Debevec and Malik, 1997; Reinhard et al., 2005) and its validated technique (Inanici, 2006) for collecting luminance data, it is possible to analyze complex datasets and correlate luminance distribution patterns with user preference. Single quantities, whether they are luminance or illuminance measures, are not very informative about the quantitative and qualitative dynamics of

lighting across an entire space. High-resolution luminance mapping techniques provide much more information about a luminous environment than a limited number of illuminance or luminance measurements.

Recent studies with luminance mapping techniques incorporate a threshold luminance value, where exceeding values are likely to cause occupant discomfort. These studies can be grouped into three areas as follows:

1. *Predetermined absolute luminance threshold*: An acceptable luminance threshold is set as a predetermined value. A recent study (Lee et al., 2007) used  $2000 \text{ cd/m}^2$  as the threshold value for the mean luminance of the unobstructed portion of the window wall. In this research, the threshold value was used to control an automated roller shade system in an open plan office space to limit direct sun and window glare while providing an adequate amount of daylight and view to the outdoors.
2. *Scene based mean luminance threshold*: Mean luminance values are calculated in a large field of view (hemispherical fisheye lenses allow data collection in  $180^\circ$  horizontally and vertically), and the discomfort threshold is determined as the multiplication of the mean scene luminance with a constant. RADIANCE 'findglare' tool (Ward, 1992) adopts this method and the default constant is 7. A mean luminance value (mL) in a scene yields to a luminance threshold of  $7 \cdot \text{mL}$  (i.e. luminance values above  $7 \cdot \text{mL}$  are identified as potential glare sources). Different glare indices, including DGI, are calculated based upon the brightness, location, and apparent size of the glare sources and the background luminance for a particular viewpoint.
3. *Task based mean luminance threshold*: Mean luminance is calculated in the task area, and the threshold is determined as the multiplication of the mean task luminance with a constant. A recent glare metric, DGP utilizes this method (Wienold and Christoffersen, 2006), whereby the threshold value is 5 times the mean task luminance by default (Wienold, 2008). In this research, psychophysical experiments were conducted on 70 subjects under varying daylight conditions in a private office and 349 unique scenes resulted in a squared correlation coefficient of 0.94 for DGP as compared to 0.56 for DGI. The researchers also developed a daylight glare evaluation software tool called 'evalglare' that can be used with HDR images.

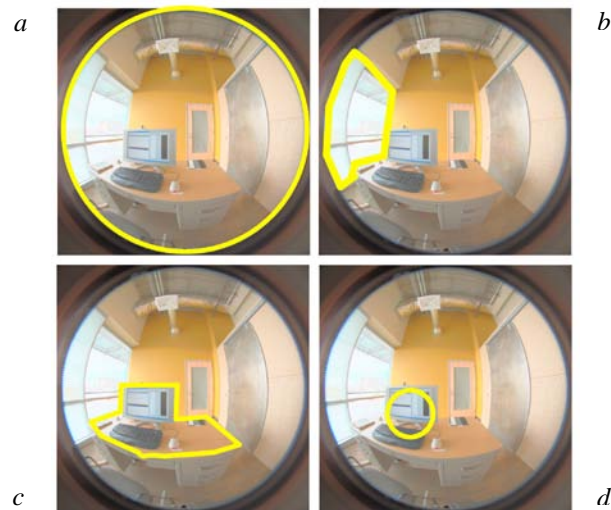


Figure 1: (a) Scene based mean luminance threshold area, (b) predetermined absolute luminance threshold area, (c) task area defined as [desk+monitor], (d) task position defined as a subtended solid angle encompassing the screen and keyboard.

In a simple daylight setting, Howlett et al. (2007) proposed a framework for other luminance-based metrics and assessed their temporal and spatial stability. Additionally, Newsham et al. (2008) tested other measures with a group of 40 subjects in a ‘glare-free’ office laboratory with low daylight levels (glass 0.20 visible transmittance) to determine which explained the greatest proportion of lighting preferences. Sarkar et al. (2006, 2008) have demonstrated applications where small cameras collect HDR information and control electric lighting systems in architecturally stable environments. Newsham and Arsenault (2009) used cameras to test several control schema for electric lights (dimming and occupancy sensing) and motorized louver blinds for short periods (2+ days each). Fan et al. (2009) advocated the use of HDR imaging techniques in real world working environments as a long term data collection method.

The research outlined above marks the beginning of a new generation of luminous field control system and metrics research while several important issues remain unresolved. These include concerns regarding occupant privacy with cameras in the workplace, technical challenges associated with physically positioning cameras to adequately control lights and shades (even in simple private offices, not to mention open office applications or other more complex settings), questions about economic feasibility of such systems so that market uptake is possible, and perhaps most importantly a lack of foundational human factors research to support both design metrics and control algorithms. The aim of this paper is to advance the area of human visual preference analysis while maintaining the work within the contexts of integrated electric lighting and shade control systems, and building design performance analysis metrics. The paper explores methods for analyzing and evaluating the luminance quantities and distribution patterns in an office space under daylight conditions without the presence of electric lighting. Illuminance based measures are reported for reference and comparison to luminance measures. The three unique luminance threshold methods described above are analyzed in connection with occupant preferences. Sensitivity analysis of thresholds is reported and new candidate luminance based metrics are reviewed.

Accurate predictions of occupant preference under daylight conditions with validated metrics and thresholds will progress the design industry in two significant ways. First, it will help designers make more informed choices among the candidate design solutions, and therefore, improve the quality of daylighting in buildings. Second, it has the potential to significantly propel lighting and shading controls beyond traditional illuminance measures, and therefore, better optimize energy savings while accommodating user preference.

## 2 METHODOLOGY

### 2.1 Research Setting

The research involves collection of large field of view luminance maps and illuminance measurements along with questionnaire data in order to study occupant visual preference and acceptance thresholds in an office space under daylight conditions. The research setting (Fig. 2) is a 3.5m x 4.5m (~16 m<sup>2</sup>) private office with a southwest facing window (33° from true South) exposure in Boise, Idaho (43° N and 116° W).

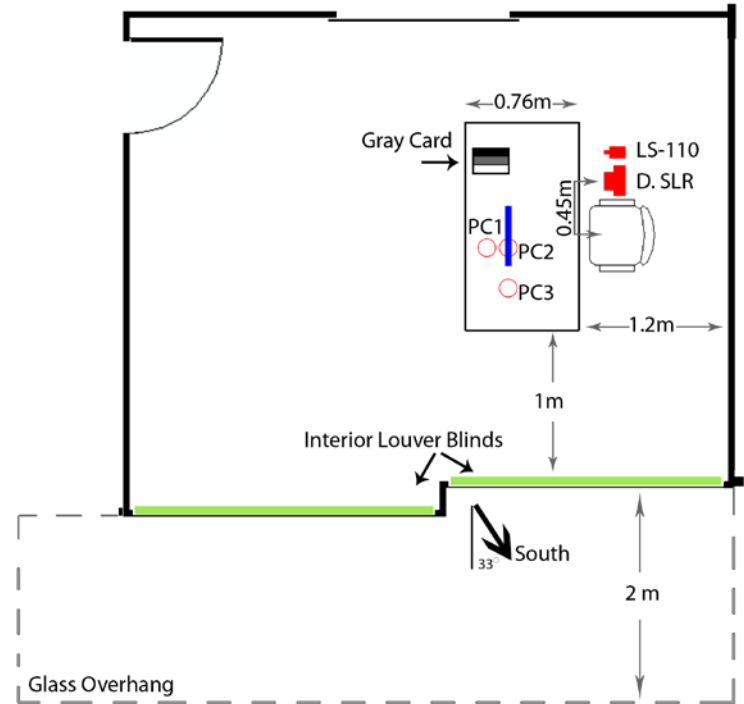


Figure 2: The research setting, (left, Fig. 2a) photograph of room looking southwest, (right, Fig. 2b) plan diagram of room.

The experiment was conducted on December 16<sup>th</sup>–17<sup>th</sup> between 11:30-16:00. Sky conditions varied from sunny to cloudy, bright with haze, and full overcast during data collection. The windows are double-glazed clear (0.65 visible light transmission) with aluminum frames and extend from the floor to 3m, and span 3.8m from wall to wall. The window has two independent interior mounted 5cm white lover blinds with lift cords and tilt wands for manual control. Electric light sources were not present in the room during the experiment.

One rectangular desk measuring 1.52m x 0.76m was positioned approximately 1m away from the window wall. The seated occupants faced a yellow painted wall (west wall). Reflectances in the room were as follows; west wall 0.36, north wall 0.38, east and south walls 0.89, floor 0.27, and desk 0.41. A 0.53m (diagonal screen dimension) LCD computer monitor (max screen luminance measured as 255 cd/m<sup>2</sup>) was set on the desk perpendicular to the window wall. The desk also had a traditional keyboard and mouse for computer control, a low gloss magazine, a X-rite ColorChecker© Gray Scale Balance Card positioned at the back edge of the desk mounted on the work surface, and a Li-Cor 210 SA Photometric Sensor. Additional photometric sensors were placed on the top of the monitor pointed toward the ceiling, on a supply air diffuser mounted 3m above the floor pointed downward toward the desk surface (similar to a typical photocell location), and on the roof of the building with an unobstructed view of the sky.

### 2.2 HDR Image Calibration

A HDR photography technique (Debevec and Malik, 1997) was used to collect luminance data in a large field of view (180° horizontally and vertically). A Canon EOS-1 Ds Mark III Digital SLR camera with a Sigma 8 mm F3.5 DG Circular Fisheye lens was positioned in the plane of the participants' eyes with a 0.45 m offset (measured from center of lens to center of eyes) from the seated participant. This camera was used to collect multiple exposure sequences and was fixed in place throughout the entire study. Each exposure captured a different luminance range and the exposure sequences were assembled into an HDR image using computational methods (Ward, 2009). The camera was calibrated through a self-calibration algorithm. Fisheye lens vignetting (i.e. light falloff of pixels far from the optical axis) was determined and corrected through image post processing, and each scene was spot calibrated using a gray card value captured with a Minolta LS-110 Luminance Meter. The resultant HDR photograph is an accurate luminance map of the scene, where pixel quantities closely correspond [less than 10% error (Inanici, 2006)] with

physical quantities of luminance (in  $\text{cd}/\text{m}^2$ ). Luminance error was found to be within this range in this study as well.

### 2.3 Participants

The participants were architecture students at the University of Idaho. Eighteen participants (7 female and 11 male) completed basic computer activities during the period of study for a duration between 20-30 minutes. Participant ages ranged from 18-39 years and the mean age was 25 years. No participants had any color blindness, 28% wore corrective glasses and 17% wore contact lenses (self reported).

### 2.4 Experimental Design

This study used a repeated measures design whereby each participant manipulated blind height and tilt for both blinds to modify the amount and distribution of daylight such that they determined the scene to be the ‘most preferable’ (‘P’) and ‘just disturbing’ (‘JD’) lighting condition from their seated position for the primary purposes of computer work, under the prevailing sky condition. Participants completed an online survey and were provided with a magazine in order to be able to determine appropriate lighting for both computer and paper tasks. Participants were instructed to consider ‘JD’ glare as less than ‘intolerable’ but more than ‘noticeable’ glare; and it is regarded as the point at which they would correct the situation (i.e. adjust the blinds) if it occurred naturally.

Before each participant entered the office, the blinds were fully retracted. To begin the experiment the participant entered the office, completed the required human subject’s consent form, and then watched a simple demonstration of how to manually adjust both blind height and louver tilt. The participants then logged onto an online survey tool and were given brief verbal instructions of how to complete the study. The participants began the study and were prompted by the survey tool to leave the room (for approximately two minutes) during the multiple exposure photograph sequences that were later assembled into HDR images. The multiple exposure sequences were taken immediately after the participants had adjusted the blinds to either their ‘P’ or ‘JD’ setting and had completed the short lighting preference online questionnaire. After each exposure-bracketed sequence was completed, the participants were prompted to re-enter the room and continued with the study. In order to minimize bias, the survey tool randomized the sequence instructing participants to create their ‘P’ and ‘JD’ scenes. Figure 3 demonstrates the scenes that are defined as ‘JD’ or ‘P’ by one of the participants.

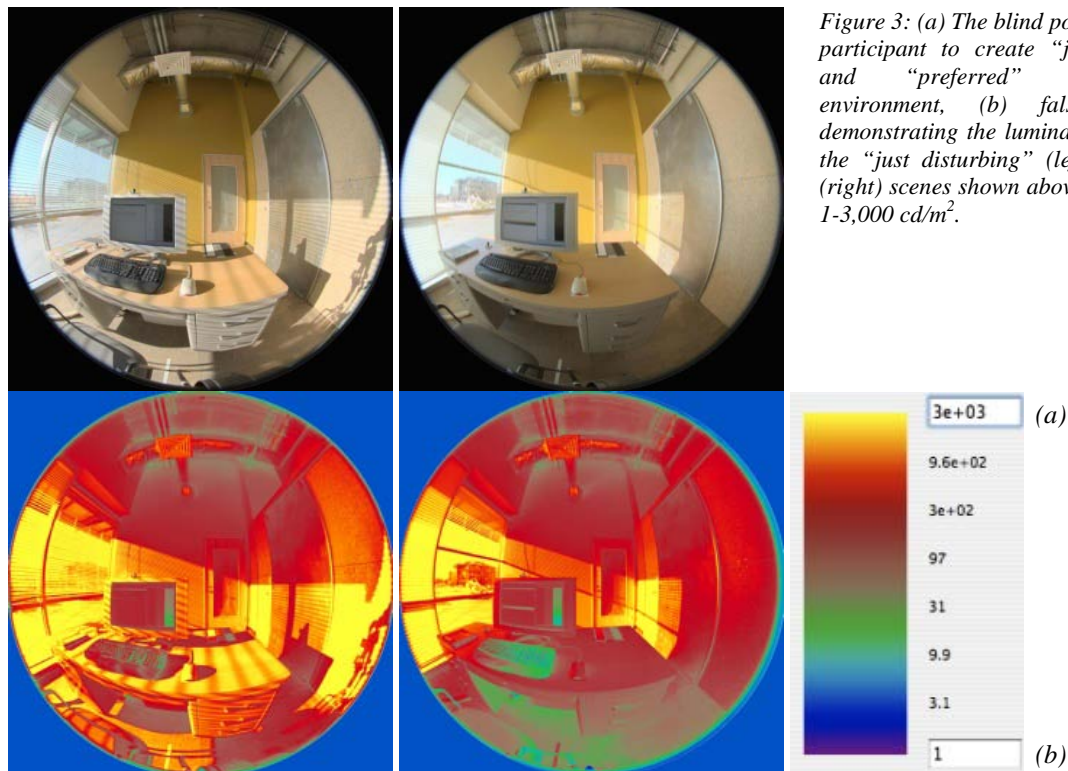


Figure 3: (a) The blind positions adjusted by a participant to create “just disturbing”(left) and “preferred” (right) luminous environment, (b) false color images demonstrating the luminance distributions for the “just disturbing” (left) and “preferred” (right) scenes shown above. The scale is from 1-3,000  $\text{cd}/\text{m}^2$ .

Over the course of the two-day study, several different combinations of sky condition and blind position were recorded resulting in a data set with 18 ‘P’ and 18 ‘JD’ scenes. The online survey tool recorded participants’ visual preference for each scene as well as the extent to which the subjects were able to create a ‘JD’ visual environment. All subjects strongly agreed or very strongly agreed that they were able to create a ‘P’ setting, while due to weather conditions, four participants were not absolutely confident with their ability to create a ‘disturbing’ environment. There were also four participants that experience greater than a 15% difference in outdoor illumination levels between the two settings. These phenomena are expected in daylighting research and therefore, all data were included in analysis.

### 2.5 Questionnaire Items

Six Likert scale questionnaire items were repeated for the ‘JD’ and ‘P’ scenes. Each item is presented as a statement and the participants rated their level of agreement with each statement for both scenes they created. Table 1 lists the question items and response scale.

Table 1: Likert Scale Items and Participant Response Scale

Likert Scale Items
Q01 - I am pleased with the visual appearance of the office
Q02 - I like the vertical surface brightness
Q03 - I am satisfied with the amount of light for computer work
Q04 - I am satisfied with the amount of light for paper based reading work
Q05 - The computer screen is legible and does not have reflections
Q06 - The lighting is distributed well
<b>Response Scale:</b> 7=Very Strongly Agree, 6=Strongly Agree, 5=Agree, 4=Neither Agree or Disagree, 3=Disagree, 2=Strongly Disagree, 1=Very Strongly Disagree

## 3 RESULTS

HDR photographs and illumination data were analyzed for all 36 cases (18 participants x 2 scenes) in order to determine which candidate metrics best explained the relationships among occupant preference ratings and daylight patterns in the office space. Candidate metrics were initially screened for their ability to differentiate ‘JD’ and ‘P’ scenes using paired t-tests. Each metric was also individually tested with a standard least squares model of fit to each questionnaire item. The adjusted correlation coefficient squared ( $_{adj}r^2$ ) values can be used to estimate the proportion of the variation in the participants’ response (to each questionnaire item) around the mean that can be attributed to terms in the model rather than to random error. The  $_{adj}r^2$  values were used to rank candidate metrics regarding their ability to predict user response.

### 3.1 Illumination and Sun Penetration Measures

Table 2 reports the descriptive statistics of the illumination data gathered for all 18 participants, as well as the responses to the questionnaire items for both ‘JD’ and ‘P’ cases. Not surprisingly, an extremely wide range of desktop illuminance levels for both ‘P’ (214 - 20,144 lux), and ‘JD’ (743 - 21,334 lux) cases were found. The vertical illumination measured at the camera near the seated participants’ eye position (E\_Veye) and the horizontal illumination at the top of the monitor (E\_monitor) produced  $t < 0.01$  while the desktop illumination (E\_desk) produced  $t < 0.05$  when testing the ability of each metric to differentiate between ‘JD’ and ‘P’ scenes. The responses to question three (QU3) correlated best with E\_monitor ( $_{adj}r^2 = 0.467$ ), E\_desk ( $_{adj}r^2 = 0.384$ ), and E\_Veye ( $_{adj}r^2 = 0.344$ ) in the given order. The responses to QU5 correlated best with E\_Veye ( $_{adj}r^2 = 0.346$ ). The illumination at the ceiling (E\_ceiling) is statistically incapable of differentiating between ‘JD’ and ‘P’ scenes and ranks consistently as the poorest measure for predicting occupant satisfaction for all questions. Figure 4 contrasts the illumination values associated with ‘JD’ and ‘P’ scenes for both E\_monitor and E\_ceiling. Figure 4a reveals a marked separation between the E\_monitor values for ‘JD’ scenes and ‘P’ scenes, whereas data for E\_ceiling in Figure 4b is far less discreet.

Avoiding direct sun penetration is a commonly used rule pertaining to visual comfort in office environments. It is interesting to note that 11 of 12 subjects that participated in the experiments under either sunny or partly sunny sky

conditions chose to introduce some amount of direct sun into the office for the ‘P’ cases. This outcome agrees with previous research (Boubekri and Boyer, 1992), which argues that possible cheering and pleasant effects of sunlight exposure increases glare tolerance.

Table 2 - Descriptive Statistics for illuminance measurements (a) and questionnaire responses (b).

	a. Illumination Measures (lx)					b. Questionnaire Items					
	E_Veye	E_Monitor	E_Desk	E_Ceiling	E_Outdoor	QU1	QU2	QU3	QU4	QU5	QU6
Median JD	2475	2782	4817	2612	31564	4	4	5	5	4	4
Median P	1174	1519	2070	1487	33552	6	6	7	6	7	5
Mean JD	2155	5478	7888	2203	30498	3.9	3.9	4.2	4.1	4.2	3.6
Mean P	1365	1798	3623	1897	31215	6.1	5.7	6.4	5.5	6.5	5.6
Max JD	3783	17267	21334	3902	52368	7	7	7	7	7	6
Max P	2495	10528	20144	3762	47137	7	7	7	7	7	7
Min JD	229	457	743	251	7865	1	1	2	2	1	1
Min P	136	180	214	251	9121	5	3	5	1	5	3
StdDev JD	1237	5518	7075	1379	11893	1.6	1.7	1.4	1.6	1.7	1.6
StdDev P	1287	2257	5344	1253	11772	0.7	1.0	0.7	1.6	0.7	1.0

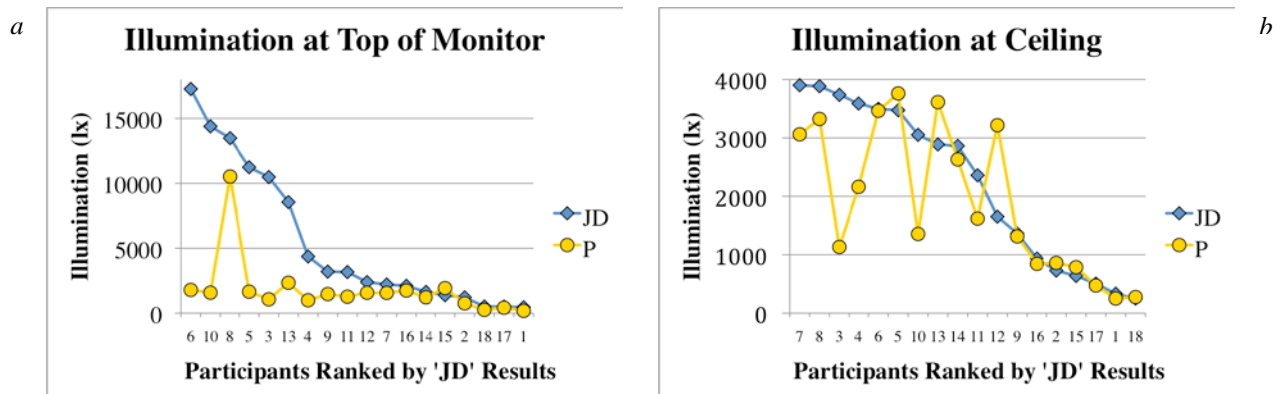


Figure 4 – (a) the illumination on top of the monitor, (b) the illumination measured near the ceiling in a common photocell location.

### 3.2 Predetermined absolute luminance threshold

Predetermined luminance values (100, 200, 500, 1000, 2000, and 3000 cd/m<sup>2</sup>) were studied for their ability to explain the variance of ‘P’ and ‘JD’ scenes. It is interesting to note that all luminance thresholds tested were statistically able to differentiate between ‘P’ and ‘JD’ scenes (paired  $t < 0.01$ ). Somewhat surprisingly, there were only small differences in  $adjr^2$  values for threshold values 500, 1000, 2000 and 3000 cd/m<sup>2</sup> when compared to the Likert question items. As expected, low luminance values of 100 and 200 cd/m<sup>2</sup> produced substantially lower  $adjr^2$  values. Question 3 showed consistently higher  $adjr^2$  values than other questions. Figure 5a shows that all “P” scenes have less than ~10% of pixel values that exceed 2000 cd/m<sup>2</sup> and Figure 5b shows a similar result at less than 7% of pixel values that exceed 3000 cd/m<sup>2</sup>. As expected, there is wide variability between subjects. Yet, the percentage of pixels exceeding a particular luminance threshold value can be distinguished for the analyzed office under the studied lighting conditions, above which only ‘JD’ scenes occur (~10% at 2000 cd/m<sup>2</sup>). However, below the threshold there is a mix of ‘P’ and ‘JD’ scenes. Therefore, it is not possible to set a simple binary threshold to differentiate ‘JD’ and ‘P’ scenes. The percent of the scene that exceeds 2000 and 3000 cd/m<sup>2</sup> is consistent within subjects, in that a ‘JD’ scene set by a given participant has a percent of pixels exceeding the threshold than the ‘P’ scene set by the same participant. The only exception is participant 12 where the outdoor illumination dramatically increased between the ‘JD’ and ‘P’ scenes.

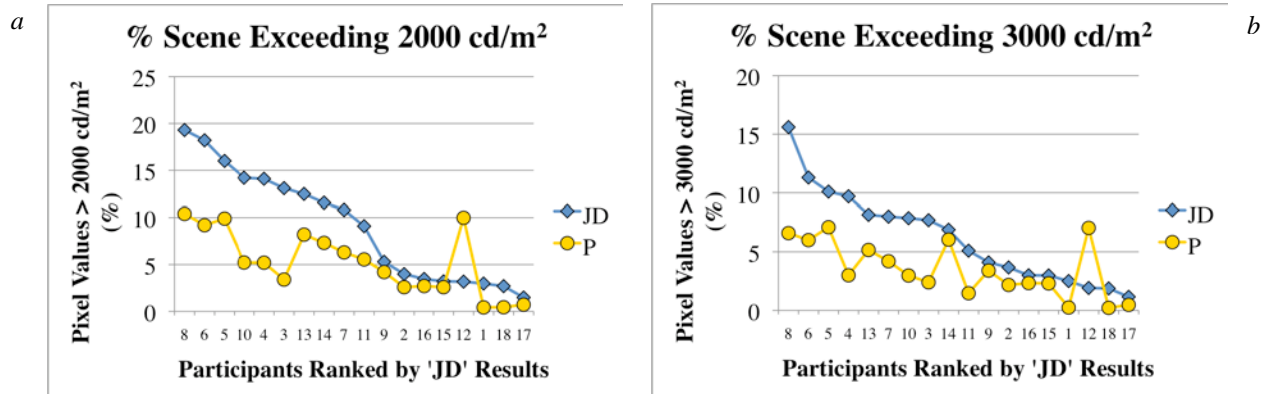


Figure 5: Percentage of pixel values that exceed a predetermined luminance threshold value of 2,000  $\text{cd/m}^2$  (a), and 3,000  $\text{cd/m}^2$  (b).

In addition to testing the percent of scene pixel values that exceeded absolute luminance thresholds, several tests related to glare algorithms using absolute luminance values to identify glare sources were conducted. Detailed reporting for statistical results for DGI and DGP are provided in Table 3. Sensitivity analysis was conducted to determine which absolute luminance values used to identify glare sources were more effective at differentiating between ‘P’ and ‘JD’ scenes and to explain the variability within subjective questionnaire responses. Given the statistical results of the percent of scene pixels exceeding the luminance thresholds that was just described, a different range of absolute values was tested with regard to glare source identification for use with glare algorithms. We tested 500, 1000, 2000, 3000  $\text{cd/m}^2$  again for glare source identification, and added 4000  $\text{cd/m}^2$  as another threshold.

Table 3 shows that the single best predictor of participant satisfaction (relative to all questions) is typically the DGI values derived from the glare source identification threshold of 500  $\text{cd/m}^2$ . However, if more attention is paid to QU3, then 2000  $\text{cd/m}^2$  is a strong candidate. In fact, the  $\text{adj}R^2$  values for any given question with DGI at various luminance thresholds are markedly different. However, for DGP, the single best predictor of participant satisfaction (relative to all questions) is typically the DGP values derived from the 2000  $\text{cd/m}^2$  glare source identification threshold (Fig. 6), but the differences in the  $\text{adj}R^2$  values are arguably negligible.

Table 3 – Statistics of DGI and DGP using glare source identification of various absolute luminance values. Values in bold represent the strongest  $\text{adj}R^2$  values for each question, ignoring values below 0.10.

	From 'findglare'					From 'evalglare'				
	dgi500	dgi1000	dgi2000	dgi3000	dgi4000	dgp500	dgp1000	dgp2000	dgp3000	dgp4000
Paired t - Prob >  t	< 0.01	0.0114	< 0.01	0.0187	0.0203	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
$\text{adj}R^2$										
QU1	<b>0.121</b>	0.096	0.076	0.005	-0.006	0.173	0.166	0.176	<b>0.178</b>	0.173
QU2	<b>0.133</b>	0.094	0.079	-0.012	-0.022	0.200	<b>0.179</b>	<b>0.179</b>	0.174	0.160
QU3	0.251	0.228	<b>0.255</b>	0.132	0.127	0.398	0.403	<b>0.408</b>	0.399	0.390
QU4	0.026	-0.013	-0.017	-0.019	-0.023	0.046	0.041	0.037	0.032	0.026
QU5	<b>0.269</b>	0.206	0.158	0.077	0.078	0.400	0.395	<b>0.406</b>	0.401	0.390
QU6	<b>0.215</b>	0.120	0.061	-0.012	-0.004	<b>0.240</b>	0.214	0.210	0.212	0.204

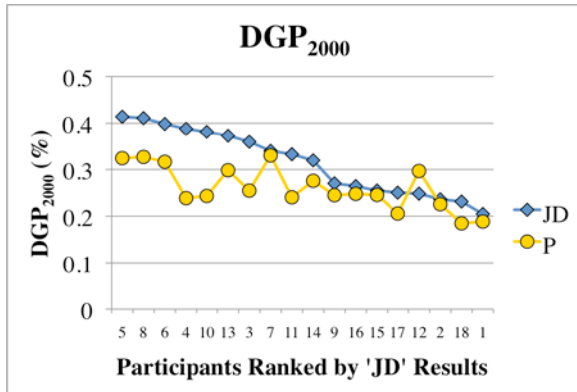


Figure 6: DGP<sub>2000</sub>

### 3.3 Scene based mean luminance threshold

Figure 7 illustrates each scene's mean luminance ranked in descending order by 'JD' results. The mean luminance threshold metric is consistent within subjects (paired- $t < 0.01$ ). A one-way threshold for mean luminance of the scene can be identified at  $\sim 800$  cd/m<sup>2</sup>. This metric produced a relatively strong  $adjt^2$  value (0.44) with Question 3 (QU3).

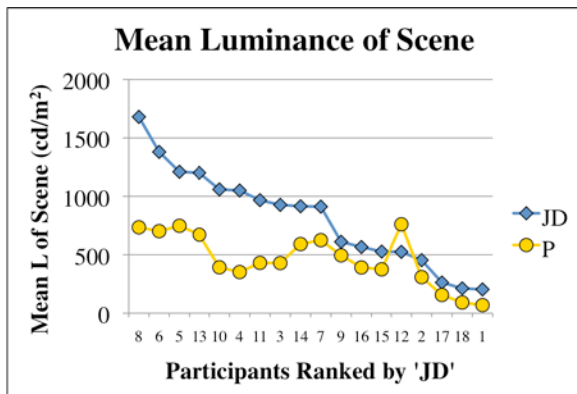


Figure 7: Mean luminance (cd/m<sup>2</sup>) for each scene ranked in descending order based upon 'JD' results.

The percentage of pixel values that exceed 7\*mL for each scene is illustrated in Figure 8. A higher percentage indicates potentially a larger area of glare sources within the scene. This metric proves to be inconsistent (and statistically insignificant), in that several data sets have a higher percentage of pixel values that exceed 7\*mL for "P" than for "JD" scenes.

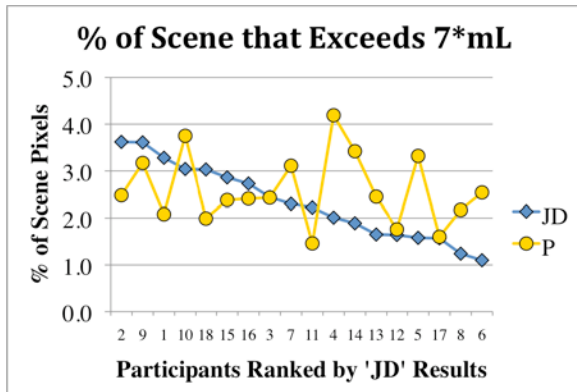


Figure 8: Percentage of pixel values that exceed the threshold of '7 times the mean scene luminance'

RADIANCE 'findglare' identifies glare sources as a multiplier of scene mean luminance. Once identified, the glare sources are input to glare algorithms including DGI. Figure 9a shows the results of the default 'findglare' output for DGI. According to Hopkins (1972) and Chauvel et al. (1982), DGI values of 28 are 'just intolerable', of 25 are 'just uncomfortable', of 19 are 'just acceptable' and of 16 are 'just imperceptible'. As the graph shows, the results of this investigation are not well explained by DGI with sources identified by 7\*mL. In fact the data from 'JD' and 'P' scenes are not significantly different (paired- $t = 0.67$ ). DGP can also be calculated using the scene's mean luminance value. In 'evalglare', when no task position is given, the mean luminance of the scene is referenced in order to identify glare sources. Figure 9b shows the improved ability of DGP 7\*mL to differentiate between 'JD' and 'P' scenes (paired- $t < 0.01$ ). Sensitivity analysis was conducted for DGP calculations to determine whether different glare source identification multipliers (3\*mL, 5\*mL, 7\*mL, or 10\*mL) could produce improved squared correlation coefficients with respect to each question. The multiplier that produced the highest  $adjr^2$  value for all questions was DGP 10\*mL.

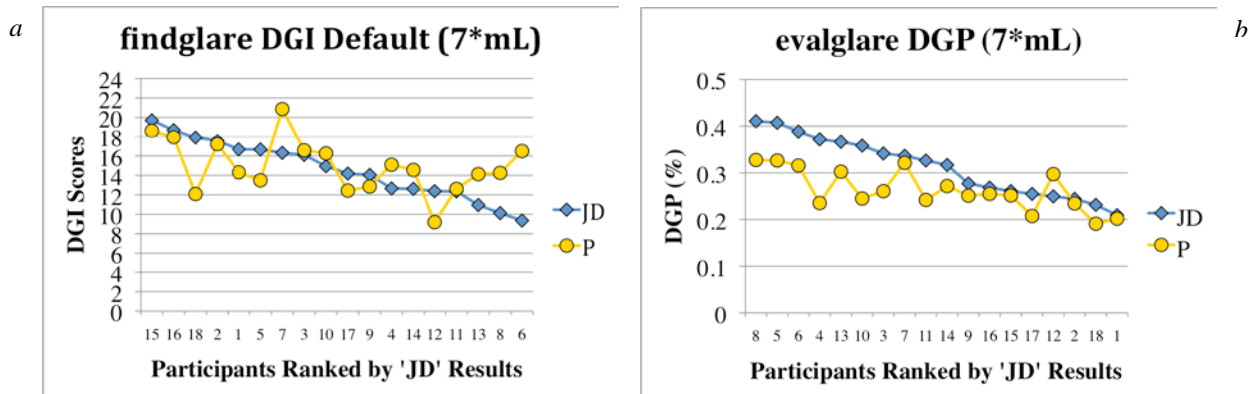


Figure 9: The results of DGI from 'findglare' (a) and DGP from 'evalglare' (b) using 7\*mL for glare source identification.

### 3.4 Task based mean luminance threshold

To assess the third threshold method described previously, mean luminance of task values were calculated one of two ways, either as an area of interest including the computer screen and the desktop (Fig. 1c), or as a subtended solid angle encompassing the monitor and keyboard (Figure 1c). The mean luminance of the task area encompassing the desktop and monitor (Fig. 8a) accounts for the highest  $adjr^2$  values for all questions except QU4 ( $adjr^2 = QU1$  0.19, QU2 0.31, QU3 0.59, QU5 0.51, QU6 0.32). The ratio of 'mean luminance of the task' to 'mean luminance of the scene' (Fig. 8b) best explained the results to QU4 ( $adjr^2 = 0.26$ ). The 'percent of scene pixels exceeding four or five times the mean luminance of the task' (Fig. 10c) was not statistically able to differentiate between 'P' and 'JD' scenes.

The results for the default DGP calculations [glare source identification defined as five times the mean luminance of the task position ( $DGP5 * mL_{task}$ ) as shown in Figure 1d)] were not as strong as mean luminance of the task or the ratio of the mean luminance of task:scene. For example the  $adjr^2$  for  $DGP5 * mL_{task}$  with QU3 was just 0.38 as compared to 0.59 for mean luminance of the desktop and monitor.

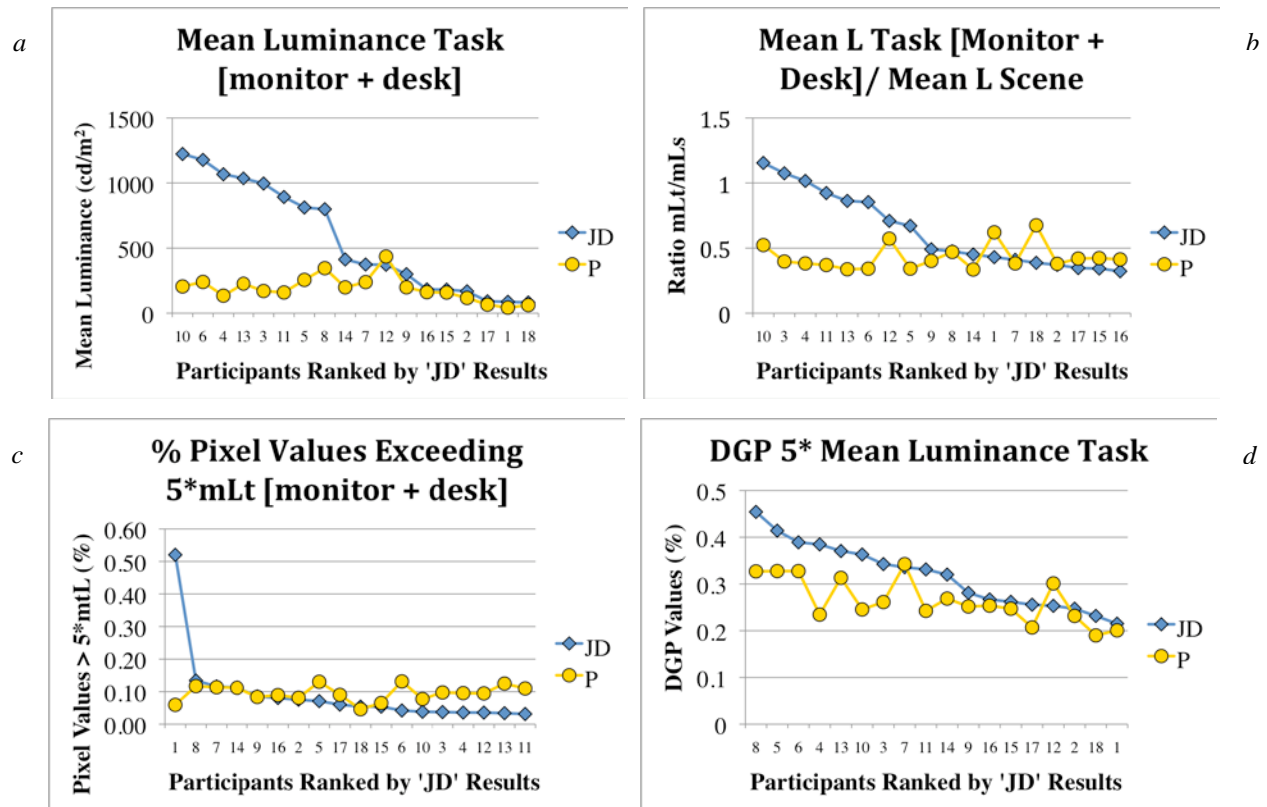


Figure 10: (a) Mean luminance task [monitor + desktop], (b) ratio of mean luminance of task [monitor + desktop] to mean luminance of scene, (c) percentage of pixel values that exceed the threshold of 5 times the mean luminance of the task [monitor + desktop], (d) DGP using 5 times the mean task luminance as the glare source identifier.

### 3.5 Other Candidate Metrics

In total, over 150 different illuminance and luminance metrics were tested for their ability to explain the variance in subjective questionnaire responses. The top tests are listed for each question as ranked by highest  $adjr^2$  values (Table 4). The single highest  $adjr^2$  value was for QU3 (I am satisfied with the amount of light for computer work) with the metric 'mean luminance of glare sources ( $7 * Mean L_{Task}$ )' as shown in Figure 9a. Other strong correlations that are notable include QU1 (I am pleased with the visual appearance of the office) with the metric 'maximum luminance of the scene' and with 'standard deviation of the scene' (Fig. 11a); QU2 (I like the vertical surface brightness) with the 'ratio of the mean luminance of the task [monitor + desktop] to the mean luminance of the scene' (Fig. 11b); and QU5 (The computer screen is legible and does not have reflections) with the 'mean luminance of the task [monitor + desktop]' (Fig. 11d).

Table 4: The top ten metrics tested as ranked by  $adjR^2$  values for each of the six Likert questionnaire items.

<b>QU1 - I am pleased with the visual appearance of the office</b>		
	<b>Test Name</b>	<b>adjR<sup>2</sup></b>
1	Max L Scene	0.445
2	Standard Deviation of Scene L	0.336
3	Mean L Glare Sources (7* Mean L Scene)	0.271
4	Mean L Glare Sources (5* Mean L Scene)	0.261
5	Mean L Glare Sources (7* Mean L Task)	0.238
6	Mean L Glare Sources (10* Mean L Task)	0.237
7	Mean L Glare Sources (10* Mean L Scene)	0.234
8	DGP 10* Mean L Scene	0.203
9	Mean Task L [monitor + desk]	0.193
10	Sum Solid Angle of Glare Sources (7* Mean L Scene)	0.190

<b>QU4 - I am satisfied with the amount of light for paper based reading work</b>		
	<b>Test Name</b>	<b>adjR<sup>2</sup></b>
1	Mean L Task [monitor + desk] / Mean L Scene	0.264
2	Mean L Task [monitor + desk]	0.193
3	Mean L Glare Sources (7* Mean L Task)	0.149
4	Mean L Glare Sources (10* Mean L Task)	0.141
5	Mean L Glare Sources (5* Mean L Task)	0.139
6	Mean L Glare Sources (7* Mean L Scene)	0.123
7	% of Pixels > 5* Mean L Scene	0.107
8	Mean L Glare Sources (10* Mean L Scene)	0.100
9	Mean L Background [non-glare] L (7* Mean L Task)	0.098
10	Mean L Glare Sources (5* Mean L Scene)	0.097

<b>QU2 - I like the vertical surface brightness</b>		
	<b>Test Name</b>	<b>adjR<sup>2</sup></b>
1	Mean L Task [monitor & desk]	0.307
2	Mean L Task [monitor + desk] / Mean L Scene	0.291
3	Mean L Glare Sources (7* Mean L Task)	0.260
4	Mean L Glare Sources (3* Mean L Task)	0.255
5	Mean L Background [non-glare] L (7* Mean L Task)	0.237
6	Mean L Glare Sources (5* Mean L Task)	0.233
7	Mean L Glare Sources (10* Mean L Task)	0.233
8	Mean L Background [non-glare] L (10* Mean L Task)	0.230
9	Mean L Glare Sources (7* Mean L Scene)	0.218
10	Mean L Background [non-glare] L (5* Mean L Scene)	0.216

<b>QU5 - The computer screen is legible and does not have reflections</b>		
	<b>Test Name</b>	<b>adjR<sup>2</sup></b>
1	Mean L Task [monitor + desk]	0.508
2	Mean L Background [non-glare] L (10* Mean L Task)	0.495
3	Mean L Background [non-glare] L (7* Mean L Task)	0.488
4	Mean L Background [non-glare] L (5* Mean L Task)	0.436
5	Mean L Glare Sources (3* Mean L Task)	0.419
6	Mean L Background [non-glare] L (3* Mean L Task)	0.417
7	Mean L Glare Sources (7* Mean L Task)	0.414
8	Mean L Glare Sources (10* Mean L Task)	0.410
9	Mean L Background [non-glare] L (10* Mean L Scene)	0.408
10	Mean L Background [non-glare] L (3* Mean L Scene)	0.407

<b>QU3 - I am satisfied with the amount of light for computer work</b>		
	<b>Test Name</b>	<b>adjR<sup>2</sup></b>
1	Mean L Glare Sources (7* Mean L Task)	0.639
2	Mean L Glare Sources (5* Mean L Task)	0.592
3	Mean L Task [monitor + desk]	0.590
4	Mean L Glare Sources (10* Mean L Task)	0.580
5	Mean L Glare Sources (3* Mean L Task)	0.549
6	Mean L Glare Sources (7* Mean L Scene)	0.499
7	Mean L Background [non-glare] L (7* Mean L Task)	0.482
8	Mean L Glare Sources (5* Mean L Scene)	0.479
9	Horizontal Lux On Top of Monitor	0.467
10	Mean L Background [non-glare] L (10* Mean L Task)	0.464

<b>QU6 - The lighting is distributed well</b>		
	<b>Test Name</b>	<b>adjR<sup>2</sup></b>
1	Mean L Glare Sources (10* Mean L Task)	0.349
2	Max L Scene	0.345
3	Mean L Task [monitor + desk]	0.317
4	Mean L Glare Sources (5* Mean L Scene)	0.314
5	Mean L Glare Sources (7* Mean L Task)	0.306
6	Mean L Glare Sources (7* Mean L Scene)	0.306
7	Standard Deviation of Scene L	0.305
8	Mean L Background [non-glare] L (7* Mean L Task)	0.261
9	Mean L Background [non-glare] L (10* Mean L Task)	0.260
10	Mean L Task [monitor + desk] / Mean L Scene	0.258

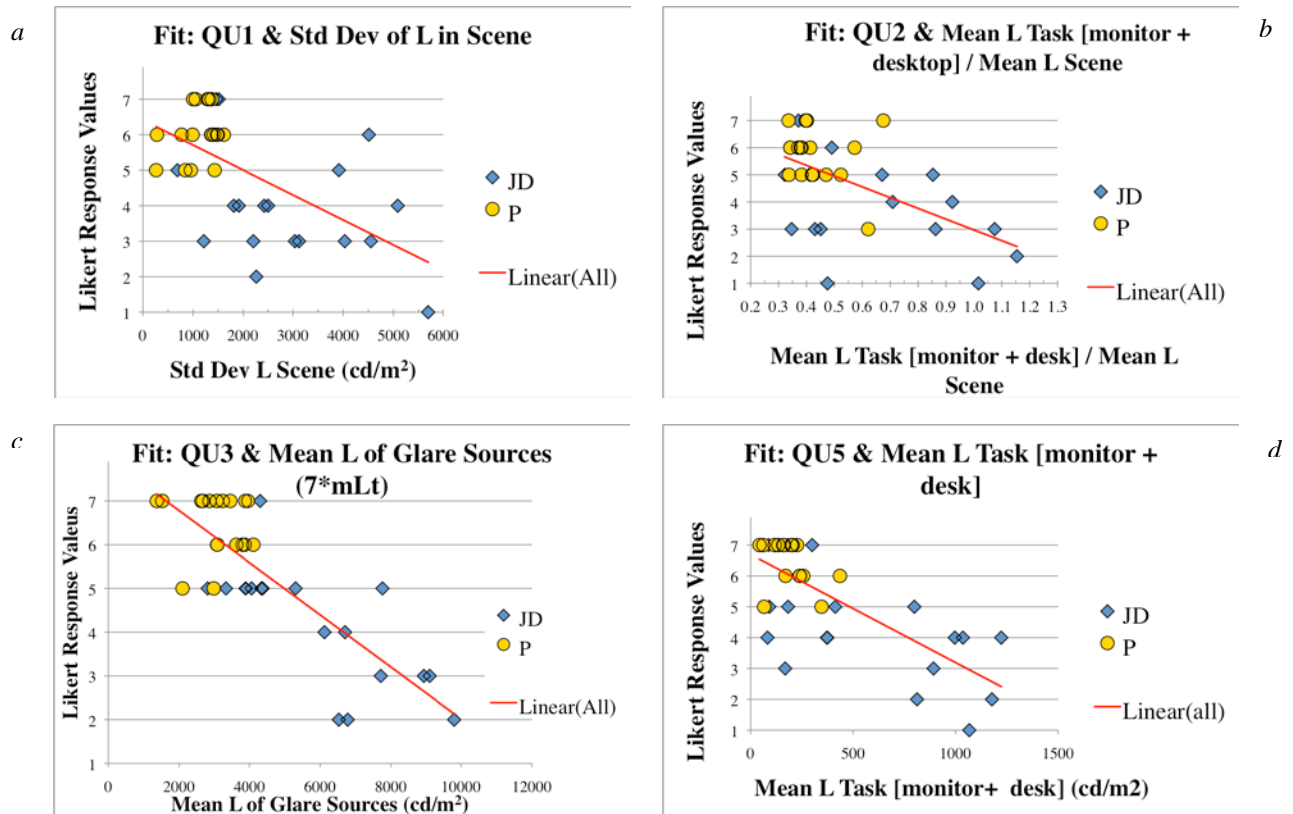


Figure 11: (a) Model of fit for QU1 and standard deviation of the luminance in the scene, (b) QU2 and the ratio of the mean luminance of the task [monitor + desktop] to the mean luminance of the scene, (c) QU3 and the mean luminance of the glare sources based upon the glare source identification threshold of  $7 \times$  the mean luminance of the task position, (d) QU5 and the mean luminance of the task [monitor + desktop].

#### 4 DISCUSSIONS AND CONCLUSION

This paper investigated the ability of common illuminance and advanced luminance based measures to differentiate between participants' 'most preferred' luminous environment and those with 'just disturbing' glare. It also identifies the measures that most successfully explain the variance in participants' response to subjective visual preference questions. It can be seen throughout this paper that QU3 and QU5 generally show the highest  $\text{adj}r^2$  values, and therefore, it appears that these two questions are the most meaningfully related to the participants' preference of the environment studied. This is not surprising given that the primary nature of the work in the office space during these experiments was computer related. Question 3 often had the best fit with the metrics studied and therefore we use it frequently for discussion purposes below. The relatively low  $\text{adj}r^2$  values for QU2 could be indicative of the nature of the experiment because it focused on computer work (completing the online survey) even though paper materials were provided in the room for reference when participants responded to QU2. These findings can help to focus future research toward the metrics that correlate best with the questions of interest (Table 4).

The results of the illuminance analysis confirmed previous research regarding the limitations of ceiling mounted illuminance sensors as a proxy control position to maintain desktop illumination. Ceiling illumination was not statistically capable of differentiating between participants' 'P' and 'JD' scenes. While this capability is not expected of current daylight harvesting systems, it does give some explanation as to why users so commonly intentionally disable current daylight harvesting technology. It is also interesting to note that  $E_{\text{monitor}}$  was better able to explain the variance in responses to QU3 (I am satisfied with the amount of light for computer work) than either  $E_{\text{desk}}$  or

E\_Veye. This suggests that daylight harvesting systems should consider photosensor placement at the top of monitor to improve user satisfaction while also avoiding many of the roadblocks to a desktop photosensor location.

The analysis of sun penetration for preferred scenes revealed the fact that 11 of 12 participants preferred to allow sun into the space when it was available. This suggests allowing carefully positioned direct sun in spaces to improve user satisfaction or when heating is needed. The control system is therefore of critical importance and it is necessary to allow users to override systems to meet their needs. It is clear from the results that when sun strikes the task area [monitor + desk], it was perceived as 'JD'. Obviously, this is a more complicated issue in offices with multiple occupants due to multiple task areas and view perspectives.

Predetermined absolute luminance thresholds tested included 1) percent of scene pixels exceeding various absolute thresholds, and 2) DGI and DGP produced by first identifying glare sources based upon various absolute thresholds. All 36 scenes (even the darkest overcast sky 'P' scene) had many pixel values in excess of 2000 cd/m<sup>2</sup>, thus limiting the usefulness of this simple metric. However, extending the 2000 cd/m<sup>2</sup> threshold with a proportional value (~10%) to define the percentage of pixels exceeding the threshold greatly increases its usefulness and predictive ability. In general, it is difficult to interpret high luminance values since they may point to unsatisfactory lighting conditions, such as poor visibility and discomfort, or to good lighting qualities such as highlights and sparkle. From a practical standpoint, highlights, sparkle, veiling reflections and glare are produced similarly; therefore, the discriminating factor becomes the angular size of the source with high luminance (Worthey, 1991). Increased percentages of pixel values exceeding the threshold indicate larger areas of high luminance, therefore, higher potential of visual discomfort. For QU2 and QU3, the percent of scene pixels exceeding 2000 cd/m<sup>2</sup> produced higher  $adjr^2$  values than any other threshold, whereas QU5 and QU6 correlated best with the percent of scene pixels exceeding 500 cd/m<sup>2</sup>. The highest correlation was for QU5 with 500 cd/m<sup>2</sup> ( $adjr^2 = 0.39$ ). However, following closely was the correlation for QU3 with 2000 cd/m<sup>2</sup> ( $adjr^2 = 0.38$ ). These results provide some justification for using an absolute luminance threshold but suggest it should be coupled with a proportional area value for discrimination.

DGP produced with various absolute threshold glare source identifiers consistently produced higher  $adjr^2$  values than the equivalent DGI tests. The highest correlation for QU3, and QU5 were both with DGP based upon 2000 cd/m<sup>2</sup> thresholds ( $adjr^2 = 0.41$  for both). This provides some additional support for selecting 2000 cd/m<sup>2</sup> as a glare source identification threshold, however the sensitivity analysis shown in Table 3 reveals only a small improvement over values ranging from 500-3000 cd/m<sup>2</sup>. It also shows that DGP based on 2000 cd/m<sup>2</sup> performs slightly better than simple absolute luminance thresholds tested. However, the rather small improvement in the variance explained may not necessarily be worth the extra computational expense associated with its calculation.

Scene based mean luminance thresholds tested included 1) mean luminance of the whole scene, 2) the percent of pixels exceeding a mean luminance threshold multiplier, and 3) DGI and DGP produced by first identifying glare sources based upon a mean luminance threshold multiplier. The results for DGI 7\*mL and the metrics based upon the 'percent of pixels exceeding various mean luminance threshold multipliers' were not statistically capable of differentiating between 'P' and 'JD' scenes. However, DGP results based upon the mean luminance threshold multipliers were able to differentiate between scene types (paired  $t < 0.01$ ) and produced an  $adjr^2$  value of 0.43 with QU3 for DGP 10\*mL. Surprisingly, the simplest metric, mean luminance of the whole scene, actually performed the best with respect to QU3 ( $adjr^2 = 0.44$ ). This should not necessarily be interpreted as the strength of mean luminance of the scene as an analysis metric. In practice, adaptation luminance is usually taken as the average luminance of the relevant viewpoint, but it is a gross simplification. The adaptation luminance is affected both from the average and the variance of the luminance distributions (Ishida and Iriyama, 2003). The results should rather be assessed as the weakness of the mean luminance threshold multiplier construct.

Task based mean luminance thresholds produced the highest  $adjr^2$  value out of the three distinct luminance analysis methods previously practiced. Note that the subjects were asked to perform computer and paper tasks. Therefore the task is centered at their fovea. The human visual system can be quite insensitive to large luminance differences in the total field of view, but it is very sensitive to small luminance differences in the foveal region. An extreme variation in the task area causes discomfort. In this category the thresholds tested included 1) mean luminance of task zones [monitor + desktop], 2) the ratio of mean luminance of task zones [monitor+desktop] to mean luminance of scenes, 3) the percent of pixels that exceed various mean luminance of task zone [monitor+desktop] multipliers, and 4) DGP based upon its traditional definition of various task position mean luminance multipliers. The highest overall correlation in this category was for QU3 with mean luminance of task zones ( $adjr^2 = 0.59$ ). The ratio of mean luminance task:scene successfully differentiated between 'P' and 'JD' scenes (paired  $t < 0.05$ ) but produced low  $adjr^2$

values. The percent of pixels exceeding mean luminance of task zones could not differentiate between 'P' and 'JD' scenes. Finally, of the DGP metrics tested, DGP 5\*mLtask showed the best correlation with participant response to most questions. However, the  $\text{adj}r^2$  for DGP5\*mLtask are consistently lower than the simple measure of mean luminance of the task zone [monitor + desktop] for every question. Surprisingly, the  $\text{adj}r^2$  values from DGP5\*mLtask (QU3 = 0.38) were the lowest of any of the DGP constructs tested; that is, DGP based upon 2000 cd/m<sup>2</sup> and DGP 10\*mL produced higher squared correlation coefficients (QU3 = 0.41, 0.43 respectively). Given that the 'JD' scenes often had some amount of direct sun on the computer screen, it is not unreasonable to expect the mean luminance of the task metric to explain this phenomenon well.

As stated above, over 150 different illuminance and luminance metric tests were conducted for this research. The most meaningful finding is that 'mean luminance of glare sources' metrics based upon various task and scene mean luminance multipliers consistently emerged within the top ten metric rankings for the Likert items. Aspects of task and scene luminance as well as luminance adaptation are accounted for with this metric based upon the glare source identification mechanism and the relative intensity of the glare sources. This metric (Mean L Glare Sources identified by 7\* Mean L Task) represented the best overall correlation ( $\text{adj}r^2 = 0.64$ ) with any question (QU3) of all metrics tested.

Standard deviation of scene luminance was a consistent metric within subjects and shows that all preferred scenes are below  $\sigma=1610$  cd/m<sup>2</sup>. This metric appears to correlate fairly well with participant's responses related to general visual appearance (QU1) and luminous distribution (QU6). As discussed earlier, adaptation luminance is affected both from the average and the variance of luminance distribution (Ishida and Iriyama, 2003). Adequate luminance variations create a stimulating and interesting environment that improves the preference ratings of the occupants, whereas excessive luminance variability tends toward creating uncomfortable spaces.

*In conclusion, DGP consistently performed better than DGI.* In several cases, simple metrics such as mean luminance of the entire scene perform better or equally well with more complicated metrics such as DGP and DGI. In these cases, using the least complicated metric is advisable. *Limiting the percentage of pixels that exceeded 2000 cd/m<sup>2</sup> in the field of view proves to be an useful metric.* Metrics that require the identification of task areas are by definition position specific, whereas whole scene metrics are likely to perform better where scenes are not stable over time (e.g. when objects move or where there are multiple task positions, etc). Furthermore, locating cameras or sensors sufficiently close to the seated users' eye position in order to capture task areas appropriately is simply not practical in real world office applications (Newsham and Arsenault, 2009).

The ability of several luminance metrics examined to statistically differentiate between 'P' and 'JD' scenes is encouraging. However, it is difficult to establish two-way thresholds (above x = comfort, below x = discomfort) due to several known dynamic variables (individual preference, temporal variability, setting variability). This suggests that calibration for luminance based lighting and blind controls under various settings is not straightforward and makes predictive modelling complex because of the need to account for occupant positions and individual susceptibility to glare. These results suggest that the most practical approach for assessment of the three primary methods is the 'predetermined absolute luminance threshold' measure.

As with any research, these results must be interpreted and applied appropriately. Our research was conducted with a relatively small sample of generally young and healthy vision participants, during winter months with subsequent low sun angles and cold outdoor air temperature, and in a private single occupancy office with very large windows. Therefore there are obvious restrictions to generalizability of the results. For example, the results should not be expected to directly translate to open plan office environments. There may be bias associated with the winter testing period related to allowance of additional sun penetration than might otherwise be present if the study were conducted during a different time of year. Nonetheless, the analysis methods described and many of the metrics tested are useful to other office settings with daylight. The results provide important progress in the field of luminance based daylighting performance analysis and provide guidance to the development of luminance based daylighting control systems. The nature of this research design limited the variability in participant responses since they intentionally created 'P' and 'JD' settings. This design facilitated testing metrics for their ability to discern between 'P' and 'JD' scenes, however the best fit analyses shown in Figure 11 and Table 4 would have benefitted from additional variability.

Future research plans include additional settings and daylighting conditions. Effects associated with age, time of day, time of year, and participant susceptibility to glare will be studied with a larger sample. The research thus far has

focused on the difference between participant-created 'P' and 'JD' scenes under daylighting conditions only and as manipulated by manual louver blinds. Future research will incorporate experimenter-created or automated environments in addition to participant-created environments in order to increase variability in user responses and demonstrate more diversity in scene types. Emphasis will be placed on preferred scenes to better understand this range with respect to optimization of automated blind and electric lighting controls.

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