A Study of Luminance Distribution Patterns and Occupant Preference in Daylit Offices

KEVIN VAN DEN WYMELENBERG[1,2], MEHLIKA INANICI[1]

[1] University of Washington, College of the Built Environment, Seattle, WA, 98103, USA
[2] University of Idaho, Department of Art & Architecture, Boise, ID 83702, USA

ABSTRACT: New research in daylighting metrics and developments in validated digital High Dynamic Range 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 the occupant preference of patterns of luminance within these contexts. Three existing luminance threshold analysis methods (scene average based luminance threshold, predetermined absolute luminance, and task average based luminance) are studied as well as additional candidate metrics for their ability to explain luminance variability of 18 participant assessments of 'preferred' and 'just disturbing' scenes. The most consistent and effective existing metric is found to be 'absolute luminance threshold', where the criteria is determined as limiting the percentage of pixels that exceed the threshold (~10 % of pixel values> 2000 cd/m2 were rated as 'just disturbing').

Keywords: luminance based lighting controls, discomfort glare, occupant preference, high dynamic range imaging

INTRODUCTION

Successful daylight designs of office buildings can provide significant energy savings when properly integrated with daylight sensing lighting control systems. However, previous research shows that spaces (excepting large volume toplit spaces [1]) designed to integrate daylighting and electric lighting controls rarely produce the energy savings purported during design stages [2]. Discrepancies in realized savings are attributed to complicated specification, installation, and commissioning [3, 4] and are compounded by operational issues associated with suboptimal manual blind (or shade fabric) operation and user dissatisfaction, resulting in systems being disabled [2].

Commercially available lighting control systems are exclusively based upon illuminance, often measured at the ceiling plane looking toward the work plane. In general, illuminance-based metrics drive lighting design decisions and control system technology due to their predominance in professional standards [5], and the historic measurement limitations including the cost of luminance measurement equipment. However, a literature survey on determinants of lighting quality [6] 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 (such as Blackwell [7], Boyce [8], Rea and Ouelette [9]) and visual comfort metrics such as Daylight Glare Index (DGI) [10] and Daylight Glare Probability [11] (DGP) 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 horizontal illumination. As a result, luminance-based lighting control systems can potentially provide better energy savings and user satisfaction than traditional illuminance-based systems.

With the developments in digital High Dynamic Range (HDR) photography [12, 13] and its validated technique [14] 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. Luminance mapping techniques provide much more information about a luminous environment than a limited number of measurements. However, there is a need to determine appropriate data analysis techniques that can be used to quickly analyze the information and provide useful feedback for lighting design decisions and control strategies.

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. *Scene average based luminance threshold*: Average luminance values are calculated in a large field of view (hemispherical fisheye lenses allow data collection in 180° horizontally and vertically), and the discomfort threshold is determined as the multiplication of the average scene luminance with a constant. Radiance 'findglare' tool [15] adopts this method and the default constant is 7. An average luminance value (L) in a scene yields to a luminance threshold of 7*L (i.e. luminance values above 7*L 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.
2. *Predetermined absolute luminance threshold*: An acceptable luminance threshold is set as a predetermined value. A recent study [16] used 2000 cd/m^2 as the threshold value for the average luminance of the unobstructed portion of the window wall. In this research, the threshold value is used to control an automated roller shade system in an open plan office space to control direct sun and window glare while providing an adequate amount of daylight and view to the outdoors.
3. *Task average based luminance threshold*: Average task luminance is calculated in a given area, and the threshold is determined as the multiplication of the average task luminance with a constant. A new glare metric, DGP [11] utilizes this method, where the threshold value is determined as 4 times the average task luminance. 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 of 0.94 for DGP as compared to 0.56 for DGI [17].

It is important to note that both Radiance 'findglare' tool and DGP allow the user to set a predetermined threshold value.

In a simple daylit setting, Howlett et al. proposed a framework for other luminance-based metrics and assessed their temporal and spatial stability [18]. Additionally, Newsham et al. 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 [19]. Sarkar and his colleagues have demonstrated applications where small cameras collect HDR information and control electric lighting systems in architecturally stable environments [20, 21].

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 blinds (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 lack of a foundation of solid human factors research to support design metrics and control algorithms.

The aim of this paper is to advance the area of human preference analysis while maintaining the work within the contexts of the lighting and blind 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. The three unique luminance threshold methods described above are analyzed in connection with occupant preference, and other candidate metric solutions 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.

METHODOLOGY

The research involves collection of large field of view luminance maps and illuminance measurements along with occupant surveys to study the occupant preferences in an office space along with quantitative measurements. The research setting (Fig. 1) is a 3.5m x 4.5m (~16 m^2) private office with a southwest facing window (33° from true South) exposure in Boise, Idaho (43° N and 116° W).

The experiment was conducted on December 16th–17th, 2008 between 11:30-16:00. Sky condition varied from sunny to cloudy, bright with haze, and full overcast during data collection. The windows are double-glazed clear with aluminium 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.

Figure 1: The research setting

One rectangular desk measuring 1.52m x 0.76m was positioned approximately 1m away from the window wall. The seated occupants faced a painted wall. A 0.53m (diagonal screen dimension) LCD computer monitor (max screen luminance measured as 255 cd/m^2) 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 (typical photocell location), and on the roof of the building.

A HDR photography technique was used to collect luminance data in a large (180° by 180°) field of view [12-14]. A Canon EOS-1 Ds Mark III Digital SLR camera and Sigma 8 mm F3.5 DG Circular Fisheye lens was positioned in the plane of the subjects' eyes with a 0.45 m offset (measured from center of lens to center of eyes) from the subject. 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 [22]. 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 with physical quantities of luminance (in cd/m^2).

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).

The participants were directed to manipulate blind height and tilt for both blinds in order to create the interior lighting condition they perceived as the 'most preferable' luminous environment possible from their seated position for the primary purposes of computer work, under the prevailing sky condition. They also created another interior lighting condition that they perceived as 'just disturbing'. 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 'just disturbing' 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.

Experimental Procedure

This study used a repeated measures design whereby each participant positioned the blinds to modify the amount and distribution of daylight such that they determined the scene to be the 'most preferable' and 'just disturbing' lighting condition. 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 'most preferred' or 'just disturbing' setting and had completed the short lighting preference online questionnaire. After each exposurebracketed sequence was completed, the participants were prompted to re-enter the room and continued with the study. In order to minimize the bias, the survey tool randomized the sequence instructing participants to create their 'most preferred' and 'just disturbing' scenes. Figures 2 demonstrates the scenes that are defined as "just disturbing" and "preferred" by one of the participants.

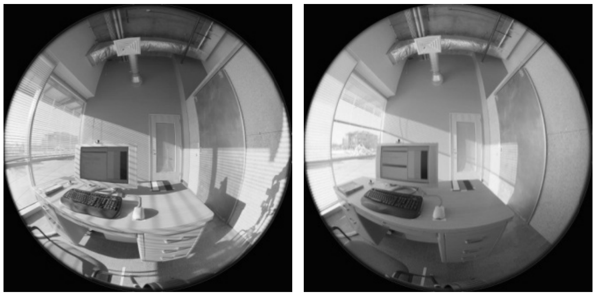

Figure 2: The blind positions adjusted by a participant to create "just disturbing"(left) and "preferred" (right) luminous environment.

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 'preferable' and 18 'just disturbing' scenes. HDR photographs and illumination data were analyzed in order to see which candidate metrics best explained the relationships among occupant preference ratings and daylight luminance patterns in the office space. The online survey tool assed participants' visual preference for each scene while it also recorded the extent to which the subjects were able to create a 'just disturbing' visual environment. All subjects strongly agreed or very strongly agreed that they were able to create a 'preferred' setting, while due to weather conditions, four participants were not absolutely confident with their ability to create a 'disturbing' environment.

RESULTS

The results were analyzed using luminance maps and illuminance measurements in conjunction with participant questionnaire response. The following analyses are performed to study each of three luminance threshold methods described earlier.

Average scene luminances were studied for all 36 cases for their ability to explain variance of 'preferred' and 'just disturbing' scenes (Fig. 3). The most notable result is that an average threshold value can be distinguished for the analyzed office under the studied lighting conditions, above which only 'just disturbing' scenes occur (~800 cd/m^2), however, below the threshold value, there is a mix of 'preferred' and 'just disturbing' scenes. Therefore, it is not possible to set a threshold average scene luminance value to demarcate "just disturbing' and 'preferred' scenes. Yet, the average scene threshold metric is consistent in the sense that a 'just disturbing' scene set by a participant has a higher scene average than the 'preferred' scene set by the same participant. The only exception is participant 12 where the outdoor illumination dramatically increased between the 'just disturbing' and 'preferred' scene.

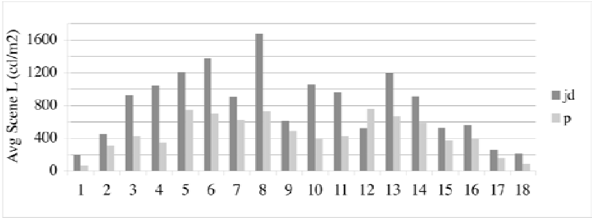

Figure 3: Average scene luminances (cd/m2) for analyzed scenes ('jd'stands for 'just disturbing' and 'p' stands for 'preferred' scenes).

The percentage of pixel values that exceed 7 times the average scene luminance for each scene is illustrated below (Fig. 4). A higher percentage indicates potentially larger glare sources. This metric proves to be inconsistent, in that some data sets have a higher percentage of pixel values that exceed '7 times the average scene luminance' for 'preferred' than for 'just disturbing' scenes.

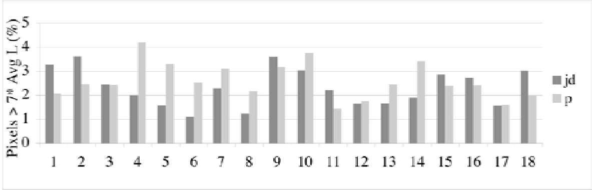

Figure 4: Percentage of pixel values that exceed the threshold of '7 times the average scene luminance'

Predetermined luminance values (2000 cd/m2 and 3000 cd/m^2) were also studied to explain variance of preferred and just disturbing scenes. Figure 5 shows that 'preferred' scenes have less than ~10% of pixel values exceeding 2000 cd/m^2 and Figure 6 shows a similar result at less than 8% of pixel values exceeding 3000 cd/m^2.

To assess the third threshold method described previously, task luminance was calculated, and the threshold was set as '4 times the average task luminance'. Average task luminance is calculated as the average of the pixels that correspond to the desk and the computer screen. Figure 7 illustrates the percentage of pixels that exceed the threshold. This metric provides unstable results for both within subject and between subject measures. For most participants, the percentage of pixel values that exceed '4 times the average scene luminance' is higher in the 'preferred' scene than for the 'just disturbing' scene.

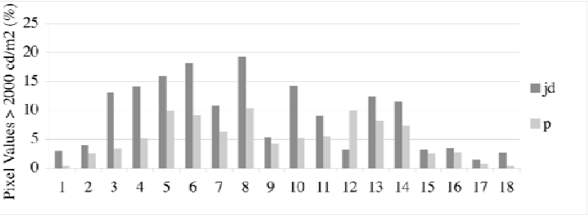

Figure 5: Percentage of pixel values that exceed a predetermined luminance threshold value of 2,000 cd/m^2

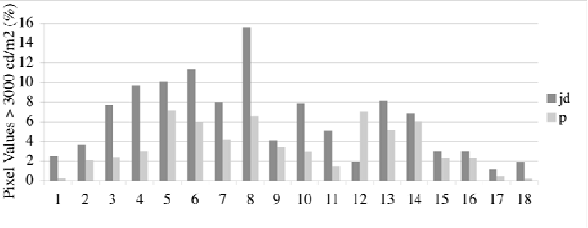

Figure 6: Percentage of pixel values that exceed a predetermined luminance threshold value of 3,000 cd/m^2

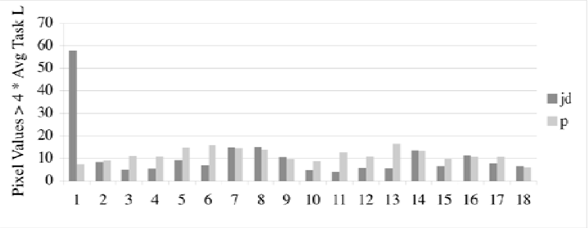

Figure 7: Percentage of pixel values that exceed the threshold of '4 times the average task luminance'

DISCUSSIONS AND CONCLUSION

This paper investigates the three practiced luminance threshold metrics, (i) scene average based threshold, (ii) predetermined absolute threshold, and (iii) task average based threshold to identify the presence or absence of glare in a luminous environment.

In isolation, none of these metrics adequately explained the variability of scene preference. For instance, in all 36 scenes (even the darkest overcast sky 'preferred' scene), had many pixel values in excess of 2,000 cd/m^2. However, extending the 2,000-cd/m^2 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 the 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 determining factor becomes the angular size of the source with high luminance [23]. Increased percentages of pixel values exceeding the threshold indicate larger areas of high luminance, therefore, higher potential of visual discomfort.

Both predetermined absolute thresholds provided consistent results for both within subject and between subject measures, whereas the other two threshold methods did not. It is also the least complicated metric. For instance, task luminance-based metric requires the identification of the task area, and therefore it dependent upon position and scene stability.

Table 1: Summary of analyzed metrics

Predictive metric	Stability within subjects Max=(18)	(Preferred threshold), % of 'jd' scenes above threshold
Avg L	17	(761 cd/m^2), 56%
SD L	18	(1610 cd/m^2), 78%
SD:Avg scene L	10	-
% pixels > 2,000 cd/m^2	17	(10.4%), 50%
% pixels > 3,000 cd/m^2	17	(7.1%), 45%
% pixels > 5*Avg L	8	-
% pixels > 7*Avg L	8	-
% pixels > 10*Avg L	10	-
% pixels > 20*Avg L	10	-
Avg task L:Avg L	12	(0.68), 39%
Avg task L:Max L	9	-
% pixels > 4*Avg task L	4	-
% pixels > 5*Avg task L	5	-
Brightest 10% L:Avg L	8	-
DGI	14	-
DGP	15	(34.2%), 39%
E_{desk}	16	-
$E_{monitor}$	17	-
Vertical E_{eye}	17	(2495 cd/m^2), 50%
Avg scene L:$E_{global\ horizontal}$	18	(0.0277), 39%

Several additional metrics were considered in an attempt to better explain the data (Table 1). It is interesting to note that a simple variability metric, standard deviation of scene luminance, was the most consistent metric within subjects and explained the greatest proportion of just disturbing scenes above the threshold (σ=1610 cd/m^2). The adaptation luminance is affected both from the average and the variance of luminance distribution [24]. 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.

The ability of several metrics examined to consistently differentiate preferred scenes from just disturbing scenes is encouraging. However, as expected, it is difficult to establish two-way threshold (above x = comfort, below x = discomfort) due to several known dynamic variables (individual preference, temporal variability, setting variability). This suggests that calibration for luminance controls under various settings is straightforward and makes predictive modelling difficult because of its dependency on occupant positions. These results suggest that the most practical approach for assessment of the three current methods is the 'predetermined absolute luminance threshold' measure. As the next step, this line of research will be expanded to investigate other potential metrics for effective luminance assessment within additional settings and daylighting conditions for use with automated lighting and blind controls and for predictive design performance assessment.

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