Image-obfuscation as a means for privacy-conscious visual data acquisition from building systems

Subramaniam S\textsuperscript{1}, Hoffmann S\textsuperscript{1}

\textsuperscript{1} Department of Civil Engineering, Technische Universität Kaiserslautern, Germany

sarith@rhrk.uni-kl.de

Abstract. In the last two decades, numerous studies have demonstrated the viability of using High Dynamic Range Imaging (HDRI) to quantify lighting conditions in the built environment. Several human factor studies have demonstrated correlation between visual comfort perceived by occupants and glare metrics calculated by analysing HDR images. However, the use of HDRI in real-world applications has been severely limited owing to privacy concerns. This research investigates the feasibility of employing obfuscated (i.e. deliberately distorted) HDR images for analysing glare. The authors present a pilot study where visual conditions inside an office-space were simulated and captured as HDR images using a validated, physically-based renderer. The images were then obfuscated to various degrees by application of blur filters. Glare metrics calculated for the obfuscated images, when compared with the metrics generated for the original HDR images, were found to be within 2\%-12\% relative error. The proof-of-concept demonstrated through this study provides the framework for field-testing of an HDR-based lighting control system in a real office space.

1. Introduction

The availability of daylight in commercial workspaces has been associated with improvement in occupant well-being and productivity. In surveys, occupants have indicated a preference for locations with a view of the outdoors than in closed spaces with no external views\cite{1, 2}.

An effective daylight control strategy is one that will ensure task-adequate brightness inside a space and minimize visual discomfort due to glare\cite{3}. Active strategies for glare control include the use of devices such as blinds, adjustable shades, and more recently, electrochromic glazing. Owing to the temporal variations in daylight during a typical day, such devices need to be adjusted periodically to minimize glare and optimize useful daylight. While automated lighting control systems have been commercially available for many years, there exists a gap between the purported and actual performance of these systems. Studies have shown that in spaces where such automatic systems are installed, the automatic control is often overridden by the occupants. Additionally, meta-analyses have indicated a significant disparity between the projected and realized benefits of daylighting control systems\cite{4, 5}.

The shortcomings in the performance of daylight responsive lighting control systems are attributable to the way in which they estimate the lighting conditions in a space. These devices are automatically actuated by microcontrollers or building management systems whose control algorithms rely on photosensor-derived vertical and horizontal illuminance/irradiance measurements to account for lighting conditions in a space\cite{6-8}. Illuminance, especially of a single representative location in space, while easily measurable, is not always a reliable predictor of visual comfort. The lighting metrics that have demonstrated high correlation with perception of visual discomfort typically take into account
luminance of potential glare sources, their size and vertical illuminance [9]. Several field studies conducted since early 2000s have demonstrated that images acquired from commercial cameras can be reliably employed to measure luminance and illuminance data through High Dynamic Range Imaging (HDRI) [10-13]. The process of image-acquisition involves capturing multiple images at different exposure levels and then fusing them together to create a High Dynamic Range image. Unlike standard image formats like JPG or PNG, which usually store 8-bit data per pixel, HDR images store between 24 to 48 bytes per pixel, thus facilitating the storage of a wide range of brightness values encountered in natural lighting conditions [14-16].

HDR images can also be generated through physically-based rendering engines like Radiance. Radiance, a command-line ray-tracing tool developed primarily by Greg Ward at the Lawrence Berkeley National Laboratory [17]. It employs a 32bit/pixel RGBE data format capable of storing the wide range of luminance values encountered in daylit spaces. Based on the numerous validation studies conducted on the accuracy of Radiance in simulating daylighting conditions, and resulting glare, the use of Radiance for predicting glare through HDR images during design stages is widely advocated and practiced [18-21].

Currently, the most commonly used tool for glare assessment from HDR images is a command line program called Evalglare [22-24]. Among the several glare-based metrics calculated by Evalglare, Daylight Glare Probability (DGP), is the most prominent and is widely used [25-27]. Evalglare requires fisheye HDR images for analysing glare. Figure 1 shows a scenario where the luminance captured through an HDR image has been evaluated using false-colour mapping as well as Evalglare.

Figure 1. Image (a) shows an HDR image generated through Radiance. Image(b) shows the corresponding false colour mapping of luminance values and image (c) shows the location of potential glare sources identified by evalglare. The colours assigned to the glare source by evalglare are arbitrary.

2. Motivation and working hypothesis

Although HDRI has proven to be a reliable means of acquiring data that can be used to quantify the luminous conditions existing in space, its applications in real-world applications have been limited. The photographs captured for generating HDR images can compromise the privacy of individuals and/or reveal sensitive information about the photographed space [28-30].

The research underlying this paper investigates whether glare analysis of low-quality or deliberately distorted HDR images can produce results comparable to those obtained through high resolution HDR images. The rationale behind distorting the HDR images is to obscure the activity and identity of occupants, thus alleviating, to some extent, privacy-related concerns. An example of distortion using blur filters is shown in Figure 2. The authors hypothesize that, if an obfuscation technique is uniformly applied across the entire image, the values of DGP derived through obfuscated HDR images will be comparable to those derived through original HDR images. The subsequent sections describe the methodology and results from a simulation-based pilot study conducted for testing this hypothesis.
3. Methodology
The goals of the pilot study described in this paper are to identify an obfuscation method that allows for progressive distortion of HDR images, establish automated glare analysis workflows from images and finally ascertain the feasibility of such images as a replacement for standard HDR images.

Figure 3 shows the room considered for the simulations. This room, which is modelled after an actual office space in Germany, consists of a south-facing full-height glazing. The occupants are subject to direct insolation, and consequently visual discomfort, especially during the winter months when the solar profile angle is low. The 3D model shown in Figure 3 was created in SketchUp® software from physically measured dimensions at the site. The model was then exported to a format compatible with the Radiance rendering system using a plugin called Su2Rad [31].

Figure 4 shows two typical HDR images generated with Radiance from the exported model. For the purposes of generating HDR images for glare analysis conducted in the study, six camera locations were chosen, three each on east and west wall, at a height of 2.4 meters from the floor level. The location of
the cameras is highlighted in Figure 3 and Figure 5 shows HDR images generated for these camera locations at a single point-in-time. A total of 426 such images were generated for 71 sky conditions the purposes of the pilot study.

![Figure 3](image1.jpg)

**Figure 4.** Fish-eye HDR images generated with Radiance for the same daylighting condition at two camera settings.

![Figure 5](image2.jpg)

**Figure 5.** Falsecolour mappings of HDR images generated for the same daylighting condition at the six virtual camera positions. As is apparent from the images, the cameras are placed on either side of the room and at variable distances from the glazing. The value mapped through falsecolor is candela/m², the unit of luminance.

The sky conditions considered for the simulations were created using the Perez Sky Model implemented in a Radiance tool called Gendaylit [32, 33]. The location details and hourly radiation values required for the Perez Sky Model were obtained from Typical Meteorological Year (TMY) data for Berlin, Germany. The rationale for choosing the 71 conditions is explained further through Table 1.
Table 1. Timesteps considered for generating the HDR images considered in the study.

| Detail                        | Quantity | Comment                                                                |
|-------------------------------|----------|-------------------------------------------------------------------------|
| Total timesteps considered    | 120      | Hourly, from 9AM to 4PM (inclusive), between 1st November to 15th November |
| Timesteps with direct sun     | 71       | The 49 hours that were filtered out consisted of overcast conditions.   |
| HDR images generated          | 426      | 1 image/hour for 71 hours, captured by 6 cameras                        |

An example of HDR images generated for different sky conditions is shown in Figure 6. The entire set of HDR images generated for the specified daylighting conditions and camera settings were then obfuscated to various levels by using procedural software filters. The authors initially tested image interpolation algorithms involving linear, bicubic and Lanczos filters. Since the interpolation algorithms usually reduce the size of the resulting image, they were found to drastically underestimate the luminance of glare sources in the HDR images. Subsequently, Gaussian blur filters were tested and were found to provide a reasonable balance between distortion and retention of useful luminance data. Figure 7 provides an example of the level of distortion achieved through progressively higher levels of blurring. As is evident from the general shape patterns and the magnitude of luminances mapped through false-colour, details relevant to the analysis of visual discomfort are retained to a certain extent even in distorted images. The next section provides a summary of the glare data obtained through the obfuscated images.

Figure 6. Falsecolour mappings of images generated for the same camera position for alternate hours on 3rd November. The value mapped through falsecolour is candela/m², the unit of luminance.

Figure 7. Progressive obfuscation of a single HDR image using a Gaussian blur filter. The value mapped through falsecolour is candela/m², the unit of luminance.
4. Results

Of the 426 HDR images generated for this study, 115 images contained daylight luminance and vertical illuminance levels lower than the threshold at which they could be effectively analysed. This threshold is based on the minimum vertical illuminance and minimum qualifiable DGP level assigned in Evalglare. 34 images yielded DGP values higher than 0.59, a value above which glare is characterized as intolerable. The remaining 277 images yielded DGP levels where the glare could be characterized as either imperceptible or perceptible. The obfuscated derivatives of these 277 images were also analysed with Evalglare to determine the DGP levels obtained after obfuscation.

Table 2. Categorical summary of the DGP values calculated for the 426 original HDR images generated for the study.

| Scenario | Instances | Comment                        |
|----------|-----------|--------------------------------|
| DGP<0.2  | 115 (27%) | DGP is not defined for low lighting conditions |
| 0.2<=DGP<=0.35 | 190 (45%) | Imperceptible glare |
| 0.35<DGP<=0.59  | 87 (20%)  | Perceptible to intolerable glare |
| DGP>0.59  | 34 (8%)   | Beyond intolerable glare       |

Figure 8 summarizes the relative error in DGP calculation as a function of obfuscation level. Relative error for an individual image was calculated as:

\[
\text{Error\%} = \frac{\text{Abs}(\text{DGP from Original Image} - \text{DGP from obfuscated Image})}{\text{DGP from Original Image}}
\]

As indicated by the Figure 8, for all the distortion levels considered in this study, the mean error in the calculation of DGP was less than 5%. The box-plots in the figure also show that the error increased...
slightly and progressively as the order of distortion was increased. The one major outlier in Figure 8 relates to an instance where the blurring resulted in the erasure of several potential glare sources from the blurred images. The HDR images, both original and blurred, for this instance are shown in Figure 9. As can be noticed by the coloured patches on the original and blurred HDR images, progressive blurring resulted in a reduction of the number of identified glare sources and caused the retained glare sources to shrink in size.

![Figure 9](image-url)

**Figure 9.** Glare sources identified in the outlier scenario in Figure 8. Distortion has been abbreviated to dist. The value of DGP calculated for each of the images is provided in parenthesis.

DGP values calculated within the range of 0.35 to 0.59 can be further categorized according to perceptible, disturbing or intolerable glare as shown in Table 3 [23]. A higher relative error in DGP calculation will lead to the glare being incorrectly categorized. Assuming that an automatic lighting control system will be actuated based on these glare categories, it is possible that larger values of relative errors in calculation of DGP will cause the control system to perform incorrectly. Figure 10 provides a relative comparison of the obfuscation levels as a function of the accuracy with which glare was categorized. For the 87 instances when the glare was categorized between perceptible to intolerable, images that were distorted using blur filters of up to 15%, led to incorrect categorization in 11 or less instances.

**Table 3.** Glare categorization within DGP range of 0.35 to 0.59.

| Range       | Category       |
|-------------|----------------|
| 0.2 <= DGP <= 0.35 | Imperceptible  |
| 0.35 <= DGP <= 0.40 | Perceptible   |
| 0.40 < DGP <= 0.45 | Disturbing    |
| 0.45 < DGP <= 0.59 | Intolerable   |
Figure 10. Number of instances, out of a total of 87, when the DGP values were incorrectly categorized.

5. Discussion and conclusion
The results summarized in the last section indicate that the error associated with the DGPs calculated through obfuscated images is usually within a relative error margin of 5%. In cases where the errors were encountered, the incorrect categorization of error was within a single category. Furthermore, the DGP values were more often underpredicted than overpredicted. For example, in Figure 10, for the 20% blur scenario, of the 16 (out of 87) instances when the glare rating was miscategorized, the glare rating was underpredicted in 14 (87.5%) instances. The underprediction of DGP values can be partially attributed to the fact that potential error sources with smaller solid angles are typically obscured during blurring.

In conclusion, the results from this pilot study indicate that obfuscated images can be employed for glare analysis, especially in cases where the results from such an analysis is intended to categorically actuate a lighting control system. As is logically expected, higher levels of obfuscation were associated with greater margins of error in DGP calculation. So, any real-world applications of obfuscated HDR images for glare analysis will require the selection of an obfuscation level that can strike a balance between privacy of occupants as well as accuracy of data acquisition.

Future initiatives planned for this research relate to a field study involving the use of miniature cameras mounted on a single-board computers for the purposes of HDRI acquisition.

References
1. Boyce P R 2014 Human factors in lighting. 3rd ed., Florida, USA: CRC Press.
2. Galasiu A D and Veitch J A 2006 Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. Energy and Buildings. 38(7) 728-742.
3. DiLaura D L, Mistrick R G, Houser K H, and Steffy G 2011 The lighting handbook: reference & applications. 10 ed., New York, USA: IES.
4. Williams A, Atkinson B, Garbesi K, Page E, and Rubinstein F 2012 Lighting controls in commercial buildings. LEUKOS, 8 161-180.
5. Meerbeek B, te Kulve M, Gritti T, Aarts M, van Loenen E, and Aarts E 2014 Building automation and perceived control: A field study on motorized exterior blinds in Dutch offices. Building and Environment. 79(0) 66-77.
6. Mistrick R G and Casey C A 2011 Performance modeling of daylight integrated photosensor-controlled lighting systems. *Winter Simulation Conference* Pennsylvania State Univ., University Park, PA, United States BT - 2011 Winter Simulation Conference (WSC 2011), 11-14 Dec. 2011

7. Li D H W and Tsang E K W 2005 An analysis of measured and simulated daylight illuminance and lighting savings in a daylit corridor. *Building and Environment*. 40(7) 973-982.

8. Doulos L, Tsangrassoulis A, and Topalis F 2008 Quantifying energy savings in daylight responsive systems: The role of dimming electronic ballasts. *Energy and Buildings*. 40 36-50.

9. Van Den Wymelenberg K and Inanici M 2016 Evaluating a New Suite of Luminance-Based Design Metrics for Predicting Human Visual Comfort in Offices with Daylight. *LEUKOS*. 12(3) 113-138.

10. Inanici M and Galvin J, Evaluation of High Dynamic Range Photographic as a Luminance Mapping Technique. 2004, LBNL: California, USA.

11. Inanici M 2006 Evaluation of high dynamic range photography as a luminance data acquisition system. *Lighting Research and Technology*. 38(2) 123-134.

12. Jakubiec J A, Van Den Wymelenberg K, Inanici M, and Mahic A Year Accurate measurement of daylit interior scenes using high dynamic range photography *Proceedings of the CIE 2016 Lighting Quality and Energy Efficiency Conference*. 2016.

13. Inanici M and Hashemloo A 2017 An investigation of the daylighting simulation techniques and sky modeling practices for occupant centric evaluations. *Building and Environment*. 113 220-231.

14. Reinhard E, Heidrich W, Debevec P, Pattanaik S, Ward G, and Myszkowski K 2010 *High dynamic range imaging: acquisition, display, and image-based lighting*. 2 ed., Massachusetts, USA: Morgan Kaufmann.

15. Debevec P E and Malik J Year Recovering high dynamic range radiance maps from photographs *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*. 1997. ACM Press/Addison-Wesley Publishing Co.

16. Debevec P Year Image-based lighting *ACM SIGGRAPH 2006 Courses*. 2006. ACM.

17. Ward G 1994 The RADIANCE lighting simulation and rendering system. *21st annual conference on Computer graphics and interactive techniques* Florida, USA

18. Inanici M N 2003 *TRANSFORMATION OF HIGH DYNAMIC IMAGES INTO VIRTUAL LIGHTING LABORATORIES*. *Building Simulation 2007* Eindhoven, Netherlands

19. Inanici M, Transformations in architectural lighting analysis: Virtual lighting laboratory. 2004, University of Michigan.

20. Inanici M 2010 Evaluation of High Dynamic Range Image-Based Sky Models in Lighting Simulation. *LEUKOS*. 7(2) 69-84.

21. Jakubiec J A and Reinhart C F 2012 The ‘adaptive zone’—A concept for assessing discomfort glare throughout daylit spaces. *Lighting Research and Technology*. 44(2) 149-170.

22. Wienold J, Reetz C, and Kuhn T 2004 Evalglare: a new RADIANCE-based tool to evaluate glare in office spaces. *3rd International Radiance Workshop* Fribourg, Switzerland

23. Wienold J Year Evalglare 2.0 - new features *15th International Radiance Workshop*. 2016. Padova, Italy.

24. Pierson C, Wienold J, and Bodart M 2018 Review of Factors Influencing Discomfort Glare Perception from Daylight. *LEUKOS* 1-38.

25. Wienold J and Christoffersen J 2006 Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings*. 38(7) 743-757.

26. Mardaljevic J, Andersen M, Roy N, and Christoffersen J 2012 Daylighting Metrics: Is There a Relation between Useful Daylight Illuminance and Daylight Glare Probability? *Building Simulation and Optimization Conference (BSO12)* Loughborough, UK

27. Suk J and Schiler M 2013 Investigation of Evalglare software, daylight glare probability and high dynamic range imaging for daylight glare analysis. *Lighting Research and Technology*. 45(4) 450-463.
28. Painter B, Mardaljevic J, and Fan D Year Monitoring daylight provision and glare perception in office environments *Proc CIB World Congress*. 2010.

29. Korshunov P, Nemoto H, Skodras A, and Ebrahimi T 2014 *Crowdsourcing-based evaluation of privacy in HDR images*. SPIE Photonics Europe. Vol. 9138. SPIE.

30. Kruisselbrink T, Dangol R, and Rosemann A Year Practical issues in field studies using luminance cameras *CIE Expert Workshop on Research Methods for Human Factors in Lighting*. 2018. Copenhagen, Denmark: CIE.

31. Bleicher T 2008 *su2rad* - Radiance exporter for SketchUp. *7th International Radiance Workshop* Fribourg, Germany

32. Perez R, Seals R, and Michalsky J 1993 All-weather model for sky luminance distribution—preliminary configuration and validation. *Solar Energy*. 50(3) 235-245.

33. Perez R, Seals R, and Michalsky J 1993 To all-weather model for sky luminance distribution—preliminary configuration and validation. *Solar Energy*. 51(5) 423.