Evaluation of a low-cost method of HDR photography for Daylight Assessment

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Abstract: Evaluation of the daylight performance of buildings can be done with luminance or illuminance measurements. While illuminance has been used in the past for sufficiency of light, luminance-based metrics show the best fit to occupant responses in visual comfort surveys. Luminance measurements are now possible with High Dynamic Range (HDR) techniques that offer a higher spatial resolution at a large field of view. This research evaluates the HDR image acquisition method using smartphone cameras and the calibration of the HDR images using lux meters. Smartphone cameras have been evaluated for their ability to record luminance values in a range of brightness conditions. The error between the low-cost HDR approach and the conventional approach of HDR imaging is determined and a method for correction factors is proposed. A visual comfort survey of a daylit workshop building is done to evaluate the feasibility and accuracy of the low-cost HDR approach.

Keywords: Daylighting; High Dynamic Range; smartphone camera; visual comfort survey.

1. Introduction

Daylighting has been used as the primary source of lighting in high-performance buildings. It is a common way to reduce the energy consumption of the building (Kurnia et al., 2017) since it has the potential to reduce lighting energy by 40% (Du et al., 2014). The Energy Conservation Building Code (2017) of India mandates a minimum of 40% of the workspaces in buildings (60% for Super ECBC level) to have good daylighting and controls. Office workers perform 10%-25% better when they have the best possible view and daylighting; students in classrooms with the best daylighting were found to have 7% - 18% higher scores than those with the least daylighting (Loisos, 1999). Hence it is important to evaluate the daylight performance for visual comfort for a healthy and productive environment, and to save energy.

To evaluate of the daylight performance of buildings, we can measure as illuminance or luminance. The use of an illuminance meter (also, lux meter) is more common because a lux meter is less expensive than a luminance meter. However, for daylit spaces, luminance-based metrics show a better fit to subjective responses in visual comfort surveys than illuminance based metrics (Van Den Wymelenberg, 2012). High Dynamic Range (HDR) images can quickly capture the luminance within a large field of view at a high resolution (Debevec et al., 1997; Van Den Wymelenberg, 2012). The HDR images are calibrated

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with spot measurements of luminance values from the scene. Past studies show that luminance values extracted from such calibrated HDR images are reasonably accurate compared to luminance values measured by luminance meters. Inanici (2006) and Garcia-Hansen et al. (2013) used Digital Single-Lens Reflex (DSLR) cameras, compared the HDR image pixel values with luminance meter readings, and found an average errors of 10% and 8%, respectively.

This study evaluates smartphone cameras as a low-cost HDRI method which can be useful for building owners, building performance evaluators, lighting experts, and researchers to study light distribution. Low-cost HDRI methods can also be used for sensors towards visual comfort for lighting and blinds control. This approach holds the potential to replace the traditional illuminance-based photosensors to control the overall lighting and façade systems. This paper also looks at using lux meters to replace expensive luminance meters for the calibration of HDR images. A Workshop Building is evaluated using the visual comfort surveys and the results are used to evaluate the feasibility and accuracy of the low-cost HDR acquisition and calibration method.

2. Research Methodology

In this study, seven smartphone cameras (iPhone XR, iPhone 8, iPhone 7, iPhone 6s, iPhone 5s, One plus 6 and One plus 5) and a DSLR camera are used to capture the luminance data of a scene with a wide range of brightness levels. To evaluate the performance of the cameras, the luminance data of the HDR images are compared with the LS-100 luminance meter readings. For the calibration of the luminance values in the HDR image, the exitance-based luminance is measured using KM-LUX-99 Digital Lux Meter. Finally, visual comfort survey of a workshop building is conducted, and the results are used to assess the feasibility of the smartphone-based low-cost HDR approach.

2.1. Data Collection

To acquire HDR images of the scene using all the cameras, normal low dynamic range (LDR) images are acquired along with the luminance value of the calibration card. The set of LDR images for each scene are captured by varying the shutter speed over a range of five values while keeping other settings constant. These settings are *ISO* of 100, and *white balance* set to Daylight (6500 K). An app called the CameraPixels Lite (2018) is used for iOS phones and manual camera settings are used for Android phones.

For the measurement of the calibration card, the exitance of the white card placed at the foveal center of the camera is recorded using KM-LUX-99 Digital Lux Meter before and after capturing the LDR images. The method of measuring exitance is described in Section 2.3. The exitance value recorded is used to calculate the luminance of the white card using Equation (2). This luminance value is used in the for calibrating the HDR images in Photosphere (2009), a MacOS based software.

2.2. Data Processing

The LDR images are fused to make an HDR image for each scene in Photosphere (2009). The camera response curve for the specific camera is also applied to the HDR image in Photosphere (2009). Each HDR image is calibrated as described above. The image file is saved in the (RGBE).hdr format

2.3. Testing the exitance-based luminance calibration method

To minimize the error in using KM-LUX-99 Digital lux meter for the calibration process of the HDR images, two exitance measurement methods are compared

1. By placing the Lux Meter at an angle of 45° to the surface to measure illuminance.
2. By placing the Lux Meter parallel to and 3" away from the surface to measure illuminance.

The exitance is calculated using Equation **Error! Reference source not found.**). The more accurate of he two methods is selected for calibrating the luminance values of the HDR images.

$$\text{Calculated Exitance (Ex)} = \text{Measured Luminance (L)} * \pi \quad (1)$$

$$\text{Exitance-based Luminance (L)} = \text{Exitance measured (M)} / \pi \quad (2)$$

2.4. Testing the performance of seven smartphone cameras for the HDR image with different brightness condition

This step tests the performance of seven smartphone cameras to compare the luminance values from the HDR images and those from the luminance meter readings (Garcia-Hansen et al, 2013). The smartphone cameras for this research are selected based on their ability to capture images with in-built manual settings or by using an app. A scene with a wide range of luminance values (highest = 16,980 cd/m² and lowest = 11 cd/m²) is selected (see Figure 1). The data collection for this step includes LDR image acquisition and luminance readings of the four spots identified in Figure 1. This is repeated for all the smartphone cameras and the DSLR. Further, these images are post-processed using Photosphere (2009) as mentioned in Section 2.2.

The luminance value of the four spots is extracted from the camera HDR image in Photosphere (2009). These luminance values are compared with the luminance readings taken using LS-100 Luminance meter and the DSLR luminance values.



Figure 1 showing the position of the four spots whose luminance readings were measured using luminance meter.

2.5. Evaluating the CEPT University Workshop building for daylight performance

The CEPT Workshop building holds studios for Woodworking, Metalworking, Ceramics & Clay, Weaving/Textile, and Fab Lab. The workshop has a rectangular planform with an area of 1685 sq. m. The workshop building has a north-facing window with high ceiling and large clear span garage doors (see Figure 2).

The survey is conducted for 34 participants for all the spaces in the workshop building. A visual comfort survey questionnaire form is developed based on a survey conducted by Van Den Wymelenberg (2012) and Moeed Chaudhary (2017). LDR images of the scene for each participant (Front, Right and Left) are also acquired at the time the survey is administered.

Analysis of the 34 visual comfort survey forms is carried out. The goal is to investigate the sufficiency of daylight, visual appearance and daylight issues in the spaces. The opinion of 34 participants in the survey is analyzed. The analysis is carried out based on 1) seven-point Likert scale 2) five-point semantic differential scale and 3) Glare condition.

2.6. Assessing the Low-cost method of HDRI for Daylight Evaluation using the Workshop building

After acquiring a good understanding of the visual comfort performance of the workshop building from the survey, the building is used to evaluate the feasibility and accuracy of the low-cost HDR acquisition and calibration method using metrics recommended by Van Den Wymelenberg (2012).

A total of 435 LDR images for 29 participants were captured and processed to get 87 HDR images. Two visual comfort metrics are calculated for each HDR image 1) mean Luminance within 40° horizontal band of vision and 2) percent of luminance below 1000 cd/m² within a 40° horizontal band[1]. To do this, masks are created for the 40° horizontal band of vision in Photoshop (2007) and applied to all the HDR images and the metrics are calculated using a Windows-based software called hdrscope (2013).

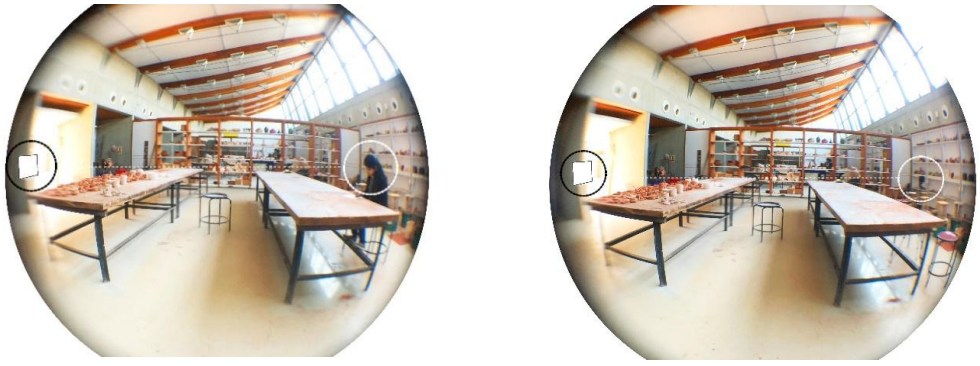


Figure 2 showing the workshop interior captured using the iPhone 8 with a fisheye lens, the scene with white card and participant's position (left), the scene with white card and camera position (right).

[1] These metrics were selected because they showed the highest squared correlation for any metric based upon space-independent mask in the study conducted by Van Den Wymelenberg (2012).

3. Results and Discussion

3.1. The exitance-based luminance calibration method

The values for the exitance measured with a lux meter held 3" away and parallel to the surface are consistently closer to those arrived at using the luminance meter. This method of exitance measurement is used for going forward in this study.

3.2. Performance of seven smartphone cameras for HDR image with different brightness conditions

The luminance values measured with a luminance meter for four surfaces are 1) Very low brightness surface (11-13 cd/m²) 2) Low brightness surface (105-112 cd/m²) 3) Medium brightness surface (431-576 cd/m²) 4) High brightness surface (14410-16980 cd/m²). These luminance values are compared with the luminance values extracted from the calibrated HDR images. In Figure 2, it is observed that the high brightness surface has a very high error for all the smartphone cameras, but not for the DSLR camera.

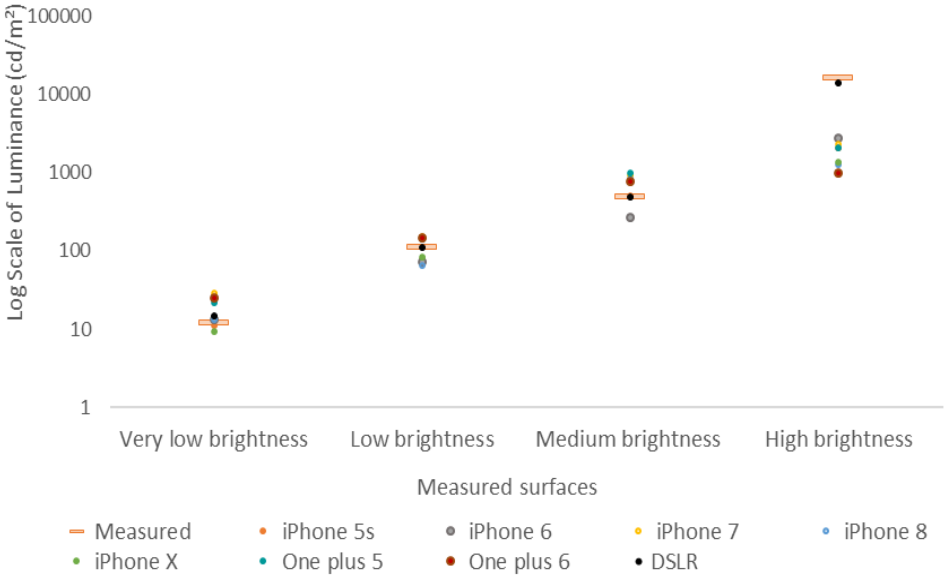


Figure 2 showing the difference between measured and HDR luminance.

The average error percentage (average over four surfaces) for the smartphone cameras is always more than 45%. iPhone 8 shows the lowest average error percentage of 45% and iPhone 7 shows the highest average error percentage of 113%. Meanwhile, DSLR camera performs well with an average error percentage of only 8% which confirms the findings of Inanici (2006).

To compare the ability of the smartphone cameras to capture the luminance of high brightness scene (measured at 16,980 cd/m²), we calculated the ratio of the HDRI based luminance to the measured luminance. iPhone 6 captured a luminance of 2913 cd/m² which is 17% of the measured

luminance. This is the highest ratio of all smartphone cameras. Other smartphone cameras could capture only 5% to 15% of the high brightness scenes. On the other hand, the DSLR camera captured 95% of the measured luminance. It appears that the ability of the smartphone cameras to capture high luminance values is limited with the typical HDR calibration procedures.

Smartphone cameras can capture an HDR image by using an app (CameraPixels Lite, 2018) or manual settings of the in-built camera. Such apps are easily available, and they are quick and easy to use. The apps allow manual settings and bracketing function. This makes HDR imaging easily accessible with smartphone cameras. However, the high errors after the standard calibration procedures can make their luminance values unreliable.

As they are, the utility of these smartphone cameras would have to be limited to learning the concepts and the techniques of HDRI. However, this method can be used more widely beyond education, if the errors can be corrected. A correction could need to be done for each camera for a wide range of luminance values. This can be done as a laboratory calibration process for a range of luminance values. This would provide a set of correction factors, with individual correction factors for each luminance range, for each smartphone camera. These correction factors could then be applied to pixels in an HDR image that falls in that luminance range. We demonstrate the proof-of-concept for doing this manually in section 3.4. We found that doing this for each HDR image is a tedious process and this correction approach needs to be encoded in software such as hdrscope. Hdrscope could provide an interface that allows the user to enter a set of correction factors for a specific camera, which is then applied to the image.

3.3. Visual comfort survey of the Workshop Building

The visual comfort survey establishes a real context for using the smartphone camera HDR approach. The seven-point Likert scale (very strongly disagree to very strongly agree) is used for space-related questions and the participants are asked to give an opinion on the visual appearance and the amount of light.

Table 1 showing the responses for the seven-point Likert scale.

Question	Agree (%)	Neither agree nor disagree (%)	Disagree (%)
The environment is visually comfortable for the intended work.	88	9	3
Satisfied with the amount of light for the intended work.	85	9	6
Satisfied with the amount of light for the paper-based work.	91	6	3
The light is distributed well.	76	9	15

Most of the participants agree that the workshop space is a visually comfortable environment for the intended work. They are also satisfied with the amount of light and agree that the light is distributed well. The sufficiency and good distribution of light could be due to the north light provided in all the workshop spaces which also have vertical white surfaces with high reflectance values.

The Five-point semantic differential scale (dim to bright) consists of scene related questions and the participants are asked to give an opinion on the brightness of the scene. The results of the visual

comfort survey for the five-point semantic differential scale are in Table 2. Most of the participants found the front, left and right scene to be towards the bright side.

Table 2 showing the responses for the five-point semantic differential scale

Question	Bright (%)	Just right (%)	Dim (%)
Brightness of the front scene	50	44	6
Brightness of the left scene	32	59	9
Brightness of the right scene	32	53	15
The light is distributed well.	76	9	15

The Workshop building has achieved visual comfort in terms of visual appearance, amount of light and the distribution of light. The sufficiency of light inside the space is achieved due to the north-facing clerestory windows and the high reflectance interior surfaces. The brightness level of the workshop spaces seems to be just right according to the participants. A higher number of participants reported the spaces towards the bright side than towards the dimmer side. There were no intolerable glare conditions reported. However, some perceptible and disturbing glare were reported, for glare sources such as brightness of the sky, brightness of the hardscape outside the window, sun patches in the space, and brightness from some interior vertical surfaces.

3.4. Applicability of the low-cost HDR techniques for evaluation of the workshop space

Once the visual comfort of the CEPT workshop building has been documented using the survey, the results provide a context to study the applicability of the low-cost HDR technique. The objective is to understand the usefulness of the smartphone camera and its limitations regarding the ability and the accuracy for luminance-based metrics calculation.

These are two errors in the method that needs to be discussed in the context of calculating the luminance-based metrics. The iPhone 8, which is the smartphone used to capture the images of the Workshop has an average error (average across the tested surface luminance values) of 58%. Table 3 shows the errors of this camera for HDR luminance for the surfaces tested. It is observed that the error increases for higher luminance values. The workshop space has surfaces with high reflectance values that have high luminance values. This can result in the inability of the smartphone camera to capture the high luminance scenes. This can result in errors for the visual comfort metrics that are calculated. The workshop, along with the context from the visual comfort survey is used to see how these errors would lead to erroneous conclusions.

Table 3 showing the error percentage of the surfaces measured using the iPhone 8.

Surfaces	Measured Luminance (cd/m^2)	Error %
Very low brightness surface	11.1	21%
Low brightness surface	106.1	38%
Medium brightness surface	450.5	82%
High brightness surface	16980	93%

Mean luminance 40° horizontal band (M1) and Percent of luminance below 1000 cd/m² (M2) are calculated in hdrscope (2013) using a single region of interest. For these metrics, the borderline between comfort and discomfort (BCD) according to Van Den Wymelenberg (2012) is 500-700 cd/m² for M1, and 87%-94% for M2. It should be noted that the BCD is based on Van den Wylemenberg's study carried out for south-facing office space and may not be directly applicable to a workshop space. Even so, the objective here is to use smartphone camera-based HDRI for calculating the metrics and analyzing them to reveal the usefulness of the low-cost method.

For M1, it is observed that 91% of all the 87 scenes from the workshop are lower than the BCD range, 6% of all the scenes are above the BCD range and only 3% of all the scenes are within the BCD range. Given the errors noted in Table 3, the scenes with low mean luminance values are likely to stay below the BCD after corrections and are unlikely to lead to a different conclusion. However, scenes with mean values between 250 cd/m² and 500 cd/m² may end up in the BCD after correction, thus changing the conclusion about the space. Similarly, scenes with high mean luminance are likely to lie above the BCD after correction. This clearly shows the need to correct the HDR values unless the scenes are in low to very low brightness conditions or very bright conditions.

To demonstrate this point further, the raw luminance values for each pixel in two scenes were extracted and correction factors were applied manually to each pixel value using data from Table 3. In Figure 3, it is observed that for M1, the low brightness scene stays below the BCD, but the high brightness scene moved from just below the BCD to above the BCD. For M2, the low brightness scene stayed above the BCD, but the high brightness scene moves from within the BCD to just below the BCD.

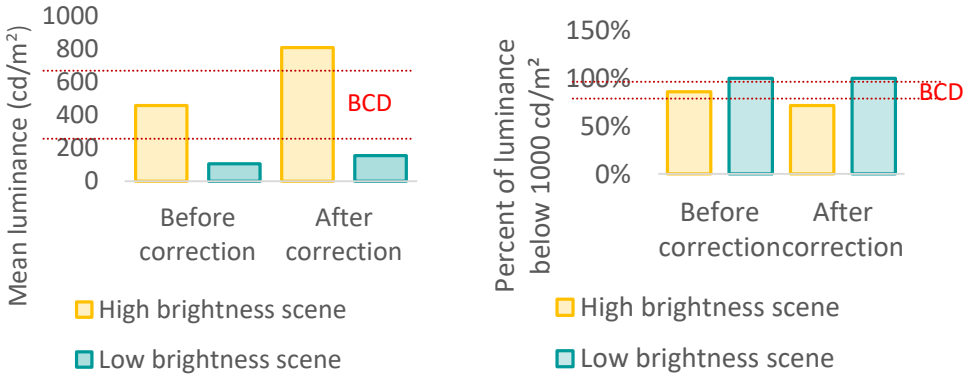


Figure 3 showing the before and after correction of the luminance data for M1 (left) and M2 (right).

4. Conclusion

HDR imaging is a relatively new method for quickly capturing a large dataset of luminance levels in a space. In this study, low-cost methods for HDRI are evaluated for daylighting evaluation of spaces.

Lux meter for calibration of HDRI images is found to be reasonably accurate (average error of 7%) when used with a white card or a colored card that has a reflectance value higher than 40%, and measurements are taken 3" away and parallel to the card.

The use of smartphone cameras is an inexpensive and fast method of LDR image acquisition for HDRI. These instruments are more easily accessible than the conventional method of HDRI. Apps such as CameraPixels Lite (2018) allow manual settings and have bracketing functions to make the LDR acquisition easier. Photosphere (2009) also allows a quick fusing of the LDR images to convert them into HDR images. However, while the calibration of the HDR images in Photosphere (2009) may be adequate for DSLR-sourced HDRI, it needs to be improved for smartphone camera-sourced HDRI. hdrscope (2013) can calculate the luminance-based metrics by applying a mask to the HDR images.

Of the 6 smartphones studied, the maximum luminance was captured by iPhone 6 and which could only capture 17% of the measured luminance (16,980 cd/m^2), while the DSLR could capture 95%. This study shows that larger errors are observed for high brightness scenes, and this may be because the smartphone cameras sensors are being optimized by manufacturers for low lighting conditions and hence tend to have problems for luminous overflow under high brightness conditions.

This low-cost method of HDRI also allows the calculation of the luminance-based metrics using hdrscope (2013). However, smartphone camera-sourced HDRI gives large errors for luminance values. Hence these HDR luminance data need to be corrected for reliable data to evaluate a space. The DSLR camera in this study performs well and its average error is less than 8%.

The low-cost method for HDRI investigated in this study holds some promise for daylighting and visual comfort evaluation of spaces if correction factors for each camera are established, included in software such as hdrscope. We recommend this as a future research and development activity.

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