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# LUMINANCE MEASUREMENTS USING SMARTPHONE CAMERAS

THOUNAOJAM A.[1*], VAIDYA P.[2], MUNDHE P.[3] & MASKARENJ M.[4]
[1,2] Indian Institute for Human Settlements, Bengaluru, India
[3] Environmental Design Solutions, Delhi, India
[4] Catholic University of Louvain, Louvain-la-Neuve, Belgium
[1]*amandat@iihs.ac.in*, [2]*pvaidya@iihs.ac.in*, [3]*mundhepooja03@gmail.com*,
[4]*marshal.maskarenj@gmail.com*

**Abstract:** We evaluate the daylight performance visual comfort buildings by measuring light in luminance and illuminance using luminance and lux meter respectively. Detailed measurements of illuminance in a space using these methods on a grid can be time-consuming, while luminance meters to measure luminance values are quite expensive. Recent studies indicate that luminance-based metrics have the best fit to occupant responses in visual comfort surveys. But High Dynamic Range (HDR) techniques can quickly capture a large field of view at a high resolution and can be done with DSLR cameras that are more accessible than luminance meters. This research goes one step further to evaluate the HDR acquisition method using even more accessible smartphone cameras. The method includes calibration of the HDR images using lux meters which are affordable and easily available. A variety of smartphone cameras were evaluated in a wide range of brightness conditions in a scene. 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. Vignetting corrections for the smartphone camera lens have been demonstrated. A visual comfort survey of a primarily daylit workshop space is done to document as a test case to evaluate the feasibility and accuracy of the low-cost HDR approach. Lux meter for calibration of HDRI images is found to be reasonably accurate (average error of 7%). Of the 6 smartphones studied, the maximum luminance was captured by iPhone 6 and which could only capture 17% of the measured luminance. The fisheye lens used in this study increases the FOV from 68º (no fisheye) to 136° (with fisheye) but the FOV outside 100° was not useful due to large vignetting effect.

***Keywords:*** *High Dynamic Range; Luminance; Illuminance; visual comfort survey; luminance-based metrics.*

## 1. Introduction

Architects and builders have used daylighting as the primary source of lighting for centuries, and now recently we see this in high-performance buildings. Studies have also shown that lack of awareness in integration of daylight in design can result in excessive daylight exposure or lack of adequate daylighting (Wijesundara & Gamage, 2021). Beyond the energy savings benefits, where it has the potential to reduce lighting energy by 40% (Du, Hellström, & Dubois, 2014), daylighting has a positive impact on health and wellbeing of the occupants. 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). Recent studies explore the effect of daylight variation on spatial quality, human perception, and impact of daylight on circadian rhythms of the body. Hence it is important to evaluate the daylight performance for visual comfort (Pathirage & Perera, 2022, Gochenour & Andersen, 2009)

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 (Wymelenberg Kevin Van Den, 2012). High Dynamic Range (HDR) images can quickly capture the luminance within a large field of view at a high resolution (Debevec, Paul E.; Malik, 1997; Wymelenberg Kevin Van Den, 2012) and can provide a more accessible way to do luminance measurements. However, HDR images need to be calibrated with spot measurements of luminance values from the scene, which still require expensive luminance meters.

Past studies show that luminance values extracted from such calibrated HDR images are reasonably accurate compared to luminance values measured by luminance meters. Inanici (Inanici, 2006) and Garcia-Hansen et al. (Garcia-Hansen, Cowley, Smith, & Isoardi, 2013) used Digital Single-Lens Reflex (DSLR) cameras, compared the HDR

*Corresponding author: Tel: +91 8095303188 Email Address: amandat@iihs.ac.in
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image pixel values with luminance meter readings, and found an average errors of 10% and 8%, respectively.

This study looks at accessible measurements in two different ways. One, it evaluates smartphone cameras as a low-cost image acquisition method. Two, it evaluates a method to do spot measurements of luminance for calibrating HDR images using low-cost lux meters. Combined together, this 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 with cheap digital cameras to control lighting and blinds for visual comfort. This study also looks at the method of correcting the vignetting effect of a low-cost fisheye lens. 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

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 evaluated. They 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 ("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 2.4. The exitance value recorded is used to calculate the luminance of the white card using Equation (6). This luminance value is used in the for calibrating the HDR images in Photosphere (Photoshpere, 2009), a MacOS based software.

### 2.2. VIGNETTING CORRECTION

The vignetting correction mask is applied for images taken using the fisheye lens to correct the brightness decrease observed from the center of the picture to its periphery. This needs to be corrected to ensure accuracy in the luminance maps. The vignetting experiment is carried out in an artificial sky (see figure 1). The white and the gray card experimental set-up are arranged in a semi-circle under the artificial sky. The whole set up consisted of 52 gray and white cards.

Figure 1 showing the experimental set-up for the vignetting correction of the fisheye lens used in the artificial sky simulator.

In order to determine the vignetting filter to correct the vignetting effect, the first step is to create an HDR image of the 7 LDR images. This is done by fusing the LDR images in the Photosphere (Photoshpere, 2009). The luminance values of the center of each card are extracted from the HDR image. The luminance extracted are further calibrated using the physical measurements as shown in equation (1).

$$\text{CF white card} = \text{Llum } 0° / \text{LHDR0°} \quad (1)$$
$$\text{CF gray card} = ((\text{Llum } 2° / \text{LHDR2°}) + (\text{Llum } 1° / \text{LHDR1°}))/ 2$$

where CF white card and CF gray card are the calibration factor of the white and gray card respectively.

Llum 0°, Lum 2°, and Llum 1° are the physical luminance measurements measured at a central white card, the gray card positioned at 2° on the first quadrant and the gray card positioned at 1° on the second quadrant.

Finally, the calibrated luminance is as shown in equation (2)

$$LHDR\_cal_{\theta x} = LHDR_{\theta x} * CF \quad (2)$$

where LHDR_calɵx is the luminance at ɵx after calibration, LHDRɵx is the luminance at ɵx extracted from the HDR image and CF is the calibration factor of the white or gray card.

The vignetting effect is further determined for each card using the equation (3) and finally, the vignetting filter is established as the inverse of the vignetting effect as shown in equation (4).

$$V_{\theta x} = LHDR\_cal_{\theta x} / Llum_{\theta x} \quad (3)$$

where Vɵx is the vignetting effect at ɵ = x°, LHDR_calɵx is the luminance at ɵx after calibration and Llumɵx is the luminance measured at ɵ = x° with the LS-100 Luminance meter.

$$\text{Vignetting Filter} = 1/V_{\theta x} \quad (4)$$

Using the vignetting filter, a polynomial fit function is developed using Excel and this function is used to convert into a grayscale image called the digital filter. The digital filter is a .hdr mask file which can be applied to each and every scene HDR images for vignetting correction using hdrscope ("hdrscope Software," 2013).

2.3. DATA PROCESSING

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

2.4. 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

- By placing the Lux Meter at an angle of 45° to the surface to measure illuminance.
- By placing the Lux Meter parallel to and 75 mm away from the surface to measure illuminance.

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

$$\text{Calculated Exitance (Ex)} = \text{Measured Luminance (L)} * \pi \quad (5)$$

$$\text{Exitance-based Luminance (L)} = \text{Exitance measured (M)} / \pi \quad (6)$$

2.5. TESTING THE PERFORMANCE OF SEVEN SMARTPHONE CAMERAS FOR THE HDR IMAGE WITH DIFFERENT BRIGHTNESS CONDITION

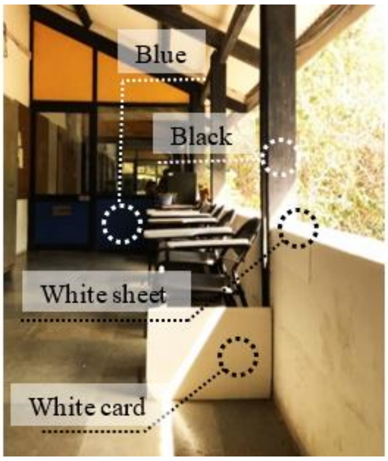


Figure 2 showing the position of the four spots whose luminance readings were measured using luminance meter.

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, (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 2). The data collection for this step includes LDR image acquisition and luminance readings of the four spots identified in Figure 2. This is repeated for all the smartphone cameras and the DSLR. Further, these images are post-processed using Photosphere (Photoshpere, 2009) as mentioned in Section 2.3.

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

2.6. 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 3).

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 (Wymelenberg Kevin Van Den, 2012) and Moeed Chaudhary (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.

2.7. 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 (Van & 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. To do this, masks are created for the 40° horizontal band of vision in Photoshop ("Adobe Photoshop CS3 Extended," 2007) and applied to all the HDR images and the metrics are calculated using a Windows-based software called hdrscope ("hdrscope Software," 2013).

Figure 3 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).

## 3. Results and Discussion

3.1. THE EXITANCE-BASED LUMINANCE CALIBRATION METHOD

The values for the exitance measured with a lux meter held 75 mm 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 4, it is observed that the high brightness surface has a very high error for all the smartphone cameras, but not for the DSLR camera.

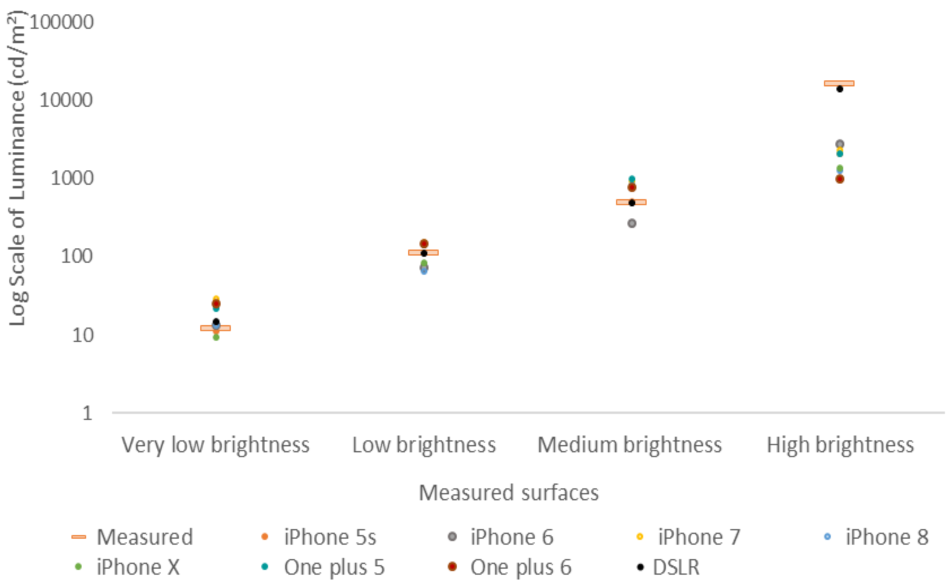


Figure 4 showing the difference between measured and HDR luminance.

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 (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, ("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 3.5. 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. VIGNETTING CORRECTION

To correct the vignetting effect of the images captured using the fisheye lens, the vignetting correction is carried out. It is observed that without the fisheye lens, the iPhone 8 camera could capture a 68° FOV and with the fisheye lens, it could capture a 136° FOV (see figure 5 left).

It is observed that the calibrated luminance values are very close to that of the measured luminance. The vignetting effect is further determined for each card using equation (3).

In figure 5 (right), there is a high variation observed in the measured and HDR luminance after a 50° angle. The fisheye lens could capture a 136° field of view (FOV). According to (Choudhury, 2016) the approximate FOV of a human eye is 120° horizontally and 135° vertically. However, the fisheye lens gave a reliable 100° field of view (FOV). Hence, a mask with 100° projection angle is applied in all the camera HDR images for vignetting correction but this may result in the exclusion of the glare sources in the periphery of the scene.

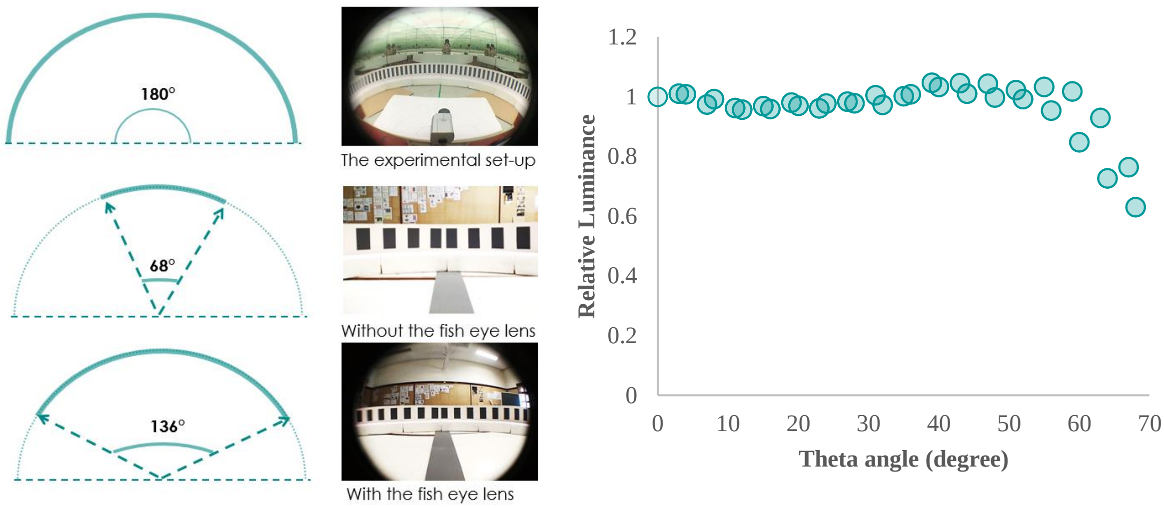


Figure 5 shows the comparison of the calibrated luminance and the measured luminance (left) and the vignetting effect of the measured and the HDR luminance (right)

3.4. 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 (see table 1). 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.

### 3.5. 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 $cd/m^2$ (M2) are calculated in hdrscope ("hdrscope Software," 2013) using a single region of interest. For these metrics, the borderline between comfort and discomfort (BCD) according to Van Den Wymelenberg (Van & Wymelenberg, 2012) is 500-700 $cd/m^2$ 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 $cd/m^2$ and 500 $cd/m^2$ 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 5, 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.

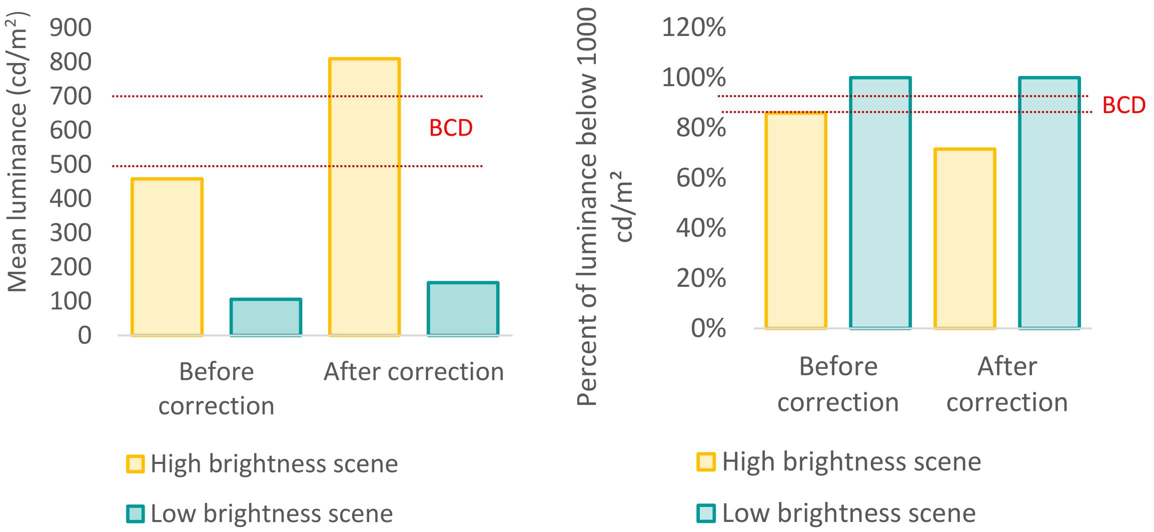


Figure 6 showing the before and after correction of the luminance data for M1 (left) and M2 (right).

## 4. Conclusion

HDR imaging is a relatively new method for quickly capturing a large dataset of luminance levels in a space. In this study, smartphone cameras and lux meter-based calibration are evaluated as low-cost methods for HDRI based luminance analysis of daylit 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 any colored card with a reflectance value greater than 40%, and measurements are taken 75 mm away and parallel to the card.

In this study, CameraPixels Lite ("CameraPixels Lite," 2018), a smartphone app was used for LDR acquisition. Photosphere (Photoshpere, 2009) was used for fusing of the LDR images to convert them into HDR images. It was found that while Photosphere (Photoshpere, 2009) may be adequate for calibration of DSLR-sourced HDR images, it needs to be improved for smartphone camera-sourced HDR images. hdrscope ("hdrscope Software," 2013) can calculate the luminance-based metrics by applying a mask to the HDR images.

Of the 6 smartphones studied, iPhone 6 captured the highest luminance of 2913 cd/m$^2$, which was only 17% of the measured luminance (16,980 cd/m$^2$), while the DSLR captured 95%. Thus larger errors are observed for high brightness scenes, which 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.

The fisheye lens used in this study increases the FOV from 68º (no fisheye) to 136° (with fisheye) but the FOV outside 100° was not useful due to large vignetting effect.

This study tested the low-cost method of HDRI for calculation of the luminance-based metrics using hdrscope ("hdrscope Software," 2013). However, smartphone camera sourced HDRI gives large errors for high 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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