ACCURATE MEASUREMENT OF DAYLIT INTERIOR SCENES USING HIGH DYNAMIC RANGE PHOTOGRAPHY

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Abstract

This paper investigates accuracy in typical High Dynamic Range (HDR) photography techniques used by researchers measuring high resolution luminance information for visual comfort studies in daylit spaces. Vignetting effects of circular fisheye lenses are investigated for reproducibility between different lenses of the same model and sharing between researchers. The selection of aperture size is related to vignetting intensity, dynamic range and potential for lens flare. Lighting variability during capture processes is also tracked, and it is recommended to measure vertical illuminance in order to validate the stability of a scene. Finally, luminous overflow—a concept where a HDR photograph cannot measure the true luminous environment—is introduced. Its effect on the glare metrics UGR and DGP is investigated by using neutral density (ND) filters to increase the dynamic range of photographs under direct sunlight. It is recommended to use ND filters in scenes with vertical illuminances greater than 5 000 lx or with direct vision of the sun.

Keywords: Lighting Measurements, High Dynamic Range Photography, Luminance

1 Introduction

High Dynamic Range (HDR) photography is used increasingly in research and practice to capture high resolution luminance data for analysis of visual perception and comfort in architectural spaces. HDR photography refers to a process by which multiple photographic exposures are taken using an ordinary digital camera and calibrated with a luminance sensor reading and specialized computer software. The result of this process is a point-in-time measurement where a discrete luminance value is associated to each pixel in a photograph. In contemporary research, one use of HDR photographs is to assess visual comfort in daylit spaces (Fan, 2009); (Painter, 2010); (Van Den Wymelenberg, 2010); (Van Den Wymelenberg, 2014); (Konis, 2013); (Konis, 2014); (Jakubiec, 2014); (Hirning, 2013); (Hirning, 2014). HDR photography is specifically attractive to researchers because of its low cost relative to laboratory sensors and its use of widely available camera equipment; however, it is also a labour-intensive process that must be carefully choreographed in order to avoid measurement errors.

When taking HDR photographs, the user is left with a huge variety of choices beyond what is recommended by existing research (Inanici, 2006). The goal of this study is therefore to analyse a selection of important factors necessary for producing accurate HDR photographs of daylit, interior spaces. Specifically, this paper analyses the measurement of lens vignetting, the choice of lens aperture, realities of HDR capture in dynamically daylit scenes, and the inability to capture the full range of luminances in very bright scenes with direct view of the sun or strong specular reflections. This final component addresses an emerging concept known as luminous overflow (Jakubiec, 2015), a condition where the dynamic range of a HDR photograph is less than the true luminous range of the visual reality. Specifically, luminous overflow is an important concept for visual comfort researchers to be aware of as reductions in peak luminance will reduce derived contrast measures, the direct component of image-calculated illuminance, and the range of predicted values detected by visual discomfort metrics.

1.1 General HDR Capture Methodology

For all HDR captures in this manuscript, the authors follow the best practice methods laid out by Inanici (2006). Additional luminance and new vertical illuminance measurements are taken in order to help quantify error sources, and in Section 5 neutral density (ND) filters are used to

increase the dynamic range of HDR photographs. The equipment list and detailed measurement processes used in this paper are as follows. Canon EOS 1D (Original) and 5D (Original, Mark II and Mark III) cameras were used to take the low dynamic range (LDR) photographs, which create a HDR photograph. These models are chosen because they have a full-frame 36 mm x 24 mm sensor, which can contain the projected image from a circular fisheye lens without cropping. Other camera brands with full frame sensors would be equally appropriate. All photos were taken mounted on a fixed tripod so as to minimize image drift and misalignment. A neutral grey card was present in the field of view for all photographs, serving as a chromatically neutral measurement source for the purposes of luminance calibration. Circular fisheye lenses with known projections are utilized as is typical in visual comfort research. The authors employed either the Sigma 8mm F3.5 EX DG or the Canon EF 8-15mm f/4L USM lenses. Because the Canon lens uses an equal-solid angle projection, its images are transformed into an equal-angle projection as used by the Radiance "-vta" angular image projection type (Ward, 1994) before being converted into a HDR image. Identical Exchangeable image file format (Exif) image metadata as relied upon by HDR software was maintained during this process.

Before and after each HDR capture process, luminance was measured from the neutral grey card using a Konica Minolta LS-110 luminance meter. Vertical illuminance in front of the lens is also measured at the same time using a Konica Minolta T-10a illuminance meter, before and after each capture process. Aperture is fixed to a specific f-stop in order to maintain the focus and depth of field of the HDR image. Exposures are taken from slow to fast beginning at 4 s such that the amount of light is halved at each exposure, resulting in LDR images with the following exposure speeds: 4 s, 2 s, 1 s, 1/2 s, 1/4 s, 1/8 s, 1/15 s, 1/30 s, 1/60 s, 1/125 s, 1/250 s, 1/500 s, 1/1 000 s, 1/2 000 s, 1/4 000 s, and 1/8 000 s. In photographic terms the halving or doubling of the amount of light arriving at the camera sensor is known as a 'one stop' change and can be adjusted by shutter speed or aperture. In Section 5's experiments with ND filters, exposure times were up to 30 s long in dim settings. White balance is always fixed to the daylight setting in order to minimize chromatic shift and sensing differences among multiple exposures or various captured scenes. All other camera post-processing functions such as image sharpening, saturation control, or noise reduction are turned off. ISO sensor sensitivity is set to 100 for the dual purposes of reducing image noise and extending the peak dynamic range of the photographs. Focus is set to manual in order to avoid different depths of field between images due to refocusing.

A step in any HDR capture process is to calibrate the image pixel values relative to sensor non-linearities (Mitsunaga, 1999). In this study, the Photosphere (Ward, 2005) software is used for this process and to convert the multiple LDR images into a single HDR photograph. In addition, the mean of the two grey card luminance measurements is used as a scaling factor to fully calibrate the image for each HDR photograph taken. Because LDR exposures are captured frequently at one stop intervals, the response curve will have a small effect on total luminous accuracy. When taking fewer LDR images, the response curve becomes more important.

1.2 Assessment of HDR Images

Inanici (2006) compared spot-measurements of luminance with HDR-derived pixel values in order to measure the validity of the captured luminance data of indoor and outdoor objects ranging from 1 cd·m^{-2}–16 000 cd·m^{-2}. However, in bright sunlit conditions, luminance can be orders of magnitude higher than the capacity of a luminance meter to measure. For example, the luminance meters utilised in this study cannot measure beyond 999 900 cd·m^{-2}, but the luminance of the sun can be as high as a billion cd·m^{-2} (Grondzik, 2006). In order to avoid this issue, the authors assess fisheye image-derived vertical illuminance relative to the measured vertical eye illuminance in such cases. In order to track the dynamic range of images, the peak luminance pixel value is also extracted from each image.

Differences in derived metrics, such as human visual comfort, are additionally tracked. The CIE-recommended UGR (CIE, 1995) and the recent DGP (Wienold, 2006) metrics are chosen for this purpose in order to understand typical differences in image evaluation associated with different capture methods. All derived visual comfort metric values are extracted using the Evalglare tool version 1.17 (Wienold, 2015). These metrics are summarized and compared by Jakubiec (2012), and are covered in detail by the sources cited above. The subjective evaluation criteria of the two metrics are documented below in Table 1.

Table 1 – Visual Comfort Metric Value Ranges

	DGP	UGR
Imperceptible	< 0,35	< 13
Perceptible	0,35–0,40	13–22
Disturbing	0,40–0,45	22–28
Intolerable	> 0,45	> 28

2 Lens Vignetting Effects

HDR images exhibit a noticeable decrease in brightness from the image centre to the perimeter of the image. This effect is known as vignetting, and for each pixel can be determined by comparing the HDR-based pixel luminance to an independent sensor-measured value (Cauwerts, 2012); (Inanici, 2006). Light reduction at the image periphery due to vignetting is particularly extreme in circular fisheye photos. Inanici (2010) found cases where light reduction was as high as 60 percent. Typically researchers employ one of two methods in measuring the vignetting effect. The first is to take a single HDR photograph with targets of known luminance arrayed about the lens opening in precise angular increments (Cauwerts, 2012). The second method is to use a single fixed target of known luminance and rotate the camera about its focal point in small increments, capturing a HDR at each angular rotation (Inanici, 2006). Both methods must be carried out under constant electric lighting conditions as daylight is too variable to be used reliably. In this study, vignetting is measured using the second method.

Cameras are mounted on a tripod with a special panoramic attachment head that allows rotation about the nodal point of the lens as depicted in Figure 1. Mounting at the camera base as typical with a regular tripod mount would result in image parallax errors. HDR photographs were captured in 5 degree rotational increments starting with the grey card at the centre of the image frame until it was located at a 90 degree azimuthal angle to the lens opening, resulting in 19 HDR images per vignetting measurement. Although lighting conditions are stable, automation software on a laptop takes the many LDR images in a time-efficient manner. This process was repeated for different apertures; aperture f-stop is known to have an effect on vignetting, typically with lower numerical apertures (larger opening) having a stronger vignetting effect. Two Canon EF 8-15mm f/4L USM and 5 Sigma 8mm F3.5 EX DG lenses were compared in order to test whether vignetting correction functions are universal or need to be derived separately for different copies of the same model of lens. Cauwerts and others (2012) found that vignetting functions are nearly universal for the same model of lens and aperture setting.

The results of this comparison are illustrated in Figure 2. Aperture selection is indicated by the colour of the dots and lines, while separate lenses are indicated by the point style. Variation between the measured vignetting across the two lenses, yielded a very low deviation from the mean of each angular measurement. The root mean square deviation (RMSD) ranges from 0,6 % to 2,9 % for the four tested apertures. Furthermore, the 5 separate Sigma lenses had a deviation of less than 2 % from the mean at f/11 and less than 1% at f/8 (3 lenses compared). Therefore the results of this study also support Cauwerts' findings: vignetting functions can be derived per model of lens and are most likely acceptable for sharing between researchers using the same equipment. Furthermore, an interesting finding is that while lower numerical apertures tend to have more extreme vignetting effects, f/8 actually exhibits less vignetting than f/11 using the Sigma lens. While the two apertures are close (1 stop) apart, it is worth noting that the common trend of lower aperture resulting in greater vignetting is not the rule.

3 Aperture Selection

Bearing in mind the results from Section 2, HDR images can be taken using any aperture as long as appropriate vignetting corrections are measured and applied. It is therefore reasonable to ask, what factors would lead one to select a specific aperture when taking a HDR photograph? Two additional issues influencing aperture selection are analysed in this section: effects on the luminous range of the capture and increased risk of lens flare.
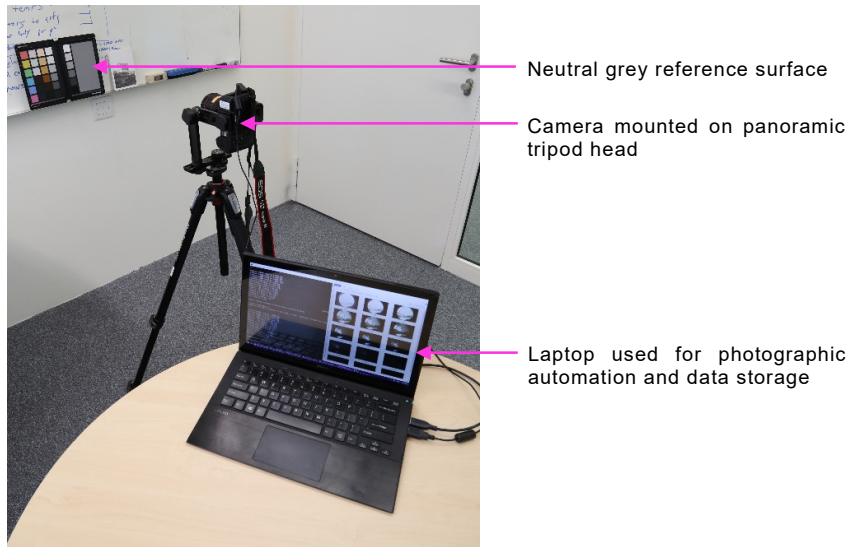
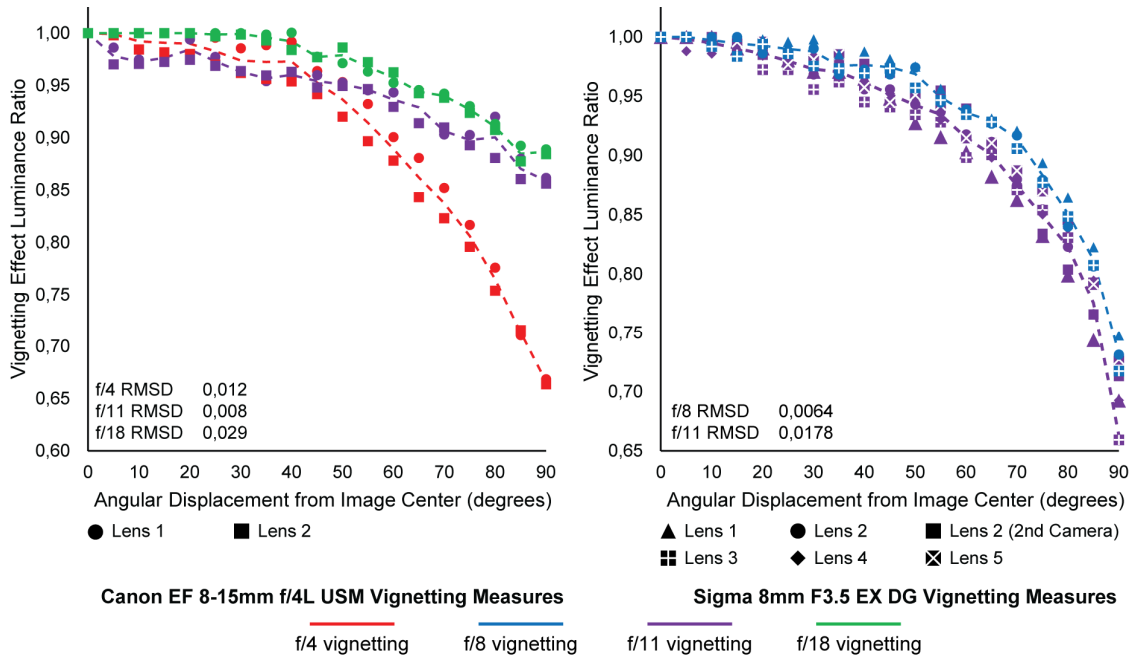**Figure 1 – Typical Vignetting Measurement Setup**

**Figure 2 – Vignetting Comparisons Between Separate, Identical
Lenses at Various Apertures**

The maximum luminances measurable from an HDR image are compared in Figure 3 based on a range of apertures covering 5 exposure stops while viewing the direct solar disc (see Figure 4). These peaks do not account for an additional luminance range boost due to vignetting correction at the image periphery. Decreasing an exposure by 1 stop, halves the amount of light; therefore, the expected dynamic range should increase by a factor of 2^5 (32) between f/4 and f/22. This geometric rule is almost perfectly observed in the measurements. At f/4 the maximum image luminance is 105 850 cd·m^{-2}, and at f/22 the maximum luminance is 3 203 156 cd·m^{-2}, a range increase by a factor of $1,978^5$ (30,26). More open apertures (lower numerical values) have a lower maximum luminance threshold when compared to smaller apertures (higher numerical values). Figure 3 also displays DGP and normalized UGR values predicted using the resulting images. UGR results were multiplied by a scaling factor of 0,01607 in order to make the two measures directly comparable in this figure (Jakubiec, 2011). It is clear from their ascending values that increased luminous range in the photograph can change visual

comfort results from very near the imperceptible range (f/4) to the disturbing or intolerable range (f/22). Therefore, using the smallest available aperture with any given lens appears to make sense if only the maximum luminance value in the scene is considered. This will result in an image with the most minimal vignetting correction necessary and the highest dynamic range; however, higher numerical apertures also lead to an increased risk of lens flare.
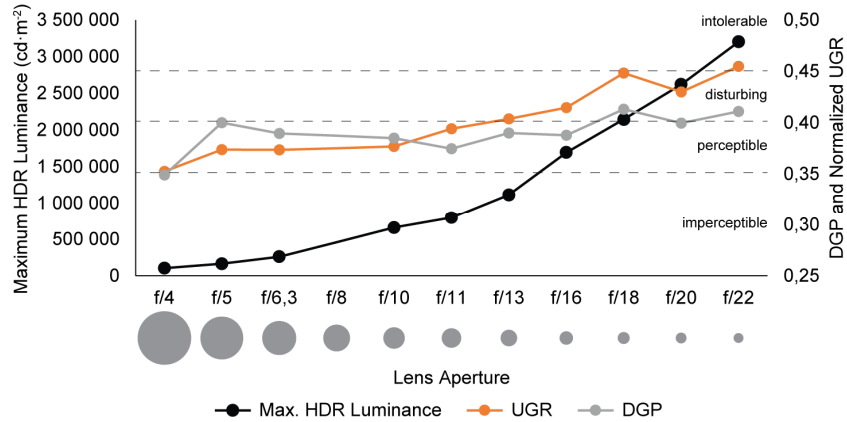

Figure 3 –Luminous Ranges and Normalized Visual Comfort Results of Standard HDR Captures Using a Range of Apertures

The visual aspects of the 10 HDR photographs in Figure 3 are analysed relative to potential for lens flare in Figure 4. Lens flare is when light is scattered within the lens and results in the appearance of false artefacts in resulting images. The dashed pink circles on top of the tonemapped images show the extent of visually perceptible flare effects, and the radius of that effect is numerically described in radians at the bottom of each photograph. In addition, an inset falsecolor luminance mapping shows the most prominent flare effects from the area around the solar disc. While higher numerical apertures show positive effects in vignetting and luminous range, there exists a trade-off in increased lens flare. Lower apertures exhibit a smaller radius of effect, such that f/4 has a noticeable 0,65 rad effect size while f/22 lens flare could potentially consume the entire image with an effect size of 3,16 rad (~π). In addition, the strength and contrast of the effects to the surroundings get progressively worse as the numerical aperture increases. As a result, the authors decide to use the f/11 aperture, because it exhibits relatively minimal vignetting and is a negotiation between an acceptable luminous range and lens flare effects. However, the purpose of sharing these measurements is to help researchers make an informed decision regarding camera settings and their potential benefits and drawbacks.
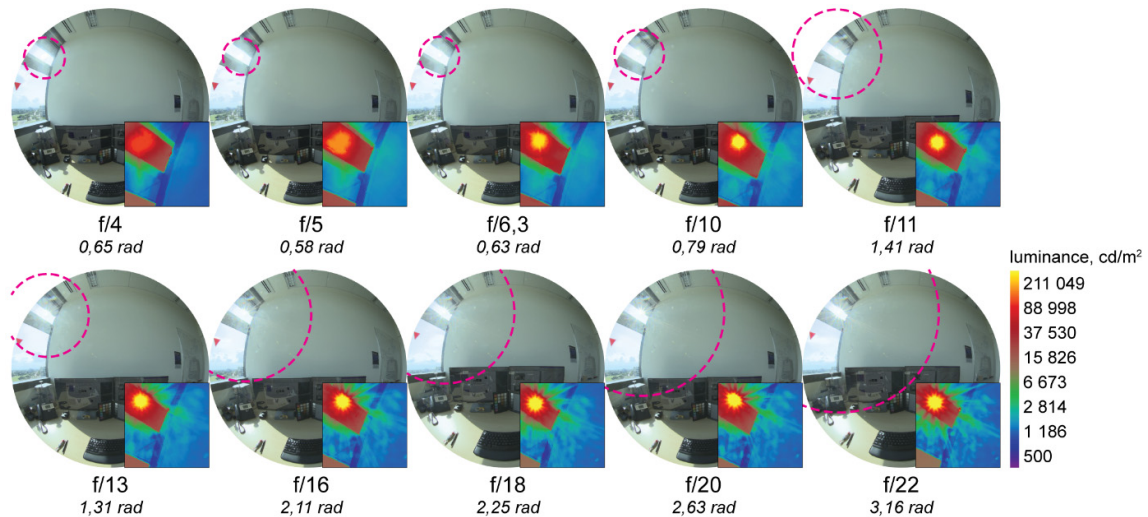

Figure 4 – Visual, Angular and Luminous Comparison of Lens Flare Effects from a Direct Solar Source

4 Environmental Variability During Capture Process

One potential source of error in capturing HDR photographs under daylit conditions is that natural light sources, the sun and sky, are rarely constant. The earth is always moving relative to the sun—1° every 4 minutes—and clouds can change position quickly, significantly altering the luminance levels sensed by the camera during the capture process. Because of this, photographers must be aware of their luminous environment. The authors recommend to take luminance measurements of a grey card and illuminance measurements at the lens opening before and after a HDR photograph as described in the capture methodology section (1.1). By doing so, lighting changes during the capture process can be quantified.

For the HDR photographs taken during this study, the deviation of these before and after measures was compared to the mean value. For example, an image with a pre-illuminance measurement of 22 910 lx and a post-illuminance measurement of 17 530 lx has a deviation from the mean of 2 690 lx ([22 910 lx - 17 530 lx] / 2). Descriptive statistical measures allow us to quantify and compare these changes in lighting, presented in Table 2 below. Relatively small fluctuations in luminance levels are seen from the grey card measurements, with a mean deviation of 4,72 cd·m^{-2} and a maximum deviation of 97,45 cd·m^{-2}; however, illuminance changes are substantial. The mean illuminance deviation is 926,8 lx. This is significant as the illuminance goal on a horizontal workplane in an office is 300–500 lx, and recent studies have shown that vertical illuminance levels of 1 500 lx in perimeter daylit zones indicate discomfort (Jakubiec, 2015); (Van Den Wymelenberg, 2014).

Table 2 – Descriptive Statistics of Luminance and Luminance Measurement Deviations during 164 HDR Photographic Capture Processes

	Luminance Deviation (cd·m^{-2})	Illuminance Deviation (lux)
Minimum	0,00	0,0
1st Quartile	0,1	20,8
Median	0,96	115,0
Mean	4,72	926,8
3rd Quartile	3,17	607,4
Maximum	97,45	15 580,0

From this comparison, it is clear that large changes in illuminance due to cloud cover and sky variability may not result in significant luminance changes at the grey card. A likely reason for this discrepancy is that the grey card often faces away from the window in order to be visible in the photograph, and only diffuse, reflected room light falls upon it. For this reason monitoring lighting changes using illuminance as well as luminance is reasonable. The authors note that extreme lighting changes were removed from our dataset for analysis in the following section. Furthermore obvious lighting changes such as clouds obscuring the solar disc during a capture resulted in the capture sequence being stopped. Although this was a frequent occurrence, it is not reflected in the data for this reason.

5 Luminous Overflow

Even the highest numerical aperture on the lenses in this study (f/22) has a peak luminous range of around 3 million cd·m^{-2} (see Section 3), significantly less than the true luminance of the unshaded sun. This inability to measure high luminances is known as luminous overflow—a condition where the dynamic range of the HDR photograph is not great enough to capture the true luminous range of the visual reality. As seen in Figure 3, overflow can have strong effects on derived visual comfort metrics such as DGP and UGR as they both strongly rely upon contrast, and the computed magnitude of such contrasts directly relate to the photographic range under conditions with specular reflections or direct vision of the sun. DGP relies upon accurate vertical illuminance measures at the eye, and the direct component of illuminance can be severely underestimated when overflow occurs.

The concept of luminous overflow has been introduced before. Stumpfel and others (2004) found that a multi-aperture approach when paired with a ND-3 filter allows capture of the full dynamic range of the sky. Other studies have investigated prototype corrective measures for images exhibiting overflow when paired with independent illuminance measurements (Jakubiec, 2015). Furthermore, partially hidden functionality in the Evalglare program exists to correct overflow based on a fixed luminance threshold (Wienold, 2015). In this study the authors elect to use ND filters to expand the dynamic range of captures. Several filters are available commercially. Three Kodak Wratten 2 filters are used: ND-1 filters transmit 10 % of light; ND-2, 1 %; and ND-3, 0,1 %. In essence, a ND-3 filter expands the potential dynamic range of a HDR photograph by a factor of 1 000; however, ND filters are not truly neutral. They introduce a chromatic shift into photographs and may reduce the middle luminous ranges substantially irrespective of whether a luminous response function (see discussion in Section 1.1) was generated for the camera alone or the camera and filter combination.

Figure 5 illustrates the benefits and detractions of using ND filters by capturing the same scene using several aperture and filter capture settings from f/4 with no filter to f/11 with a ND-3 filter, a luminous range from approximately 100 000 cd·m^{-2} to 800 000 000 cd·m^{-2}. The dark grey line (■) indicates sensor-measured illuminance and the light grey line (■) measured grey card luminance. Together they indicate that the entire capture process had minimal luminous variability. Ideally the computed image illuminance (blue line, ■) would meet the measured illuminance line, indicating an image where pixel luminances describe the measured illuminance. In addition the DGP (red line, ■) and normalized UGR (yellow line, ■) metrics are reported. Finally the green line (■) indicates peak luminance, showing the dynamic range of the photographs. Overall, the f/4 image explains only 28 % of measured vertical illuminance while the f/11 ND-3 filter image explains 71 %, due to better tracking of direct solar luminances, from 125 995 cd·m^{-2} at f/4 with no filter to 544 007 864 cd·m^{-2} using the ND-3 filter. The two sets of images at the bottom of the graph show the 1/8000 s darkest exposure for each capture—illustrating measurement limitations due to luminous overflow—and the chromatic shift of the images using ND filters. As the peak luminance increases, DGP and UGR values increase in tandem despite the scene changing very little.
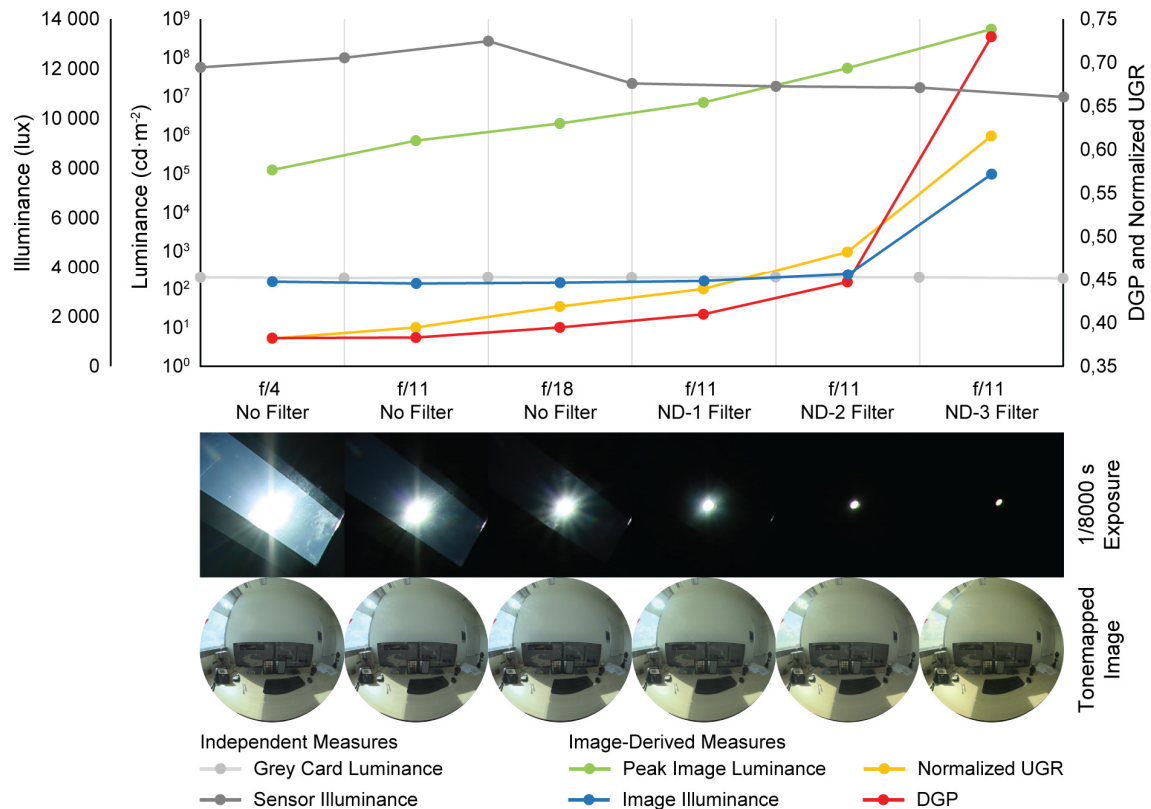

Figure 5 – Range of Luminous Overflow With Different HDR Capture Options

The f/11 ND-3 filter HDR capture does not resolve the total light in the scene when compared to the sensor-measured vertical illuminance for two reasons. The first is the aforementioned reduction in mid-range luminances when using a ND filter. Stumpfel and others (2004) corrected the colour shift when using an ND3 filter, and this may aid this phenomena. The other reason is that the total brightness of the solar disc may not be fully resolved, as its LDR pixel value is still very close to white (R:249, G:238 B:234). This is being studied further by the authors.

UGR and DGP were calculated for HDR capture pairs using no filter and a ND-3 filter with a f/11 aperture. Lighting conditions ranged from 25,56 lx to 76 100 lx vertical illuminance, representing a wide variety. These HDR image pairs were captured in quick succession under relatively constant luminous conditions. Large deviations in illuminance during the capture (> 10 %) lead to the images described by Table 2 being removed from these plots, leaving 71 pairs remaining. This comparison is documented in Figure 6. The X axes contain derived comfort measures without a filter while the Y axes contain the same using a ND-3 filter. Point colours indicate the mean vertical illuminance measured by an illuminance meter during the HDR capture process. Images in the 0 lx–2000 lx (blue, ■) and 2000 lx–5000 lx (green, ■) ranges typically have a higher discomfort evaluation when using no filter; this is because the ND-3 filter will lower the luminance ranges of the capture as described. There are usually no direct solar sources in images with such low illuminances; therefore, no benefit can be observed. The results are very different for images in the 5 000 lx–25 000 lx (dark red, ■) and >25 000 lx (yellow, ■) ranges. At such high levels of illuminance direct solar sources or bright specular reflections are often present, and HDRs captured with a ND-3 filter predict higher levels of visual discomfort due to the increased measurement range. A separate observation is that rarely does the dynamic range of the photograph move a data point using the UGR metric from one subjective category to another. In other words, most intolerable scenes are already detected as intolerable using a reduced dynamic range with the UGR metric. On the other hand, the DGP metric exhibits exactly the opposite behaviour. As its evaluation categories are so narrow, it more often occurs that a data point can move from 'perceptible' to 'disturbing' based on an increase in dynamic range.
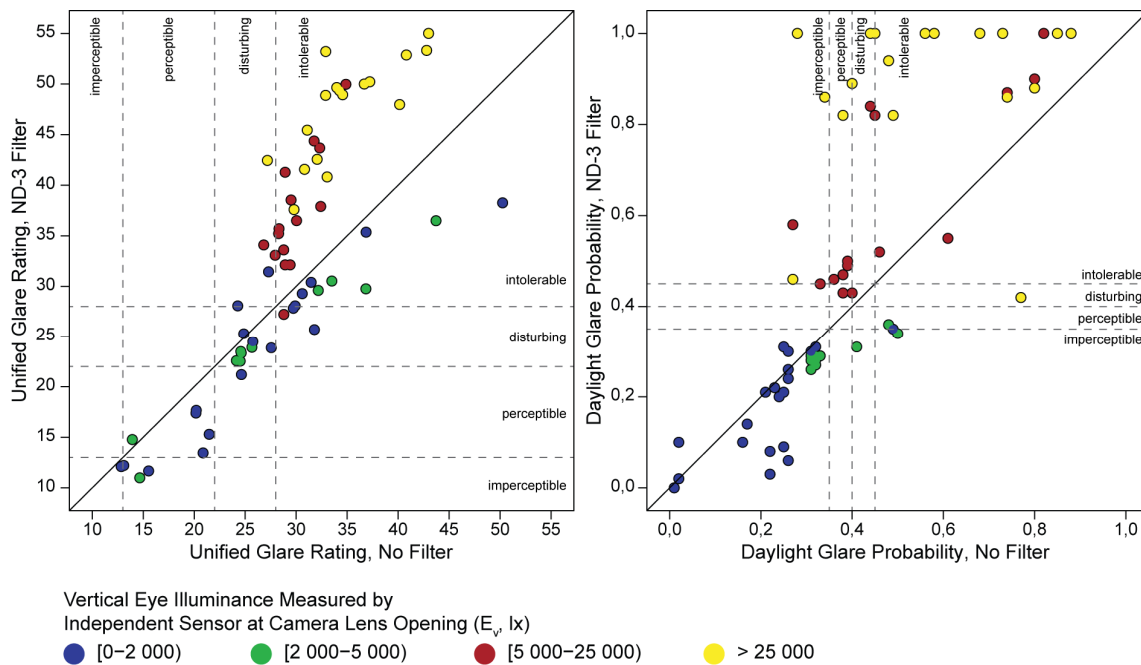

Figure 6 – UGR and DGP Evaluations Using No and ND3 Filters at f/11 Aperture

6 Discussion and Conclusion

As with all measurement techniques, users should be familiar with the potential errors of the measurement and their sources. HDR photography is no different; however, most visual comfort research has not validated the accuracy of its measurements with independent luminance or

illuminance comparisons. This paper discussed many of the common factors that contribute to the accuracy of HDR photography such as lens vignetting, choice of aperture, changing lighting conditions during the capture process and luminous overflow in order to begin this discussion in the research community.

Lens vignetting corrections have been established as a necessity (Inanici, 2006); (Cauwerts, 2012). The process of measuring and deriving vignetting corrections is unfortunately extremely onerous, necessitating a precise geometric scene or up to a 19 HDR photograph series. So it is fortuitous to confirm, using up to 5 separate same model lenses, the work of Cauwerts and others (2012) that vignetting measurements used for photographic correction can be shared and compared among researchers using the same model of lens.

The effect of aperture selection on the luminous range of HDR photographs was found to be relatively predictable to the geometric rules of f-stops. When the aperture is reduced by one stop the amount of light at the sensor is halved, and the measurement range of the photograph is doubled (see Figure 3). The authors strongly recommend that all researchers carefully measure the luminous range of their specific HDR equipment and settings relative to the task they are using it for before beginning the work. For example, if using a camera with a 1/4000 s fastest shutter speed, the luminous range reported in this paper will be halved. In the same spirit, using an ISO sensor sensitivity of 200 rather than 100 will again half the luminous range of the resulting HDR photograph. In addition, aperture selection was found to have a predictable effect on lens flare (see Figure 4). Higher numerical apertures lead to an increased risk of lens flare. The results of this flaring effect on visual comfort predictions cannot at this time be quantified in luminance units as by changing aperture, the dynamic range of the photograph also changes. Further work is necessary and is being undertaken by the authors. Still, the authors recommend a f/11 aperture for its relatively minimal vignetting and balance between an acceptable luminous range and lens flare effects

The authors recommend to track photometric changes during HDR capture processes using luminance measurements as well as illluminance measurements, because luminance may vary less when the measurement surface is conveniently located to face the camera. Vertical illuminance is likely to change significantly even when it may not be visually noticeable by the human eye or when grey card luminance is nearly constant.

Finally, the most important aspect of this paper may be the study of luminous overflow. It is prudent to validate HDR images with highly luminous pixels or in environments with direct solar access by comparing the derived illuminance of the image to an independent sensor measurement. In a study of 71 images covering a wide range of vertical illuminances and lighting conditions, it was found that for vertical illuminances over 5 000 lx, overflow is likely to have a significant impact in calculating visual comfort, and the use of ND filters is recommended. At lower illuminance levels, ND filters tended to suppress the values of derived comfort metrics. The authors would like to note that overflow can still be important in lower vertical illuminances, for example when direct sunlight shines through a fabric shade, the solar disc is still extremely bright. In such situations, it is recommended to selectively use a ND filter. Another critical finding is that DGP is more strongly effected by measurements exhibiting overflow than traditional contrast-only measures such as UGR. Overall, this casts a dark shadow on current monitoring protocols in visual comfort research, and a second half to this paper is being authored regarding methods to correct luminous overflow based on illuminance measurements.

Acknowledgements

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