Calibration of high dynamic range images for applied colour and lighting research

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The main objective of this work is to determine the most appropriate HDR picture calibration procedure for measuring luminance and colour, in a context of architecture. Three professional digital single-lens reflex cameras fitted with fisheye lenses were tested. Photometric and colorimetric accuracy was assessed in comparison with spectroradiometer measurements of 57 colour samples (Macbeth chart and additional Munsell samples). The results demonstrate that using a calibration model specific to the camera-lens association rather than the standardized RGB to XYZ colour transform matrix is necessary to achieve an acceptable colorimetric accuracy. Moreover, using a specific colour transform matrix reduces the error in luminance, especially for colourful elements. The study also shows the opportunity to share the same colour transform matrix between similar photographic materials (same brand and model). At last, among the three tested devices, one camera-lens association has higher performances and produces better quality QTVR panoramas.

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1. INTRODUCTION

A. Motivation

High Dynamic Range (HDR) imaging techniques are frequently used in lighting research to measure luminance. Part of their success lies in the opportunity to capture quickly a large field of view with a high resolution. This is of great interest for investigating luminance distribution in interior and exterior environments, and particularly for evaluating risks of glare. HDR photographs are created by combining multiple images taken with different exposures from an identical viewpoint. The technique allows to some extent recording scene's full dynamic range which is often wider than the range recordable in a conventional image taken in a single shot (a.k.a. a low dynamic range (LDR) picture). The dynamic range of the scene should be here understood as the ratio between the brightest and darkest parts of the scene.

Various merging algorithms and tools exist for creating HDR images from bracketed exposures. In the lighting community, the most widely used tools are probably the *hdrgen* command-line for Mac OS X, Linux and Raspberry Pi [1], Photosphere that works on Mac OS X and in which *hdrgen* is implemented [2], and to a lesser extent Photolux for Windows [3]. These tools take jpeg as input and consequently requires the camera response function. Other programs exist that take raw files as input, for instance, *pfstools* [4] and *raw2hdr* [5]. An advantage of merging raw pictures rather jpeg is that the camera response curve is not needed since sensor data are theoretically linear. Moreover, raw format minimizes data loss inherent to jpeg compression. A disadvantage is the large size of files to be handled.

Except Photolux, these merging tools produce HDR images that can be stored in the well-known Radiance RGBE format (.hdr), with sRGB as default output colour space. It is common practice (in the lighting community) to retrieve absolute luminance of any pixel of these HDR camera-based images using the following formula:

$$L_{ij} = CF * 179 * \left(0.2126\,\frac{R_{ij}}{E} + 0.7152\,\frac{G_{ij}}{E} + 0.0722\,\frac{B_{ij}}{E}\right), \qquad \textbf{(1)}$$

where L_{ij} is the absolute luminance at pixel i,j; CF is a calibration factor ensuring photometric accuracy; 179 is the standard luminous efficacy in Radiance; 0.2126, 0.7152, 0.0722 are calculated from CIE chromaticities for sRGB primaries and the CIE Standard Illuminant D65 white point; R_{ij}, G_{ij} and B_{ij} are floating point linear RGB extracted from HDR image after exposure compensation; and E is the exposure value, it is specified in the header of the Radiance file. Before exposure compensation, E is 1.

The calibration factor (CF) used for ensuring photometric accuracy is calculated as the ratio of the HDR-derived luminance value of a middle grey target to the luminance of the same target measured with a spot luminance meter.

B. Related work

Limitations and potentials of HDR pictures for measuring luminance have been studied in the literature. The accuracy of luminance retrieved from HDR images captured with a Nikon Coolpix 5400 fitted with a Nikon FC-E9 fisheye lens has been evaluated by Inanici [6]. Jpeg images were merged with Photosphere, and Equation 1 was used for retrieving luminance. An average error in luminance of 9.3% was observed for colour samples and 5.8% for greyscale (spot luminance measurement is the reference). HDR pictures were taken under daylighting and electric lighting (luminance range: ~0-14 000 cd/m²). Under electric conditions (luminance range: ~0-900 cd/m²), all individual errors were inferior to 20% except for red and magenta samples lit by an incandescent source (luminance range: ~0-20 cd/m²). Cai and Chung [7] observed a similar range of error with a Canon EOS 350D fitted with a Sigma 10–20 mm F4-5.6 EX (wide angle lens). Pictures were taken under 4000K fluorescent lighting (the luminance range is not specified). Photosphere was used for merging jpeg images but the authors did not mention how they retrieved luminance from images. Average error percentages are estimated to 10.1% for colour surfaces, 2.8% for grey surfaces (black excluded) and 1.5% for black surfaces.

According to these works, a deviation of luminance of less than 10% with peak values reaching up to 20% or exceptionally more can be expected from HDR photography. Errors on grey surfaces are expected to be inferior to errors on colour surfaces. But what about colorimetric accuracy? The procedure described in Section 1.A aims at ensuring photometric accuracy but, humans are trichromats and thus sensitive not only to luminance but also to colour. In some context, a colorimetric calibration might be preferred over a photometric one. Furthermore, today, lighting should also consider new advances on non-visual effects of light on occupants. And, as shown by Jung and Inanici [8], colour calibration is a way towards retrieving melanopic radiance and irradiance from HDR photograph.

Colorimetric accuracy of HDR images have already been investigated, but not on images produced with the procedure commonly used by the lighting community (sRGB matrix). Kim and Kautz [9] merged multi-exposure raw images using the HDR assembly part of Debevec and Malik's method [10]. For transforming RGB values from HDR images into XYZ values, they used a colour transform matrix (CTM) previously found by minimizing the error with XYZ tristimulus values measured with a spectroradiometer. They obtained the following ΔE_{00} medians over a Macbeth chart lit by a halogen: 0.5, 3.8 and 3.1 for Canon 350D, Nikon D100 and Nikon D40, respectively (transform matrices are specific to each camera, the lens fitting each camera is not specified). Varghese et al. [11] also investigated colorimetric accuracy of HDR pictures. They captured pictures with three cameras (lenses are not specified). HDR images were fused from raw images using *pfstools*. XYZ values were retrieved from HDR images using also a specific CTM determined by minimizing colour differences between HDR images and spectrometer measurements. On seven samples lit by two electric lighting conditions, the authors calculated an average ΔE_{00} of 1.9, 2.6 and 3.6 for Canon EOS 55D, Canon EOS 1000D and Panasonic Lumix DMC-LX7, respectively. Maximum observed ΔE_{00} are: 4.2 (orange) for Canon EOS 55D, 5.3 (yellow) for Canon EOS 1000D and 3.0 (orange) for Panasonic Lumix DMC-LX7. The authors also reported average relative errors in luminance: 7.2% for the Canon EOS 55D, 8.5% for the Canon EOS 1000D and 12.9% for the Panasonic Lumix DMC-LX7. Maximum errors observed for the three cameras are: 15.6% (red, lighting#1), 19.8% (purple, lighting#1), 15.5% (red, lighting#1).

Errors in luminance observed by Varghese et al. are in the same range than those observed by authors using sRGB matrix. The interest of using a specific CTM for retrieving luminance is thus not clear. Furthermore, is the colour accuracy observed by these authors sufficient for applied colour and lighting research? And, is the precision gained by colour calibrating HDR pictures significant in comparison to the colour accuracy resulting from a usual photometric calibration procedure?

C. Objectives

The main objective of this work is to determine the most appropriate HDR picture calibration procedure for measuring luminance and colour, in a context of lighting design of interior environments.

Three cameras fitted with fisheye lenses are tested. The study focuses on fisheye lens-based images because of their widespread use for investigating lighting in built environments. Since such lenses are particularly affected by optical problems such as flare, ghosting and chromatic aberrations, we test a more adverse case than HDR pictures taken with traditional lenses.

Two linear CTMs are used for computing XYZ values from HDR images. First, the standardized RGB to XYZ CTM [12], commonly used by the lighting community, is tested. It gives the coefficients used in Equation 1 for retrieving luminance. This assumes that camera sensor primaries are similar to sRGB primaries, which is rarely true. Then, an alternative CTM is tested. It is determined specifically for each camera by minimizing the least square error in the XYZ colour space (i.e. the error between values retrieved from HDR photography and XYZ values measured with the spectroradiometer). More details are given in Section 2.D.

In both cases, based on a physical measurements, the tristimulus values (XYZ) retrieved from HDR photography are re-scaled either by a single calibration factor (as in the common photometric calibration) or

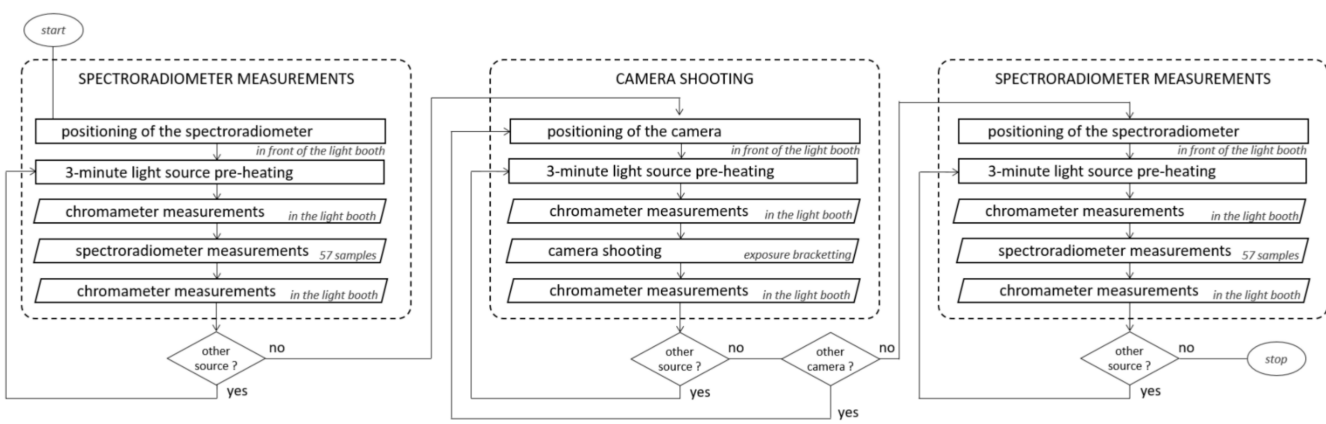

Fig. 2. Data acquisition overview.

by adjusting data with three calibration factors, one per channel, similarly to Jung and Inanici [8]. Both re-scaling methods are tested to determine if the second one improves accuracy. While in practice the first re-scaling method requires only a (il)luminance meter, a chromameter is at least needed for the second one.

Besides this, we investigate whether the CTM determined for one device (a camera and an associated lens) can be used for calibrating similar photographic material from same brand and same model. Indeed, the preliminary determination of a CTM is time-consuming and requires a lab environment. If the alternative calibration method allows reducing errors in luminance and colour, it would be interesting for practice to share transform matrices. Finally, the quality of the captured images in a perspective of visual psychophysics is also addressed.

2. MATERIAL AND METHOD

For calibrating HDR images and testing accuracy, XYZ values of colour samples were measured with a spectroradiometer and compared to values retrieved from HDR images (Fig. 1).

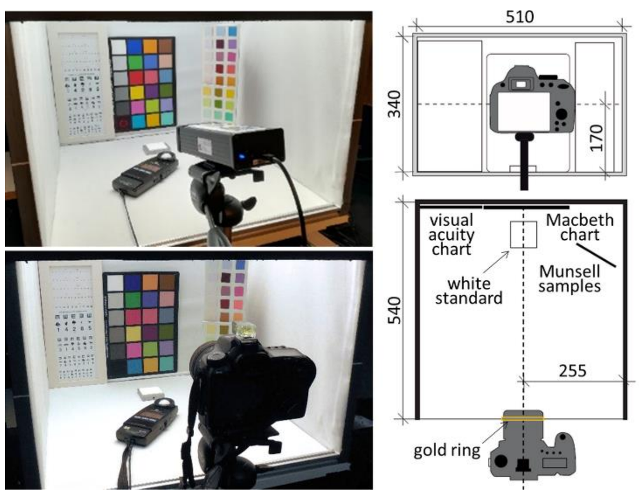

Fig. 1. Experimental setup: acquisition with a spectroradiometer, shooting with a camera and camera position.

A. Data acquisition

Figure 2 illustrates the overall procedure for data acquisition that begins and ends with spectroradiometer measurements.

1. Scene

A reference white standard (Gigahertz-Optik ref. BN-R986SQ2C), a Macbeth colour chart, 33 colour samples from the Munsell Book of Colour and a visual acuity chart (a chart with Landolts rings and tumbling E's in the upper part, and with a Rossano and Weiss-Inserm test in the lower part) were placed in a white booth with a reflectance factor of 0.81 (Fig.1). The 33 Munsell samples were selected in the Munsell Book of Colour in order to increase the gamut of the colour space covered by the Macbeth chart and to improve hue uniformity.

For determining the specific CTM of each device, the scene was lit by a cool incandescent source (training source). For testing colorimetric accuracy, it was lit by a nearly flat white LED source (test source). Light sources were located behind a polycarbonate diffuser to avoid glaring points. The LED nearly flat spectrum was obtained with a seven-channel spectrally tuneable LED projector (SourceFour LED, Lustr+,ETC Company). The correlated colour temperature (CCT) in the booth was 5050K for training source and 5400K for test source. Horizontal illuminance in the booth at floor level was about 750lx under the training source, and about 2500lx under the test source. The dynamic range of the scene was 520:1 and 1250:1, respectively. The cool incandescent source was chosen as training source because of its continuous spectrum between 380 and 780nm and for the presence of energy in the blue part of the spectrum. Light sources were measured on the white standard in the booth accounting for polycarbonate diffuser and inter-reflections (see spectral radiances in Fig.3).

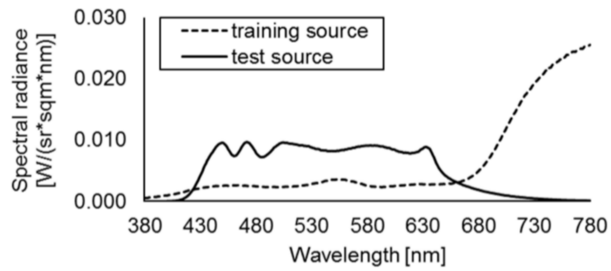

Fig. 3. Spectral radiances of training and test light sources.

As illustrated in Fig.4 which presents colour samples under training and test sources in the CIE 1931 xy chromaticity diagram, most colour samples are in the sRGB colour space. Four samples are on the border of the sRGB colour space.

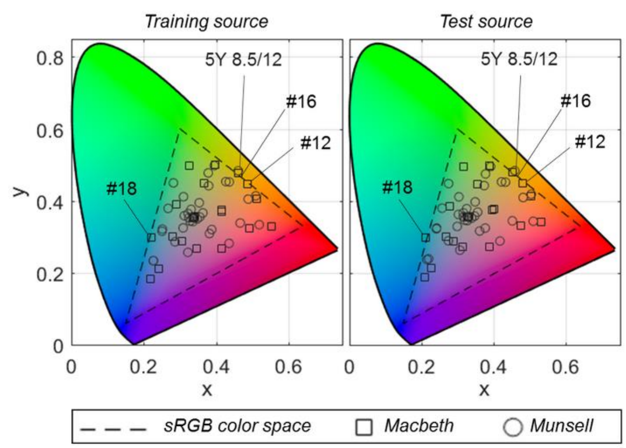

Fig. 4. Coordinates of colour samples lit by (a) the training source and (b) the test source in the CIE chromaticity diagram.

2. Measuring instruments

Cameras and lenses. Three digital single-lens reflex (DSLR) cameras fitted with fisheye lenses were studied:

- Canon EOS 40D fitted with a Sigma 4.5mm F2.8 EX DC fisheye lens (40Dfe45);
- Canon EOS 50D fitted with a Sigma 4.5mm F2.8 EX DC fisheye lens (50Dfe45);
- Canon EOS 5D Mark II fitted with a Sigma 8mm F3.5 EX DG fisheye lens (5Dfe8).

A second Canon EOS 50D fitted with another Sigma 4.5mm F2.8 EX DC fisheye lens (50Dfe45bis) was used to investigate if the same CTM can be used for another device of same brand and model. Table 1 presents the specifications of the three cameras as announced by the manufacturer. Concerning the lenses, two Sigma 4.5mm f2.8 EX DC and a Sigma 8mm f3.5 EX DG were used. Both types are 180° circular fisheye lenses producing an equisolid projection (also known as equi-area projection).

Spectroradiometer. A JETI Specbos 1211-UV spectroradiometer was used to measure XYZ tristimulus values at the beginning and the end of the entire shooting session. Its chromatic accuracy is ± 0.002 for the x,y coordinates under illuminant A. The instrument was calibrated by SCIENTEC less than two months prior the study. It was mounted on a tripod at the same position as the cameras (Section 2.A.3).

Chromameter. A CL-200A chromameter was placed at the centre of the booth floor to check the stability of the light sources during data acquisition. Horizontal illuminance and CCT were measured before and after shooting with each camera-lens association and before and after spectroradiometer measurements. Variation in illuminance was lower than 2% and variation in CCT was lower than 0.5%.

3. LDR image acquisition

Camera position. To avoid misalignment between LDR images of each sequence, cameras were mounted on a tripod. Camera height was set to the middle height of the booth. We strived for aligning the entrance pupil point (the point from which the camera captures the scene) with the edge of the light booth. Unfortunately, fisheye lenses do not have a single centre of projection: the entrance pupil point moves along the lens optical axis as the incident angle varies.

Table 1. Specifications of the three tested cameras and picture quality (Large/Fine setting).

Setting	Camera		
	Canon EOS 40D	Canon EOS 50D	Canon EOS 5D Mark II
Sensor size	22.8mm*14.8mm	22.3mm*14.9mm	36.0mm*24.0mm
Sensor type	CMOS APS-C	CMOS APS-C	CMOS 35 mm
Crop factor	1.6	1.6	1
Lens mount type	EF, EF-S	EF, EF-S	EF
Pixels	~10.1 M	~15.1 M	~21.0 M
Definition	3888*2592	4752*3168	5616*3744
File size (.jpg)	~3.5 MB	~5 MB	~6.1 MB
File size (.cr2)	~12.4 MB	~20.2 MB	~25.8 MB

For practical reason, we decided to use the gold ring of the lens as a reference given that the entrance point of our fisheye lenses is moving forward and backward from this plane. With a plumb line, this gold ring was levelled with the edge of the light booth (Fig.1). The horizontality of the camera was checked with a spirit level.

Camera setting for image acquisition. Vignetting effect is the brightness decrease observed from the centre of the picture towards its periphery. It is particularly pronounced with wide angle lenses and thus with fisheye lenses. It varies with camera settings such as the aperture. Vignetting effect of the fisheye lenses used in this study have been determined following the procedure detailed by Cauwerts et al. [13]. The aperture was set to f/10 for Sigma 4.5mm f2.8 EX DC lens, and to f/16 for Sigma 8mm f3.5 EX DG fisheye lens. This way, vignetting effects are minimized and colour samples fall in the central part of the image not impacted. The cameras' sensitivity setting was set to ISO 100 (lowest sensitivity) to minimize the noise in the picture.

Table 2. Camera settings.

Parameters	Mode
White balance	Daylight (~5200K in the Canon system)
Sensitivity	ISO 100
Focusing setting	Manual (~50cm)
Picture quality	raw
Exposure mode	Manual

Because shutter speed is a more reliable parameter than aperture size [10], we fixed the aperture (Av) and varied exposure time (Tv). Shutter speed bracketing was performed for 1-stop increments. Digital cameras were remotely controlled from a Windows PC via USB with DSLR remote pro software. Pictures were saved in raw format. Table 2 summarizes camera settings for LDR image acquisition.

B. HDR merging

To ensure that our sequences of LDR images cover the dynamic range of the scenes, the maximum images were taken for a given aperture. To accelerate the calculation time of the merging process, images were selected so that the darkest exposure has no R, G and B values simultaneously greater than 228 and that the brightest exposure has no R, G and B values simultaneously below 27 [14]. Table 3 summarizes capture settings and exposures for each scene and device. The multiple raw pictures were combined using *raw2hdr* software under Linux. Data were saved in the Radiance RGBE format using sRGB as output colour space.

Table 3. Capture settings.

Scene	Device	ISO	Av	Tv
Training	40Dfe45	100	f/10	1.6, 0.8, ½, 1/5, 1/10, 1/20, 1/40
Training	50D fe45	100	f/10	1.6, 0.8, ½, 1/5, 1/10, 1/20, 1/40, 1/80
Training	5Dfe8	100	f/16	8, 4, 2, 1, 0.5 , 1/4 , 1/8, 1/15
Test	40Dfe45	100	f/10	½, 1/5, 1/10, 1/20, 1/40, 1/80, 1/160
Test	50D fe45	100	f/10	½, 1/5, 1/10, 1/20, 1/40, 1/80, 1/160
Test	5Dfe8	100	f/16	2,1,1/2,/1/4,1/8, 1/15, 1/30, 1/60

C. Data extraction

Floating point RGB values after exposure compensation were extracted from the HDR file using the Matlab *hdrread* program [15]. Exposure value was extracted from the header with *textscan*. RGB values of each pixel were computed as follows:

$$R_{ij,camera} = 179 * \frac{R_{ij,HDR}}{E},$$

$$G_{ij,camera} = 179 * \frac{G_{ij,HDR}}{E},$$

$$B_{ij,camera} = 179 * \frac{B_{ij,HDR}}{E}, \qquad (2)$$

where 179 is the standard luminous efficacy in Radiance; $R_{ij,HDR}$, $G_{ij,HDR}$ and $B_{ij,HDR}$ are floating point RGB values after exposure compensation; and E is the exposure value.

D. Camera calibration method

Two CTMs and two re-scaling were applied to retrieve XYZ values from HDR pictures.

1. Colour transform matrix (CTM)

First, the standardized RGB to XYZ CTM (sRGB method) is used (Equation 3) [12]. The assumption is that camera's sensor primaries are sRGB primaries. The coefficients of $M_{\mathrm{sRGB}_{\mathrm{D65}}}$ are determined from sRGB primaries and sRGB white point (D65): xy_red=(.64;.33), xy_green=(.30;.60), xy_blue=(.15;.06) and xy_white=(.3127,.3290). This is the method commonly used by the lighting community to retrieve luminance from a RGB triplet. Coefficients for Y channel - that corresponds to the luminance - are those presented in Equation 1.

$$\begin{bmatrix} X_{camera} \\ Y_{camera} \\ Z_{camera} \end{bmatrix} = M_{sRGB_{D65}} * \begin{bmatrix} R_{camera} \\ G_{camera} \\ B_{camera} \end{bmatrix}, \qquad (3)$$

with

$$M_{sRGB_{D65}} = \begin{bmatrix} .4124 & .3576 & .1805 \\ .2126 & .7152 & .0722 \\ .0193 & .1192 & .9505 \end{bmatrix}$$

In the second method (minXYZ method), a specific CTM is used. It is determined, for each camera, by minimizing the least square error between the XYZ obtained with HDR images and XYZ measured with the spectroradiometer (Equation 4). For each device, the CTM was determined with the 18 Macbeth colour samples lit by the training source (cool incandescent source, 5050K).

$$\begin{bmatrix} X_{camera} \\ Y_{camera} \\ Z_{camera} \end{bmatrix} = M_{camera} * \begin{bmatrix} R_{camera} \\ G_{camera} \\ B_{camera} \end{bmatrix}, \qquad (4)$$

with

$$M_{camera} = \left(\left(RGB_{camera}^{t} \; RGB_{camera}\right)^{-1} \; RGB_{camera}^{t} \; XYZ_{spectro} \right)$$

where $XYZ_{spectro}$ are the measured XYZ values and RGB_{camera} is a matrix containing the linear RGB values extracted from the HDR file and averaged to correspond to the measurement zone of the spectroradiometer.

2. Re-scaling

Two re-scaling methods were tested. For both methods, the calibration factors were determined under the test source (LED source, 5400K).

The first method is a re-scaling with a single calibration factor determined using a grey target (Macbeth patch #22) (Equation 5).

$$\begin{bmatrix} X_{adj} \\ Y_{adj} \\ Z_{adj} \end{bmatrix} = CF_Y * \begin{bmatrix} X_{camera} \\ Y_{camera} \\ Z_{camera} \end{bmatrix}, \qquad (5)$$

with

$$CF_Y = \frac{Y_{grey\ target,spectro}}{Y_{grey\ target,camera}},$$

where $Y_{grey\ target,spectro}$ is the luminance of a grey target measured with the spectroradiometer and $Y_{grey\ target,camera}$ is the luminance of the same target extracted from the HDR file.

The second method is a re-scaling with three calibration factors, one by channel, determined using the same grey target (Equation 6).

$$\begin{cases} X_{adj} = CF_X * X_{camera} \\ Y_{adj} = CF_Y * Y_{camera}\ , \\ Z_{adj} = CF_Z * Z_{camera} \end{cases} \qquad (6)$$

With

$$CF_X = \frac{X_{grey\ target,spectro}}{X_{grey\ target,camera}}\ (\%),$$

$$CF_Y = \frac{Y_{grey\ target,spectro}}{Y_{grey\ target,camera}}\ (\%),$$

$$CF_Z = \frac{Z_{grey\ target,spectro}}{Z_{grey\ target,camera}}\ (\%),$$

where $XYZ_{grey\ target,spectro}$ are tristimulus values of a grey target measured with the spectroradiometer and $XYZ_{grey\ target,camera}$ are the values of the same target extracted from the HDR picture.

E. Performance indicators

Photometric and colorimetric accuracy was assessed using the 57 samples (24 Macbeth and 33 Munsell samples) lit by the test source.

1. Photometric accuracy

To quantify the error between luminances from HDR pictures (after calibration) and luminances captured with the spectroradiometer, the mean absolute percentage error (MAPE) was calculated with respect to the luminance measured with the spectroradiometer, as in Equation 7.

$$MAPE_{lum} = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{Y_{i,camera} - Y_{i,spectro}}{Y_{i,spectro}} \right| \ (\%), \qquad (7)$$

where $Y_{i,camera}$ is the luminance of the i[th] colour sample from the HDR image after calibration; $Y_{i,spectro}$ is the luminance of the same sample measured with the spectroradiometer; and n is the number of samples.

2. Colorimetric accuracy

For estimating colorimetric accuracy, colour differences designated as ΔE_{ab}^{*} were calculated in CIELAB (L*a*b* CIE 1976 colour space) [16].

3. RESULTS

A. Colour transform matrices and calibration factors

Equations 8 to 10 are CTMs determined, under the training source with Equation 4 (minXYZ method), for the three cameras fitted with their respective lens as detailed in Section 2.D.1.

$$M_{40Dfe45} = \begin{bmatrix} .5939 & .7048 & .2598 \\ .2624 & 1.4244 & .0605 \\ -.0100 & .1612 & 1.8226 \end{bmatrix}, \qquad (8)$$

$$M_{50Dfe45} = \begin{bmatrix} .5832 & .6349 & .2671 \\ .2493 & 1.2692 & .0759 \\ .0028 & .1362 & 1.7204 \end{bmatrix}, \qquad (9)$$

$$M_{5Dfe8} = \begin{bmatrix} .6408 & .7341 & .2378 \\ .2737 & 1.4450 & .0502 \\ .0185 & .1731 & 1.8815 \end{bmatrix}, \qquad (10)$$

Table 4 presents the calibration factors determined with the test source for the two methods (sRGB and minXYZ) and the two re-scaling methods (1CF and 3CF). As expected, values are around 1 for the second method (minXYZ).

Table 4. Calibration factors.

CTM	Re-scaling	Device 40Dfe45			50Dfe45			5Dfe8		
		CF_X	CF_Y	CF_Z	CF_X	CF_Y	CF_Z	CF_X	CF_Y	CF_Z
sRGB	1CF	-	1,53	-	-	1,68	-	-	1,73	-
	3CF	1,55	1,53	1,61	1,63	1,68	1,69	1,70	1,73	1,86
minXYZ	1CF	-	0,96	-	-	0,96	-	-	0,98	-
	3CF	0,99	0,96	0,96	1,00	0,96	0,95	0,99	0,98	0,99

B. Accuracy of the three devices

1. Photometric accuracy

Figure 5 illustrates the distribution of errors in luminance by device, and by method. Given that using a single calibration factor (1CF) or a triplet of calibration coefficients (3CF) leads to identical errors of luminance (only the Y channel is analysed for photometric accuracy), results are presented together. Average error in luminance is under 6% whatever the device and the method. With sRGB method, MAPE_lum on the 57 samples varies between 3.6 and 5.5% for the three tested devices (Table 5). With the optimized CTM (minXYZ), MAPE_lum vary between 2.7 and 4.1%. Maximum deviation in luminance (24.2%) is observed for the red sample captured with 40Dfe45. Whatever the device the mean absolute percentage error of luminance (MAPE_lum) is reduced with minXYZ method in comparison to the sRGB method. With sRGB, the maximum error of luminance is observed on Macbeth sample #15 (red) for all three devices. Using the minXYZ method allows to reduce the maximum errors of 5Dfe8 and 50Dfe45 devices by 2. However, maximum error for the 40Dfe45 device is still high.

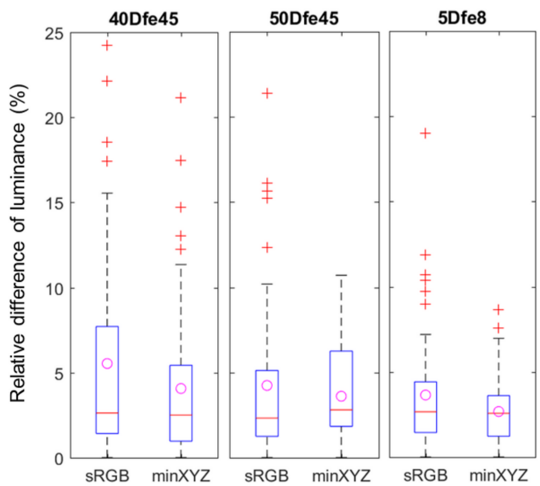

Fig. 5. Boxplot of relative difference of luminance (%), by device, 57 samples (red line is the median, magenta circle is the mean).

Figure 6 represents in the L*b* plane of CIELAB the relative difference of luminance obtained with the minXYZ method. It illustrates that large errors observed with the 40Dfe45 device are due to high variations for dark colours.

Table 5. Mean (MAPE_lum) and maximum absolute percentage error of luminance, by device, 57 samples, test source.

Calibration method	Device 40Dfe45		50Dfe45		5Dfe8	
	MAPE	maximum	MAPE	maximum	MAPE	maximum
sRGB (1CF/3CF)	5.5%	24.2% (#15-red)	4.2%	21.4% (#15-red)	3.6%	19.0% (#15-red)
minXYZ (1CF/3CF)	4.1%	21.2% (5PB 2.5/4)	3.6%	10.7% (5RP 2.5/4)	2.7%	8.7% (#13-blue)

A three-factor analysis of variance (sample x device x CTM) was conducted (the significance level is set at 0.05). It shows that the three factors have a significant effect on luminance accuracy (Table 6).

Table 6. Analysis of variance (ANOVA) summary table for luminance error.

Factors	df	Sum of squares	Mean squares	F	pvalue
sample	56	0.266	0.005	22.356	< 0,0001
device	2	0.015	0.008	36.083	< 0,0001
CTM	1	0.009	0.009	42.207	< 0,0001
sample*device	112	0.144	0.001	6.058	< 0,0001
sample*CTM	56	0.145	0.003	12.216	< 0,0001
device*CTM	2	0.001	0.001	2.372	0.098

Post hoc analyses using the Tukey HSD criterion for significance indicate that:

- the 5Dfe8 device (MAPE_lum=3.2%) can reach a photometric accuracy significantly higher than the one reached with the 50Dfe45 device (MAPE_lum=3.9%) or with the 40Dfe45 device (MAPE_lum=4.8%). The accuracy reached with the 50Dfe45 device is also significantly higher than the one with the 40Dfe45 device;

- the minXYZ method (MAPE_lum=3.4%) is significantly more accurate for retrieving photometric values than sRGB (MAPE_lum=4.5%);

- the accuracy reached with 40Dfe45 and sRGB method is significantly lower than the accuracy reached by other cameras and/or method;

- the accuracy reached with 5Dfe8 and minXYZ is significantly higher;

- and 5Dfe8 calibrated with sRGB, 50Dfe45 calibrated with sRGB or minXYZ, and 40Dfe45 calibrated with minXYZ lead to a similar photometric accuracy.

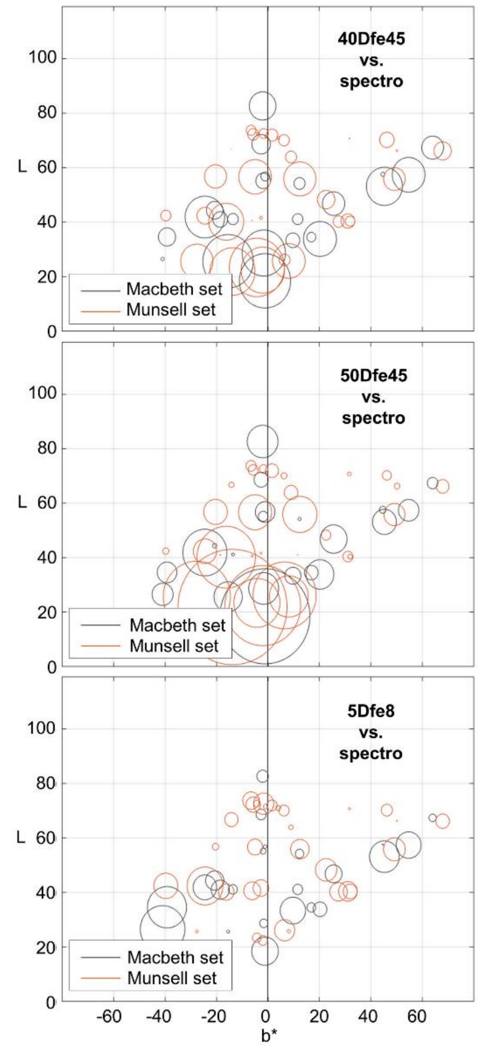

Fig. 6. Relative difference of luminance (%) in the L*b* plane of the CIELAB colour space, by device, after calibration with minXYZ method.

2. Colorimetric accuracy

Colour differences were computed in CIELAB with spectroradiometer measurements as the reference. The white standard measured with the spectroradiometer was chosen as the reference white for L*a*b* coordinates determination. Figure 7 illustrates the distribution of colour differences by device and calibration method. Average colour difference is under 6 CIELAB units whatever the device, the method and the number of re-scaling factors. Table 7 summarizes the mean, standard deviation and maximum colour differences obtained for each device.

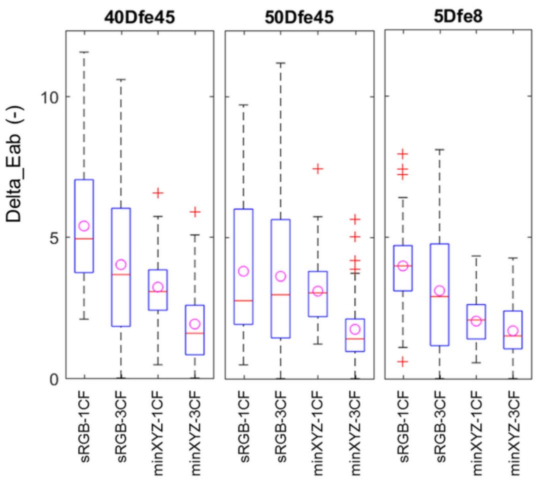

Fig. 7. Boxplot of colour differences (ΔE^*_{ab}), by device, 57 samples (red line is the median, magenta circle is the mean).

The maximum colour difference is observed on the yellow patch of the Macbeth chart captured with 40Dfe45 device calibrated with sRGB-1CF. The highest mean ΔE^*_{ab} is also obtained for this device and this method. Mean colour differences are lower with the minXYZ method than with sRGB, whatever the device and the re-scaling. We also noted that, whatever the device and the CTM, colour difference is reduced when re-scaling by three factors (3CF) in comparison to one calibration factor (1CF). Moreover, mean and maximum colour differences obtained with the minXYZ-3CF method are about half those obtained with the usual calibration method (sRGB-1CF).

Table 7. Colour differences (ΔE^*_{ab}), by device, 57 samples, test source.

Calibration method	Device					
	40Dfe45		50Dfe45		5Dfe8	
	Mean +/- std	Maximum	Mean +/- std	Maximum	Mean +/- std	Maximum
sRGB -1CF	5.4 +/-2.3	11.6 (#16-yellow)	3.8 +/-2.3	9.7 (#16-yellow)	4.0 +/-1.6	7.9 (#17-magenta)
sRGB -3CF	4.0 +/-2.7	10.6 (#16-yellow)	3.6 +/-2.6	11.2 (#16-yellow)	3.1 +/-2.2	8.1 (5Y 8.5/12)
minXYZ -1CF	3.2 +/-1.2	6.6 (#7-orange)	3.1 +/-1.2	7.4 (#15-red)	2.0 +/-0.8	4.3 (#15-red)
minXYZ -3CF	1.9 +/-1.4	5.9 (5G 7/10)	1.7 +/-1.1	5.7 (#15-red)	1.7+/- 0.9	4.3 (#15-red)

Figure 8 represents colour differences in the a*b* plane of CIELAB, and illustrates that low chroma colour samples have smallest colour differences and that, reciprocally, samples with higher chroma are responsible for highest colour differences. Using minXYZ reduces the error observed on high chroma samples in comparison to sRGB.

Table 8. Analysis of variance summary table for colour difference.

Factors	df	Sum of squares	Mean squares	F	pvalue
sample	56	1052.035	18.786	22.217	< 0,0001
device	2	101.377	50.689	59.944	< 0,0001
re-scaling	1	139.924	139.924	165.473	< 0,0001
CTM	1	495.801	495.801	586.329	< 0,0001
sample*device	112	185.262	1.654	1.956	< 0,0001
sample*re-scaling	56	163.773	2.925	3.459	< 0,0001
sample*CTM	56	501.003	8.946	10.580	< 0,0001
device*re-scaling	2	16.869	8.434	9.974	< 0,0001
device*CTM	2	20.448	10.224	12.091	< 0,0001
re-scaling*CTM	1	1.599	1.599	1.891	0.170

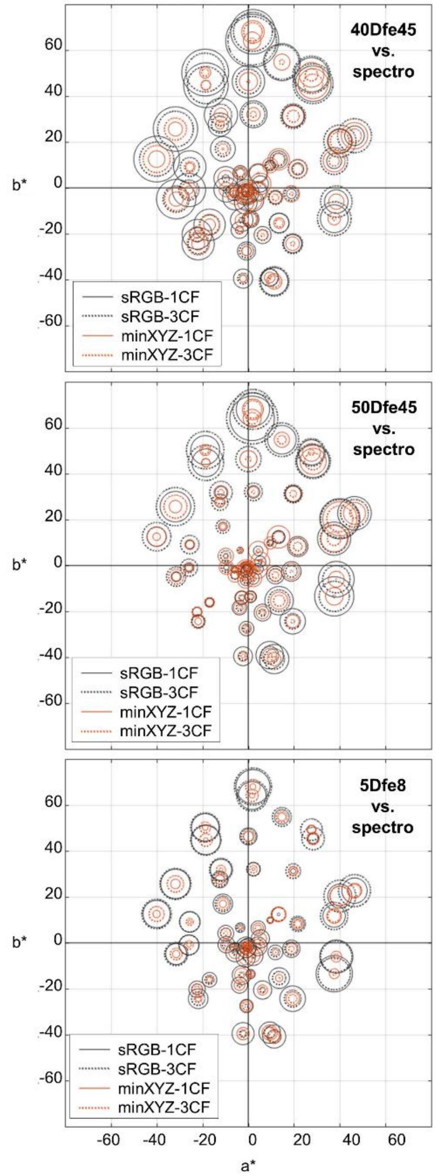

Fig. 8. Colour differences (ΔE^*_{ab}) in the a*b* plane of the CIELAB colour space, by device, 57 samples.

A four-factor analysis of variance (sample x device x CTM x re-scaling) was conducted. It shows that the four effects are significant (Table 8). The post hoc analysis using the Tukey HSD criterion for significance indicates that colorimetric accuracy achievable with the 5Dfe8 device (mean ΔE^*_{ab}=2.7) is significantly higher than with the 50Dfe45 device (mean ΔE^*_{ab}=3.1) and significantly higher than with the 40Dfe45 device (mean ΔE^*_{ab}=3.6). It is also shown that the minXYZ calibration method (mean ΔE^*_{ab}=2.3) is significantly more accurate than sRGB method (mean ΔE^*_{ab}=4.0). At last, re-scaling by three factors (mean ΔE^*_{ab}=2.7) improves significantly colour accuracy in comparison to re-scaling by a single factor (mean ΔE^*_{ab}=3.6). Post hoc tests also show that the 40Dfe45 device calibrated with sRGB-1CF allows a colour accuracy significantly lower than the accuracy achievable with the other devices and calibration methods. For the 40Dfe45 and 50Dfe45 devices, the colour accuracy achieved with the minXYZ-3CF calibration method is significantly higher than the accuracy achievable with the other methods. For the 5Dfe8 device, though the colour accuracy achieved

Table 9. Overview table of error percentages in luminance and colour differences (ΔE_{00}) observed in the literature and experimental conditions.

Reference	Camera, lens	Lighting (test)	Luminance range (cd/m^2)	Merging tool (image format)	CTM	Error in luminance (MAPE_lum-%)			Color difference ΔE_{00} (-)		
						Colour	Grey	Black	Mean	Median	Max.
The present study	Canon EOS 40D, Sigma 4.5mm*1	LED @5400K	[16-381]	raw2hdr (raw)	sRGB	5.8	3.3	17.4	-	-	-
					CTM*4	3.1	3.3	17.5	1.2	1.0	2.9 (cyan)
	Canon EOS 50D, Sigma 4.5mm*1	LED @5400K	[16-381]	raw2hdr (raw)	sRGB	4.9	4	10.2	-	-	-
					CTM*4	3.8	4	10	1.3	1.2	3.1 (white)
	Canon EOS 5D, Sigma 8mm*1	LED @5400K	[16-381]	raw2hdr (raw)	sRGB	4.6	1.4	5.3	-	-	-
					CTM*4	3.3	1.4	5.2	1.3	1.2	2.4 (red)
Inanici [6]	Nikon Coolpix 5400,	INC	[1-25]	Photosphere (jpeg)	sRGB	11.2	4.6		-	-	-
	Nikon FC-E9 *1	FLUO@3000K	[1-80]	Photosphere (jpeg)	sRGB	7.4	3		-	-	-
Cai and Chung [7]	Canon EOS 350D, Sigma 10–20 mm F4-5.6 EX	FLUO@4000K	*2	Photosphere (jpeg)	*2	10	2.8	-	-	-	-
Varghese et al. [11]	Canon EOS 55D	mixed*5	*2	pfstool (raw)	CTM*3	7.2	-	-	1.9	-	-
	Canon EOS 1000D	mixed*5	*2	pfstool (raw)	CTM*3	8.5	-	-	2.6	-	-
	Panasonic Lumix DMC-LX7	mixed*5	*2	pfstool (raw)	CTM*3	12.9	-	-	3.6	-	3.0 (orange)
Kim and Kautz [9]	Canon 350D	halogen	*2	DM*6	CTM*7	-	-	-	-	0.5	-
	Nikon D100	halogen	*2	DM*6	CTM*7	-	-	-	-	3.8	-
	Nikon D40	halogen	*2	DM*6	CTM*7	-	-	-	-	3.1	-

Notes.
*1 fisheye lens, *2 not specified, *3 CTM determined using an ultra cool daylight source (CCT not specified), *4 CTM determined using a cool incandescent source (5050K) + 3CF, *5 ultra cool daylight + real room lighting, *6 HDR assembly part of Debevec and Malik's method [10], *7 CTM determined at 5500K.

with minXYZ-3CF is higher than with minXYZ-1CF, the difference is not significant.

4. DISCUSSION

A. Photometric accuracy

The deviations in luminance observed on the 57 samples are within the expected range of error: they are under 10% for the majority of samples and maximum error in luminance reaches 20% for some punctual samples. For comparison with the literature, we computed mean absolute error percentage on the 18 colour samples of the Macbeth chart, and on the five grey samples (Table 9). Absolute percentage error on the black sample (Macbeth #24) is given separately. Table 9 also summarizes errors reported in previous works (Section 1.B).

As expected, percentage error of luminance is superior on colour samples than on grey samples. The mean absolute percentage errors of luminance on colour samples are inferior to those reported in the literature, whatever the calibration method we used.

The error in luminance on the black sample of the Macbeth chart is very high in comparison to the mean percentage error on colour and grey samples. These very large discrepancies on dark samples could partially be explained by the fact that an absolute difference of luminance has a larger influence on percentage error when the level of luminance is low than when it is high. So, the absolute error in luminance for the black sample captured with 40Dfe45 is about 3cd/m^2 while its relative error is 17.5% (luminance of black sample measured with the spectroradiometer is about 16 cd/m^2). The general light scattering in the lens and the sensor mentioned by McCann et al. [17] and Inanici [6] could also participate in the large luminance errors on dark samples. The quality of optics and sensors could explain both the differences between our devices and the fact that Cai and Chung [7] who uses a traditional lens (less affected by optical problems) observed a smaller error on black sample.

The present study highlights that using a CTM specifically determined for a device (minXYZ method) improves significantly the photometric accuracy in comparison to the sRGB matrix. The advantage of using such a CTM was not clear when comparing the results of previous works. Indeed, the luminance errors observed by Varghese et al. [11] that worked with a CTM specifically determined for their cameras are in the same range as those observed by Inanici [6] and Cai and Chung [7] that used the sRGB CTM. The significant difference we highlighted can be explained by a better control of experimental conditions as both methods were tested in a same experiment.

Nevertheless, even if significant, in average, the luminance error is only reduced by about 2%. Its interest mainly lies in the reduction by half of the large errors on red samples when sRGB method is used, as illustrated by Fig.9.

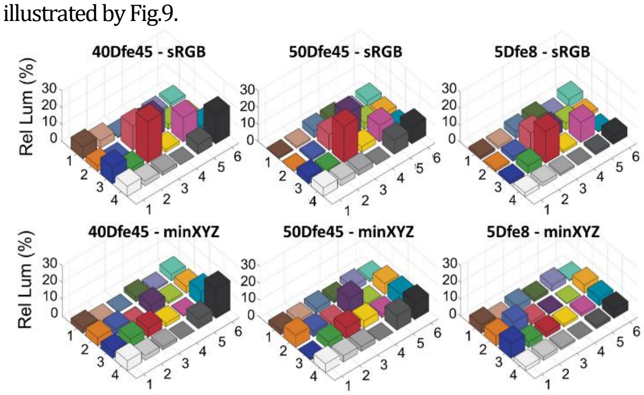

Fig. 9. Relative difference of luminance (%) on the Macbeth chart, by device and calibration method.

1. The specific context of European buildings

Indoor spaces in European buildings are often not colourful. Knowing that the ranges of errors are quite different on colour and grey samples, t-tests were conducted separately on colourful samples (3 cameras, 18 coloured samples of the Macbeth chart) and pastel colour/colourless samples (3 cameras, 17 samples – 6 neutral samples from the Macbeth chart, and 11 Munsell samples with lightness L^*_{ab}>66 and chroma C^*_{ab}<50). For colourful samples, difference resulting from sRGB (mean=0.051) and minXYZ (mean=0.034) methods is significant (t(106)=-2.037; p=0.044). For pastel colour/colourless samples, the t-test between sRGB (mean=0.026) and minXYZ method (mean=0.025) indicates that the difference is not significant (t(100)=-0.268; p=0.790).

In case of colourful scenes, the minXYZ calibration should thus be favoured for calibrating photometric values from HDR photography. The use of sRGB matrix is acceptable for other scenes.

2. Photometric accuracy with the Radiance suite of programs for retrieving luminance

The RADIANCE Lighting Simulation and Rendering System, widely known by the lighting community for investigating light in indoor environment, uses for its calculation RGB primaries and a white point slightly different from sRGB: xy_red=(.64;.33), xy_green=(.29;.60), xy_blue=(.15;.06) and xy_white=(.33, .33). Consequently, Radiance programs such as *falsecolor* and *ximage* use the following equation for retrieving luminance:

$$L_{ij} = 179 * (0.2651 * \frac{R_{ij}}{E} + 0.6701 * \frac{G_{ij}}{E} + 0.0648 * \frac{B_{ij}}{E}), \quad \textbf{(11)}$$

where L_{ij} is the absolute luminance at pixel i,j; 179 is the standard luminous efficacy in Radiance; R_{ij}, G_{ij} and B_{ij} are floating point linear RGB extracted from HDR image after exposure compensation; E is the exposure value specified in the header of the Radiance file. Before exposure compensation, E is 1.

When the HDR image is produced by simulation, Equation 11 should be used. Care should be paid when *hdrgen* and Photosphere are used for producing the HDR picture because the default output colour space of these programs is sRGB and not the Radiance colour space. Consequently, Equation 1 should be used.

We evaluate in this section the effect of the luminance error produced when using Radiance formula instead of sRGB formula for analyzing HDR photographs. A t-test was conducted on the entire set of samples (3 cameras, 57 samples) to compare MAPE_lum resulting from sRGB (mean=0.045) and Radiance formula (mean=0.07). Difference is significant ($t(340)=3.76$; $p<0.001$). A second t-test was conducted specifically on colourful samples (3 cameras, 18 samples) to compare MAPE_lum resulting from sRGB (mean=0.051) and Radiance formula (mean=0.090). Difference is again significant ($t(106)=2.645$; $p=0.009$). On pastel colour/colourless samples (3 cameras, 17 samples), the t-test conducted to compare MAPE_lum resulting from sRGB (mean=0.026) and Radiance formula (mean=0.027) shows that difference is not significant ($t(100)=0.084$; $p=0.933$).

We can conclude that, in a context of typical European indoor environments (not colourful environments), given that sRGB formula does not increase photometric accuracy on neutral samples, using Radiance program such as *falsecolor* and *ximage* for retrieving luminances from HDR pictures is acceptable.

B. Colour accuracy

For comparison with the literature, we calculated CIEDE2000 (also called ΔE_{00}) [18]. Table 9 summarizes the mean, median and maximum colour differences calculated on the 24 Macbeth samples lit by the test source, and errors reported in the literature (Section 1.B).

The colour differences observed with our three Canon cameras (specific CTMs) are in the same range or even lower than those published in the literature. But, is this range of colour differences acceptable in a building context? Few data were found in the literature regarding acceptable colour differences though it is recognized that they vary with the application. According to Mokrzycki and Tatol [19], if ΔE^*_{ab} is lower than 1 (1 CIELAB unit), observer does not notice any colour difference. Experienced observers will notice a colour difference for ΔE^*_{ab} larger than 1 and unexperienced observers for ΔE^*_{ab} larger than 2. It is for ΔE^*_{ab} above 3.5 that colour differences are clear. And above 5, colours will be judged as two different colours. Field of applications is not specified. According to Meyer [20] cited in Finlayson et al. [21], colour differences up to 6 CIELAB units are not detected in complex images.

Consequently, and in our context of colour perception in built environments, the following acceptable thresholds might be specified for assessing colour accuracy of HDR photography: mean ΔE^*_{ab} < 3.5 units; maximum ΔE^*_{ab} < 6 units.

Considering those criteria, the following analysis can be drawn. The standardized RGB to XYZ CTM with a re-scaling by a single calibration factor (method usually used in lighting research for calibrating luminance maps) does not lead to the expected colorimetric accuracy. A re-scaling by channel (3CF) reduces mean colour differences but the targets are still not achieved. The acceptability threshold values are not exceeded for any cameras when the second calibration method followed by a three-factor re-scaling is used (minXYZ-3CF).

C. Opportunity to share a specific CTM between similar devices

Our results show that using a CTM specifically determined for a camera allows reducing errors in luminance in comparison to the usual sRGB-1CF method. Moreover, it is necessary to achieve colour accuracy objectives fixed in Section 4.B. We wonder whether the CTM determined for one device can be used for calibrating similar photographic material (camera and lens of same brand and same model).

A CTM (Equation 12) was determined for a second Canon EOS 50D fitted with a Sigma 4.5mm F2.8 EX DC fisheye lens (50Dfe45bis) (minXYZ method described in Section 2.D.1).

$$M_{50Dfe45bis} = \begin{bmatrix} .5025 & .5673 & .2454 \\ .2168 & 1.1318 & .0736 \\ .0055 & .1314 & 1.5919 \end{bmatrix}, \quad \textbf{(12)}$$

This matrix was then applied to the HDR picture taken with the 50Dfe45 device under the test source, and a re-scaling by channel (3CF, Section 2.D.2) was done. The white standard measured with the spectroradiometer was taken as the reference for L*a*b*coordinates computation. CIELAB colour differences were calculated between the image calibrated with the matrix specifically determined for the camera (50Dfe45 calibrated with M_50Dfe45 given is Equation 9) and the image calibrated with the matrix determined for a similar camera/lens association (50Dfe45 calibrated with M_50Dfe45bis given in Equation 12). Mean ΔE^*_{ab} is 0.5 and MAPE_lum is 0.3%. A t-test was conducted on the entire set of samples (2 CTMs, 57 samples) to compare MAPE_lum resulting from the proper CTM M_50Dfe45 (mean=0.036) and from M_50Dfe45bis, the CTM determined for the similar device (mean=0.038). Difference is not significant ($t(112)=-0.336$; $p=0.738$). Using a CTM determined for a similar device (camera/lens association of same brands, same models) does not significantly modify photometric accuracy. A similar t-test conducted to compare mean ΔE^*_{ab} resulting from the proper CTM M_50Dfe45 (mean=1.747) and from M_50Dfe45bis (mean=2.012) shows that differences on colour accuracy are not significant either ($t(112)=-1.165$; $p=0.246$). Thus, using a CTM determined for a similar device (camera/lens association of same brands, same models) does not significantly modify colorimetric accuracy.

Given than neither colorimetric accuracy nor photometric accuracy is significantly decreased by the use of a CTM determined on another but similar device (same brand, same model), it can be stated that colour transform matrices can be shared between similar devices.

D. Image quality

In a context of lighting research for interior environments, psychophysical experiments where images are used as visual stimuli can be envisaged. Image quality is in this case an important parameter. Image quality should be here understood as "the weighted combination of all of the visually significant attributes of an image" as defined by the International Imaging Industry Association (I3A) [22]. As QuickTime Virtual Reality (QTVR) panoramas were identified by Cauwerts [23] as a promising tool for studying the appearance of lighting and space, we tested the quality of such images produced from HDR fisheye images.

Images were first calibrated using the method leading to best photometric and colour accuracy (specific CTM followed by a re-scaling by channel, minXYZ-3CF). Then they were tone-mapped with the iCAM06 algorithm [24]. The following user-controllable parameters were fixed: the overall contrast, p was set to 0.75 as in Kuang et al. [24] and the surround factor parameter, gamma_value was set to 1 (average surround). The degree-of-adaptation factor, D was set to 0.9 (quasi-complete adaptation). The output colour space is sRGB. Both transformations were done in Matlab R2017a. QTVR panoramas were finally created with PTGui Stitching Software [25].

Figure 10 presents tone-mapped fisheye images and screenshots of QTVR panoramas for each device. As announced by the manufacturer, maximum definition differs between cameras (Table 1). Given that Sigma 8mm f3.5 EX DG is designed for 35mm full frame sensors, when it is mounted on Canon EOS 5D which has a 35mm sensor, the fisheye diameter is maximum. The authors noticed that after tone-mapping with iCAM06, images obtained with 40Dfe45 and 50Dfe45 are more greenish than the one produced with 5Dfe8. That could be due to the red halo observed on the bright ceiling of the booth in images captured with the two cameras fitted with the Sigma 4.5mm fisheye lenses.

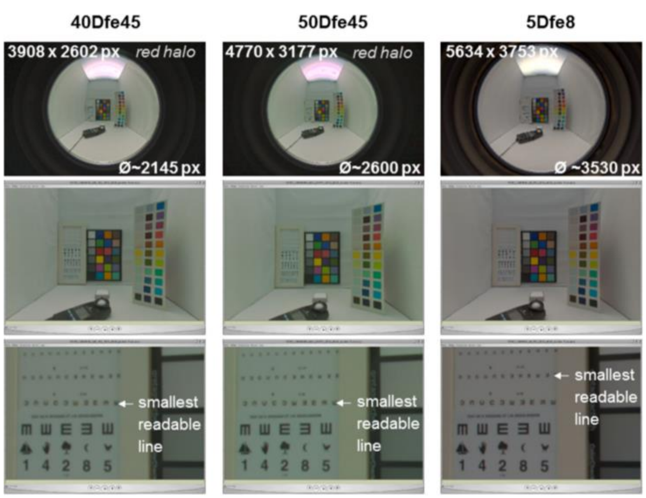

Fig. 10. Comparison of the images produced by each device.

Members of the research team assessed subjectively the sharpness of the image with the visual acuity chart placed in the scene. They also checked the absence of visual artifacts such as halos. QTVR panoramas were displayed on a 22-inch display with a native definition of 1680*1050px. Observers could virtually move their head, and zoom in and out. They were asked to determine the smallest readable line of the visual acuity chart (Landolts rings and tumbling E's). There was a consensus: everyone was able to read the fifth line of the 40Dfe45 panorama; the fifth line of the 50Dfe45 picture was also readable for everyone and less than four errors were made on the fourth line (the fourth line is smaller than the fifth); the fourth line of the 5Dfe8 image was readable and less than three errors were made on the third line.

5. CONCLUSION AND FURTHER WORK

Validation of HDR pictures for measuring luminance and colour should be pursued with larger ranges of luminance, light sources with various spectral power distributions and other sets of colour samples, both in controlled laboratory environments and in real world. Nevertheless, the following conclusions and recommendations can already be drawn from the study.

A. Concerning the photometric accuracy of HDR images.

The review of the literature did not highlight the interest of using a CTM specifically determined for each camera rather than the standardized RGB to XYZ transform matrix for retrieving luminance from HDR picture. In the present study we tested both colour transform matrices in a same experiment annihilating the differences in experimental conditions. We show that, for luminances in the range [10-400cd/m^2], the use of a CTM specifically determined for each camera allows reducing significantly errors in luminance on colourful samples (18 Macbeth colour samples), in comparison to the use of sRGB matrix. The large relative error in luminance observed on red samples with the standardized RGB to XYZ matrix can be reduced from 20% to 5%. Difference on pastel colour/colourless samples (6 Macbeth grey samples and 11 Munsell samples with L^*_{ab}>66 and C^*_{ab}<50) is not significant. We also observed that on those samples using sRGB or Radiance formula is similar, while on colourful samples the Radiance formula leads to significantly higher errors in luminance than sRGB.

Consequently, when investigating luminance distribution in common European buildings (not colourful buildings), luminance can reasonably be retrieved from HDR images using the commonly used formula derived from sRGB primaries, or luminance maps can be built and analysed with Radiance programs. For retrieving luminance of colourful elements from HDR image, the use of a colour transform matrix specifically determined for each camera is recommended.

B. Concerning the colorimetric accuracy of HDR images.

The standardized RGB to XYZ CTM with a re-scaling by a single calibration factor (method commonly used by lighting researchers for calibrating luminance maps) does not lead to the expected colorimetric accuracy. Using a CTM specifically determined for each camera is necessary for not exceeding the fixed colour difference acceptability thresholds (mean ΔE^*_{ab} < 3.5 units and maximum ΔE^*_{ab} < 6 units). For two cameras (CANON EOS 40D fitted with Sigma 4.5mm F2.8 EX DC fisheye lens and CANON EOS 50D fitted with a lens of same model), a re-scaling by three factors is recommended, and consequently a chromameter is needed when taking pictures. For the CANON EOS 5D fitted with Sigma 8mm F3.5 EX DG fisheye lens, a re-scaling by a single factor is also possible, and thus having a (il)luminance meter in situ is sufficient.

Consequently, using the standardized RGB to XYZ transform matrix is not recommended for retrieving XYZ values from HDR pictures, even for pastel/colourless elements. The use of a CTM specifically determined for the camera should be preferred. Among the three tested devices , the CANON EOS 5D fitted with a Sigma 8mm F3.5 EX DG fisheye lens does not need a chromameter when taking picture, a luminance meter is sufficient.

C. Concerning the opportunity to share a specific CTM between similar devices.

We have shown that the CTM determined specifically for CANON EOS 50D fitted with Sigma 4.5mm F2.8 EX DC fisheye lens can be used for calibrating another camera-lens association of same brand and model. By extension, we hypothesized that a CTM determined for one camera-lens association can be reasonably used for calibrating a second camera-lens association of same brand and model. The matrix we propose to share is currently validated for CCTs around 5000K and luminance values in the range of 10- 400 cd/m^2.

D. Concerning the quality of pictures in a perspective of visual psychophysics.

Among the three devices tested, we recommend using CANON EOS 5D fitted with a Sigma 8mm F3.5 EX DG fisheye lens for producing QTVR panoramas. Pictures taken with this device offers the highest definition, absence of visual artefacts and maximum sharpness.

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References

1. G. Ward, hdrgen command-line, 2006.
2. G. Ward, Photosphere, 2001.
3. D. Dumortier, B. Coutelier, T. Faulcon, and F. Roy, "Photolux: a new luminance mapping system based on Nikon Coolpix digital cameras," in *Lux Europa*, 2005), 308-311.
4. R. Mantiuk, G. Krawczyk, R. Mantiuk, and H.-P. Seidel, "High-dynamic range imaging pipeline: perception-motivated representation of visual content," in *Human Vision and Electronic Imaging XII*, (International Society for Optics and Photonics, 2007), 649212.
5. G. Ward, "raw2hdr Perl script" (2011), retrieved 24th April, 2019, http://www.anyhere.com/gward/pickup/raw2hdr.tgz.
6. M. Inanici, "Evaluation of high dynamic range photography as a luminance data acquisition system," Lighting Research and Technology **38**, 123-136 (2006).
7. H. Cai and T. Chung, "Improving the quality of high dynamic range images," Lighting Research and Technology **43**, 87 (2011).
8. B. Jung and M. Inanici, "Measuring circadian lighting through high dynamic range photography," Lighting Research & Technology, doi: 10.1177/1477153518792597. (2018).
9. M. H. Kim and J. Kautz, "Characterization for High Dynamic Range Imaging," Computer Graphics Forum **27**, 691-697 (2008).
10. P. E. Debevec and J. Malik, "Recovering high dynamic range radiance maps from photographs," in *ACM SIGGRAPH 97*, 1997), 369-378.
11. D. Varghese, R. Wanat, and R. Mantiuk, "Colorimetric calibration of high dynamic range images with a ColorChecker chart," Proceedings of HDRi 2014, Second International Conference and SME Workshop on HDR imaging, Sarajevo, Bosnia and Herzegovina, 17-22 (2014).
12. IEC, "IEC 61966-2-1: Multimedia Systems and Equipment-Colour Measurement and Management-Part 2-1: Colour management-Default RGB Colour Space-sRGB," (IEC, Geneva, 1999), p. 2.
13. C. Cauwerts, M. Bodart, and A. Deneyer, "Comparison of the Vignetting Effects of Two Identical Fisheye Lenses," LEUKOS The Journal of the Illuminating Engineering Society of North America **8**, 181-203 (2012).
14. "HDRI mailing list, February 2012, hdrgen's -x option", retrieved 29.05.2019, https://discourse.radiance-online.org/t/hdrgens-x-option/3525/2.
15. MathWorks, MATLAB Release 2017a, The MathWorks Inc., Natick, MA., 2017.
16. ISO/CIE, "ISO 11664-4:2008/CIE S 014-4:2007 Colorimetry – Part 4: CIE 1976 L*a*b* Colour Space," (CIE, Vienna, 2008).
17. J. J. McCann, V. Vonikakis, and A. Rizzi, "HDR Scene Capture and Appearance," in (Society of Photo-Optical Instrumentation Engineers (SPIE), 2017),
18. CIE, "CIE 15:2018 Colorimetry," (CIE, Vienna, 2018).
19. W. Mokrzycki and M. Tatol, "Color difference Delta E - A survey," Machine Graphics and Vision **20**, 383-411 (2011).
20. G. W. Meyer, "Wavelength selection for synthetic image generation," Computer Vision, Graphics, and Image Processing **41**, 57-79 (1988).
21. G. D. Finlayson, S. D. Hordley, and P. Morovic, "Using the spectracube to build a multispectral image database," Conference on Colour in Graphics, Imaging, and Vision, Society for Imaging Science and Technology, Aachen, Germany, 268-274 (2004).
22. I3A, "Fundamentals and review of considered test methods," (2007).
23. C. Cauwerts, "Influence of presentation modes on visual perceptions of daylit spaces," PhD thesis (Université catholique de Louvain, Louvain-la-Neuve, Belgium, 2013).
24. J. Kuang, G. M. Johnson, and M. D. Fairchild, "iCAM06: A refined image appearance model for HDR image rendering," Journal of Visual Communication and Image Representation **18**, 406-414 (2007).
25. New House Internet Services BV, PTGui, v9.1.7 PRO, The Netherlands, 1996.