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FEASIBLE SOLUTION?**

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CEILING-BASED LUMINANCE MEASUREMENTS: A FEASIBLE SOLUTION?

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Abstract

Luminance distributions would be very suitable as input for lighting control systems that aim for a comfortable lit indoor environment. Luminance distribution measurements should then correspond to the visual field of the user. However, this will interfere with office activities. Therefore, this study aims to validate whether it is feasible to approximate the luminous conditions experienced by the user using ceiling-based measurements instead. The average desktop luminance was measured using a luminance camera, under varying conditions, simultaneously from eye level and ceiling and their relations were analysed. Normalized root mean square errors were found ranging from 10,3 % to 14,3 %, while the average bias was 14,2 % between measurements from eye level and ceiling. Based on these results, it is concluded that the experienced desktop luminance cannot be exactly replicated by ceiling-based measurements. However, ceiling-based luminance measurements are able to provide a reasonable approximation that suffices for practical systems.

Keywords: Luminance Camera, Field of View, HDR, Ceiling-based, Luminance distribution, Desktop luminance, Unobtrusive measurements

1 Introduction

Lighting is an important aspect of the indoor environment, having effects on occupants' visual comfort, visual performance, alertness, circadian rhythm and general health. It has been shown that the luminance distribution is a good measure for the experienced visual comfort and visual performance (Van Den Wymelenberg and Inanici, 2014) as it directly relates to the brightness, in contrast to the more often used illuminance.

Previously, the luminance distribution was measured by spot luminance meters, which was a tedious and imprecise method due to rapid changes in the luminous environment. However, current High Dynamic Range (HDR) imaging technology has enabled the scientific community to measure the luminance distribution using image-based systems (so-called luminance cameras) (Inanici, 2006; Kruisselbrink, Aries and Rosemann, 2017). Generally, the luminance is calculated based on the floating point Red-Green-Blue (RGB) pixel values of the HDR image, which is captured using sequential exposure bracketing. Moreover, important user requirements, such as autonomy and modest costs, can now be met for the implementation of this type of sensor in lighting control systems. It is expected that luminance camera based control systems, will exceed the performance of current control systems, which are typically equipped with only an illuminance and/or motion sensor because the luminance camera can measure the full luminance distribution which contains information on numerous lighting quality aspects such as quantity (luminance, illuminance), glare, dynamics, and distribution (Kruisselbrink, Dangol and Rosemann, 2018).

Nevertheless, numerous practical issues occur when this kind of control systems are implemented in real-life. For instance, to indicate the visual comfort or visual performance, luminance distributions are needed that correspond to the visual field of the user, that is: measured from the position of the user's eye. However, this is not feasible for long term measurements because this will interfere with the daily activities within the office environment. Therefore, a suboptimal position should be chosen that does not cause interference but still approximates the visual field of the user. In this study, the image-based system is placed in the

ceiling similar to Doulos et al. (2013) and Motamed, Deschamps and Scartezzini (2017) but also similar to traditional light sensors. The advantages to place the sensor in the ceiling are that it is unobtrusive to the users and it enables the luminance camera to monitor multiple desks at once. The limitation, due to the different field of view and the different angle of view relative to the user, is the reduced relevance of the measurements. However, it remains unclear to what extent the luminous conditions can be approximated. Two studies (Fan, Painter and Mardaljevic, 2009; Motamed, Deschamps and Scartezzini, 2015) have been identified that related the relevance of different suboptimal measurement positions, in the vicinity of the user and on top of the monitor, respectively, to the visual field of the user. Both studies found relative differences, in luminance and Daylight Glare Probability (DGP), up to approximately 35 %.

The objective of this study is to validate whether ceiling-based luminance distribution measurements are able to approximate luminous conditions as experienced by the user within a typical office environment. This will indicate whether it is feasible to perform ceiling-based measurements instead of luminance distribution measurements at eye level in order to limit interference with office activities.

2 Method

In a mock-up office located in Eindhoven (Figure 1), with windows facing west (5,5 m × 1,9 m), luminance distributions were continuously and simultaneously measured with 10m intervals. Measurements were conducted for one day of clear sky conditions, one day of intermediate sky conditions and one day of overcast sky conditions during November and December 2018. Each day is described by a morning (8.30h - 12h) and afternoon (13h - 16.30h) period. For each weather condition and day period measurements were conducted with and without the electrical lighting (9x PHILIPS RC461B G2 PSD W60L60 1xLED34 S/840, providing a uniformly distributed 750 lx on the desktops) turned on, resulting in a total of 6 measuring days.

The measurements were conducted with 3 identical devices that were able to measure the luminance distribution autonomously and with a practical accuracy, similar to the device described by Kruisselbrink, Aries and Rosemann, 2017. The devices consist of a single-board computer (Raspberry Pi 3 Model B), a camera (Raspberry Pi Camera Board version 2), a fisheye lens and custom software providing an equisolid-angle luminance projection on the imaging sensor with a spatial resolution of 2130 pixels × 1600 pixels.

Two of the luminance cameras were placed at eye level using tripods representing the visual field of a seated virtual office user facing south (1) and north (2), respectively, as displayed in Figure 1. To compare these with the proposed ceiling-based solution, the third luminance camera was attached to the ceiling.

Figure 1 – The mock-up office. The two eyes represent the measurement position of the virtual user. The downward arrow indicates the measurement position of the ceiling-based luminance camera

The average luminance on the desktop area directly in front of the two virtual users was extracted from the respective luminance cameras at eye level for each individual luminance distribution. Additionally, the same desktop areas were extracted from the luminance camera attached to the ceiling, representing a similar field of view, with different distortions, from a different angle of view as displayed in Figure 2.

Figure 2 – The considered desktop areas seen from luminance cameras representing virtual user 1 (Black), the ceiling-based prediction and the virtual user 2 (Orange), respectively.

The difference between the approximated desktop luminance and the actual luminance experienced by the virtual user was indicated by the normalized root mean square error (NRMSE). Based on the NRMSE it was determined whether the ceiling-based luminance camera (approximation) is able to replace the representative luminance camera at eye level (actual values).

The comparisons were conducted for all 12 day periods containing all the different conditions. According to Equation (1), a unique calibration factor was applied, for each individual day period, to the luminance measured by the ceiling-based camera.

$$\bar{L}_{\text{eye}} = k \bar{L}_{\text{ceiling}} \quad (1)$$

where

$\bar{L}_{\text{eye}}$ Average desktop luminance during day period measured from eye level

k Calibration factor

$\bar{L}_{\text{ceiling}}$ Average desktop luminance during day period measured from the ceiling

Additionally, all measurements were compared using the NRMSE with one single fixed calibration factor, relative to each device, that matched the average desktop luminance of all ceiling based measurement to the average desktop luminance measured at the eye level.

Furthermore, Bland Altman (B&A) plots (also known as Tukey mean-difference plots) were generated to further investigate the differences between the ceiling-based and eye level based measurement. These B&A plots provide a simple way to evaluate the bias between the mean differences of two different methods (Giavarina D., 2015).

3 Results

In this section, the results of the comparison between the average desktop luminance measured from the ceiling relative to the measurements at eye level are displayed. Figure 3 shows the average desktop luminance values measured for overcast sky conditions in the afternoon with the lights off and on. It shows large correspondence between the predicted luminance from the ceiling and the actual luminance measured from eye level when a unique calibration factor is applied for each day period, although the predictions are statistically different ($p=0,0176$ and $p=0,0016$) for both virtual user 1 and virtual user 2. A similar trend is observed in both the predicted and the actual luminance measured, with small variations in magnitude. The effects are similar during mornings and other weather types.

The predicted luminance, using a fixed calibration factor for all day periods, shows only minor deviations in luminance relative to the predicted luminance using unique calibration factors for different conditions (indicated in Table 1). However, for some cases the two predictions differ largely, for instance, during an overcast morning with the electric lighting turned off relative differences are found up to approximately 45 %.

Figure 3 – Luminance of the ceiling based approximation (Orange) relative to the actual luminance measured at eye level for two afternoons of overcast sky conditions with the lights switched off and on. The dashed line represents the approximated luminance with a fixed calibration factor.

Table 1 shows that on average the NRMSE between the prediction and the actual luminance was 10,3 % with a standard deviation of 4,8 % when a unique calibration factor is applied for each day period. It also shows that this calibration factor k was very close to 1 and exhibited little variance. The NRMSE generally increases under conditions that have a high variability, such as intermediate sky conditions. As a result, the largest difference was found for

intermediate sky conditions. The largest variation was found for the prediction of the desktop luminance in front of observer 2, which was located directly next to the window.

On average the prediction using a fixed calibration factor had a NRMSE 4,3 % higher than using a unique calibration factor. However, for most of the conditions the variability of the NRMSE, indicated by the standard deviation, was more than doubled. For the individual conditions, the fixed calibration resulted in an increase in the NRMSE ranging from 0,3 % to 8,0 %. Remarkably, the variability of the NRMSE often showed a large decrease or a large increase for a fixed calibration factor relative to a unique calibration factor.

Table 1 – Difference between approximated and actual desktop luminance and calibration factor k . The standard deviation is indicated between brackets.

		k	NRMSE (SD)	NRMSE (SD) fixed
Total		0,96 (0,11)	10,3 % (4,8 %)	14,6 % (9,4 %)
Lighting	Lights On	1,00 (0,07)	9,5 % (5,1 %)	10,6 % (4,0 %)
	Lights Off	0,91 (0,11)	11,0 % (5,1 %)	18,6 % (11,9 %)
Period	Morning	0,94 (0,12)	9,8 % (4,5 %)	16,8 % (11,9 %)
	Afternoon	0,97 (0,08)	10,7 % (5,1 %)	12,4 % (5,0 %)
Sky	Clear	1,00 (0,09)	7,8 % (5,0 %)	12,6 % (7,0 %)
	Intermediate	0,98 (0,07)	12,1 % (5,2 %)	12,4 % (4,0 %)
	Overcast	0,89 (0,12)	10,9 % (2,7 %)	18,9 % (13,2 %)
Observer	2	0,93 (0,07)	10,3 % (10,3 %)	12,6 % (4,9 %)
	1	0,98 (0,13)	10,2 % (5,2 %)	16,6 % (12,0 %)

Figure 4 shows the B&A plots comparing the predicted luminance, using a fixed calibration factor, and the actual luminance measured from eye level of virtual user 1 and virtual user 2, respectively. The predictions showed a large agreement with the actual values, indicated by Pearson's correlations of 0,994 and 0,995, respectively. The B&A plots show that there was an average bias of 17,0 % relative to virtual user 1 and 11,3 % relative to virtual user 2. This shows some similarities to the NRMSE (16,6 % to 12,6 %) found in Table 1. Except for very low luminance values, all predictions were generally within the agreements limits. Shape wise, the B&A plot of user 1 and user 2 were almost identical with overestimated predictions for low luminances, underestimated predictions for high luminances, and a constant bias for the highest luminance values. However, the transition point of an over- to an underestimated prediction was found to be different with luminance values of approximately 75 cd/m² and 150 cd/m², respectively. Also, the limits of agreements, representing the 95% confidence interval, showed some minor differences.

Figure 4 – Bland Altman plot of the predicted luminance relative to virtual user 1 and virtual user 2, respectively. The black line indicates the average bias, the dashed lines indicate the agreement limits from -1.96σ to $+1.96 \sigma$ and the orange markers represent all individual predictions.

4 Discussion & Conclusion

The objective of this study was to show whether ceiling-based luminance distribution measurements are a feasible solution to replace the obtrusive measurements at eye level.

Although the predictions were statistically different compared to the actual luminance values, large similarities were found. Depending on the type of calibration, NRMSEs of 10,3 % and 14,6 % were found on average. The average bias, found in the B&A plots, was 14,2 % when fixed calibration factors were applied. These results showed that it is not possible to exactly replicate luminance measurements at eye level using a luminance camera attached to the ceiling; however, a ceiling-based luminance camera is able to approximate the experienced luminance as the differences can be considered minor.

Figure 3 showed luminance data for overcast sky conditions; nevertheless, some variations in daylight was detected which indicate that it was not a perfect overcast sky. The sky conditions were determined based on cloud coverage as determined by Royal Netherlands Meteorological Institute (KNMI) and were both classified with maximum cloud coverage. In this case, the effect of the lighting is relatively small, it is mainly exhibited during the last hour and for user 1 which is located further from the window.

On average, turning on the lighting has a positive effect on the prediction ability because it provides a relatively uniform lighting distribution on the desktop, reducing the effect of specular reflections. However, this is not true for the overcast conditions (Figure 3) because, in that case, the electric lighting adds small specular reflections to a uniform lighting distribution.

The specular reflections are the highest for clear sky conditions in the afternoon, however, the NRMSE indicates a higher performance compared to, for instance, overcast sky conditions as shown in Table 1. This might be caused by the very high luminances during the clear sky conditions that are too bright to be captured (it saturates the shortest exposure possible). As a result, extreme specular reflections are not captured. This effect provides an additional advantage for the ceiling-based measurement because it does not capture the direct sun and hence the shortest exposure does not saturate during bright light conditions. On the other side, the ceiling-based measurements limit the ability to measure glare.

Moreover, for conditions with large variability such as intermediate sky conditions, afternoon periods, and when the lighting is turned off the prediction performance was generally worse. It might be because the varying conditions differ a lot between the amount of specular reflections adding larger errors, but are also forcing to calibrate over a larger range of luminous conditions. Especially, when the calibration factor is fixed the position close to the window is outperforming the position further from the window, despite the light distribution being less uniform and more variable. Secondly, for very quick variations there might be a small influence of very minor (max 1s) differences between the timing of the exposure bracketing.

The B&A plots of Figure 4 show a distinct pattern with over- and underestimated luminance values. This effect can be caused by the two image sequences that were applied for darker and brighter conditions, respectively (Kruisselbrink, Aries and Rosemann, 2017). It is very likely, that the transition in the B&A plots coincide with the transition in image sequences as it is not caused by the absolute luminance (75 cd/m^2 to 150 cd/m^2). Furthermore, large relative deviations were found for very low absolute luminance values. After the measurements, a small bug, related to the longest exposure, was found in the code that led to an additional overestimation of the very low luminances. However, this effect is limited to absolute luminance values of a few candelas per square meter.

This study focussed on the desktop luminance, which closely relates to lighting requirements such as the desktop illuminance of 500 lx. However, there are more surfaces (background area) and areas of the visual field (40° luminance band) that might be more relevant for the visual comfort of the user (Van Den Wymelenberg and Inanici, 2016). Moreover, it is expected that environmental aspects influence the feasibility of ceiling-based luminance measurement. In this study, the feasibility was only measured for one office environment.

This study showed that the experienced desktop luminance can be approximated using a ceiling-based luminance camera. For a practical application, a fixed calibration factor is more applicable than a unique calibration factor per day period. In that case, the ceiling-based camera will introduce a NRMSE of 14,6 % and a mean bias of 14,2 %, which for practical applications such as lighting control systems will generally be sufficient, with the large advantage that it is unobtrusive. However, for research purposes, it is advised to consider a measurement position that is more appropriate.

It is recommended to conduct additional measurements in different office settings that enables the results to be generalized. Moreover, it is also valuable to replicate these measurements with different areas of interest such as the background luminance because they may be just as, or even more relevant than the desktop luminance.

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