Feasibility of ceiling-based luminance distribution measurements

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ARTICLE INFO
Keywords:
Retinal illuminance
Luminance distribution
Ceiling-based
Measurement position
Measurement uncertainty
B40 luminance

ABSTRACT
There is a high relevancy in the luminance distribution related to the perceived visual comfort. Moreover, the required technology is maturing such that it is feasible to integrate such devices in lighting control systems, which is expected to improve the overall lighting quality in office environments, or to conduct long-term field studies. Preferably, the luminance distribution measurement corresponds to the visual field of the user. However, for long-term measurements this is not feasible as this causes interference. Therefore, this study aimed to find a suitable ceiling-based position for luminance distribution measurements. In a first phase, the most suitable ceiling-based measurement position was identified for four luminance based metrics: Desktop Luminance, Monitor Luminance, B40 Luminance, and Retinal Illuminance. The results showed that a ceiling-based position above the aisle with a 20°-angle relative to the ceiling was the most suitable position because its field of view has large similarities with the field and angle of view of the user. In a second phase, the performance of this most suitable position found in phase 1 was assessed under real office conditions, and compared with the visual field of the user. The Desktop and Monitor Luminance achieved an acceptable accuracy with very basic commissioning. The Retinal illuminance was measured with a reasonable accuracy when an elaborate calibration procedure was applied. For the B40 Luminance, in all scenarios, inaccuracies above 20% were found. This study shows that ceiling-based measurements are feasible, except for the B40 luminance, however, one should account for the introduced uncertainty.

1. Introduction

Lighting is an important aspect of the indoor environment, influencing occupants’ visual comfort, visual performance, alertness, circadian rhythm, and general health [1,2]. It has been shown that the luminance distribution is a good measure for the experienced visual comfort and visual performance [3] as it directly relates to the brightness, in contrast to the more often used illuminance. Moreover, based on the luminance distribution, metrics relevant to the Non-Image Forming (NIF) effects can also be extracted [4,5].

Current High Dynamic Range (HDR) imaging technology, using sequential exposure bracketing, facilitates the lighting community to measure the luminance distribution using image-based systems (so-called luminance cameras) [6,7]. Generally, the luminance is calculated based on a linear combination of the HDR floating-point Red-Green-Blue (RGB) pixel values. Moreover, this technology is maturing and fully autonomous systems using low cost components have been achieved, and can be implemented in lighting control systems [6]. It is anticipated that luminance camera-based control systems will exceed the performance of current control systems equipped with illuminance and/or motion sensors, because a luminance camera is able to measure the full luminance distribution which contains spatially resolved information on numerous lighting quality aspects such as quantity (luminance, illuminance), glare, dynamics, and distribution [8].

Nevertheless, numerous practical issues occur when these kinds of systems are implemented in real-life office environments (e.g. lighting control systems) such as limitations in spatial resolution [9]. The spatial resolution or image resolution, accounting for the total number of pixels, relates to computational costs and the privacy sensitivity of such systems. Moreover, to indicate visual comfort or visual performance, luminance distributions are required that correspond to the visual field (FOV) of the user. This is not feasible for long-term measurements because this interferes with the daily activities within the office environment. Therefore, an alternative position should be applied such that it does not interfere and still approximates the FOV of the respective user. Furthermore, such a position should be easy to apply without
complex commissioning.

Three distinct strategies, from low to high obtrusiveness, that aim to measure the luminance distribution from an alternative position have been identified based on literature. These strategies aim to capture relevant information without interfering with the users and their activities.

The first strategy, or the ceiling-based strategy, performs top-down measurements of the luminance distribution facing the work plane from the ceiling [10–13]. Hence, a luminance distribution with a different FOV is measured from a different angle of view compared to the actual FOV of the user. The objective of this method is to minimize interference with the office activities [11] while measuring the quantity of light on the desktop surface.

The effect of ceiling-based luminance distribution measurements was quantified by Krusselbrink et al. [13]. A luminance camera was attached to the ceiling, which measured desktop luminances for two desks located directly below the camera for different weather conditions. It was shown that the mean desktop luminance cannot be replicated exactly. However, the differences were limited with an average normalized root mean square error (NRMSE) of 14.6%. The results also showed that it gets more difficult to approximate the desktop luminance under conditions with a large variability such as intermediate sky conditions. It was concluded that for practical applications, such as control systems, ceiling-based luminance measurements seem a feasible solution.

The second strategy, the partition- or monitor-mounted strategy, intends to measure the luminance distribution with an similar angle of view relative to the user by placing the luminance camera on top of a monitor or partition in line with the users primary viewing direction [14–16]. In this configuration, the obstruction for the user is limited. However, due to the translational displacement, the luminance camera omits the direct task area. Additionally, it might be experienced as very obtrusive for the office worker at the opposite workplace.

Motamed et al. [16] studied the effect of a luminance camera on top of a monitor relative to the user’s FOV on the Daylight Glare Probability (DGP) by introducing a translational change of 100 cm. Measurements in a small office space with the desktop parallel to the window resulted in a relative difference in DGP with a root mean square (RMS) value of 11%.

In the third strategy, the vicinity strategy, the luminance camera is placed somewhere in the direct vicinity of the user, this can be either by small translational [16–19] and/or angular [16,19,20] displacements relative to the user. Compared to the previous strategies this might cause some obstruction (i.e. limited elbow room, privacy intrusion), but the relevant FOV, including the direct task area, is captured.

Motamed et al. [16] also measured the effect of translational (±30 cm) and angular (±30°) displacements relative to the user’s FOV on the Daylight Glare Probability (DGP). It turned out that the DGP is more sensitive to angular changes than to translational changes of the FOV with a maximum relative difference in DGP of 32%. Additionally, Fan et al. [20] applied either translational (23–118 cm) or angular displacements (15°–45°) relative to the user’s FOV under overcast sky conditions in a one-window office. The relative difference in luminance was determined based on six luminance patches in the FOV of the user. The average relative differences were rather similar between translational and angular displacements with relative errors generally below 25%. For this research [20], it was proposed to place luminance cameras at 30° from the user’s FOV at a distance of 30–50 cm behind the user.

Finally, some alternative measurement positions have been introduced in the literature, which cannot be categorized. Goovaerts et al. [21] placed the luminance camera such that it provided an overview of the entire office environment while measuring glare, independent to a certain user, to control the automated blinds. Kim et al. [22], also to control the blinds, placed the luminance camera directly on the window surface such that the luminous conditions of the exterior environment were monitored. For such systems, one single measurement device would suffice for a single space. However, disadvantages of such systems are that they cannot be related to a user, as the lit environment experienced is largely dependent on the viewing direction. Illuminance differences up to a factor of 20 can be exhibited in an office environment [23].

Open-plan offices are currently the most applied type of office, they are cost-effective and are intended to boost collaboration [24]. Especially in Europe, these offices either lack partitions or the partitions are very low. Therefore, the strategy to place the luminance camera on a partition is not feasible. Similarly, the strategy to place the luminance camera in the vicinity of the user is not very suitable for practical application in open-plan offices due to its obtrusiveness. Ceiling-based luminance cameras seem to be the most suitable position in this context, they do not cause any obstruction and, additionally, they allow measurements for multiple users at once.

Therefore, the objective of this study is to find the most suitable position for ceiling-based luminance distribution measurements in an open office environment and to assess its performance under real office conditions. The research presented in this article consists of two phases.

In the first phase, the most suitable ceiling-based measurement position is identified for four independent indicators representing the visual performance (2x), visual comfort and the NIF effects. In the second phase, the performance of this most suitable position found in phase one is assessed under real office conditions.

2. Experimental setup

Luminance distribution measurements were conducted in a mock-up office room (5 m × 5.5 m) with a west-facing façade and window opening of 5.5 m × 1.35 m, at the Building Physics and Services laboratory at the Eindhoven University of Technology. The façade was designed such that it was similar to the ‘average’ office façade with an average simulated daylight factor of 6.2% (min = 2.1%, max = 16.5%). Four alternative ceiling-based positions were identified, as shown in Fig. 1, which were expected to be able to approximate the luminous conditions to a certain extent, relative to the FOV of six virtual users (E1–E6). The actual luminous conditions for the virtual users were also measured, at a height of 1.2 m and at a horizontal distance of 20 cm from the desktop edge, corresponding to the position of a seated users head. The lighting (9x PHILIPS RC461B G2 PSD W60L60 1xLED34 S/840) was turned on and provided a uniformly distributed 500 lx with a CCT of 4000 K on the desktop. Each desk contained an identical monitor (DELL 1708FPt, 300 cd/m²) with an identical monitor test screen [25] at full brightness.

For this research, four distinct locations were identified in the ceiling: one directly above the desks (A and A’) and three directly above the aisle (B and B’) with three distinct orientations: at 90° (1), 55° (2) and 20° (3) relative to the ceiling such that the projection center focused at the floor underneath, center of adjacent tables (B’2 to E5–6), and the center of the distant tables (B’3 to E1–2), respectively. The non-perpendicular orientations (2) and (3) were lowered 10 cm relative to the ceiling to capture some direct sight on the ceiling. As an example, positions A and A’ were grouped as one (A) because the measurement position relative to the virtual users was identical, only the absolute location was different.

Bee-Eye luminance distribution measurement devices [6,26] were applied to measure four luminance based metrics, representing visual performance (2x), visual comfort and NIF effects, as described in Sections 2.1, 2.2, and 2.3. A Bee-Eye [6,26] consists of three major components: a single-board computer, a camera, a fisheye lens, and custom software. The Raspberry Pi 3 Model B was used as single-board computer. The camera was a Raspberry Pi Camera Board version 2 with a CMOS sensor (Sony IMX219) (3.04 mm, f/2) equipped with a miniature equisolid-angle fisheye lens. The spatially resolved luminance was calculated using the R, G and B pixel coefficients originating from HDR images [7], with a validated dynamic range of at least 3–18000 cd/m².
HDR images, in a resolution of 901 x 676 pixels, were captured using sequential exposure bracketing with seven exposures ranging from 9 μs to 2 s, which were merged into a single HDR image, including a camera response curve, using the command-line HDR builder developed by Ward [27]. A photometric calibration factor was applied locally on the Bee-Eye, further post-processing was done using MATLAB R2019a. The Bee-Eyes were simultaneously calibrated (photometric calibration), in the mock-up office environment with electrical light only (500lx, 4000 K), using a Konica Minolta LS-100 luminance meter (±2%<sub>f</sub> = 8%) and a white (ρ = 0.90) and grey (ρ = 0.18) standard reflector.

2.1. Visual performance

The visual performance was indicated by the average Desktop Luminance, similar to Kruisselbrink et al. [13], because of its analogy to the often used desktop illuminance, and by the average Monitor

Fig. 1. Floorplan and intersection of the mock-up office environment. The measurement positions are indicated by the grey-orange icons. The spectral reflectances of the surfaces are indicated in italics. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Luminance. The average Desktop Luminance was extracted by masking the respective desktop area, as illustrated in Fig. 2. Similarly, the average Monitor Luminance was extracted by masking the respective monitor’s screen. For position A, no Monitor Luminance mask was applied because ceiling-based position A does not provide any view of the monitor screens.

2.2. Visual comfort

Besides visual performance, visual comfort is essential to achieve high-quality lighting [8], which is “lighting that allows you to see what you need to see quickly and easily and does not cause visual discomfort but raises the human spirit” [2]. In this study visual comfort is indicated by the average luminance in the 40° luminance band (B40). The B40 Luminance was first introduced by Loe et al. [28] as an indicator for visual comfort as it encompasses the main viewing area of a person looking around in space. Later on, Van Den Wymelenberg and Inanci [29] showed that the B40 Luminance was one of the highest-ranked metrics for subjective visual preferences. Additionally, it was indicated that this metric is scene independent when applied at eye level, and hence does not require any commissioning.

However, this scene independence is a disadvantage for a ceiling-based position because the 40° FOV of the user needs to be translated to the alternative ceiling-based position. The translation was performed manually by masking the surfaces that are represented in the reference B40 Luminance mask. Due to the different orientation and location of the ceiling-based positions certain surfaces might be omitted while others are enlarged or compressed, as is indicated in Fig. 3. This translation could be automated for a more accurate conversion if space and camera (projection equation) are well defined, but this does require complex geometric models to translate image coordinates of the reference camera to the image coordinates of the ceiling-based camera.

2.3. NIF effects

The most relevant measurable photometric quantity for the non-image forming (NIF) effects based on the luminance distribution is the Retinal Illuminance, which represents the total flux on the retina under the assumption that the sensitive cells are relatively equally distributed [30]. The total flux on the retina is largely influenced by the cutoff shading due to the human facial structure and the spatial response function of the eye [31]. The cutoff shading represented by the human FOV is based on Derlofske et al. [31] and Khademagha et al. [4] and is shown in Fig. 4. A distinction can be made between monocular vision and binocular vision, representing the areas that are covered by a single eye and both eyes, respectively. Additionally, the spatial response, due to the anatomy (not from the distribution of cells [32]), of the retina differs from the standard cosine function. Based on raytracing of a healthy 45 years old eye Van Derlofske et al. found a spatial response of the retina as illustrated in Fig. 4.

To extract the Retinal Illuminance from luminance maps, three distinct components were identified: Masking of the FOV, application of the retina’s spatial responsivity and the application of the pixels’ solid angle. Using the equisolid-angle fisheye projection equation [33] the visual field of the left and right eye were translated to an image resolution of 901 x 676 pixels as shown in Fig. 4. Additionally, Fig. 4 shows the translated spatial response using the projection equation for an image resolution of 901 x 676 pixels. The solid angle (Ω) of this projection type is constant (equisolid) for each pixel, which was 1.22⋅10^{-6} sr. By combining the FOV, the spatial response and the solid angle of each pixel the illumination on the retina for a single eye can be determined. The Retinal Illuminance (E_{ret}), as experienced by the user, was assumed to be the average Retinal Illuminance for both eyes.

To extract the Retinal Illuminance experienced by the user while measuring from a ceiling-based position the FOV and the spatial response were manually translated, the solid angle remains equal. The FOV was translated similar to the B40 Luminance mask in Section 2.2. Again, some differences were introduced for the different surfaces. The retina’s spatial response was translated by extrapolating the focal point (sensitivity of 100%) of the reference measurement at eye level to the ceiling-based FOV. Subsequently, the reference spatial response, divided into quartiles, was scaled such that the midpoint was allocated to the extrapolated focal point for the ceiling-based position, introducing distortions in the X and Y direction. Moreover, the total sensitivity of the ceiling-based masks was aligned with the total sensitivity of the reference masks. The Retinal Illuminance masks, for the left eye, are illustrated in Fig. 5.

3. Phase 1

3.1. Methodology

In the first phase of this study, luminance distribution measurements were performed aiming to find the most suitable ceiling-based position in the mock-up office described in Section 2. Three calibrated Bee-Eye luminance distribution measurement devices (BE1-BE3) were used to measure the four alternative ceiling-based positions consecutively in combination with two reference measurements at eye level (E1-E6). Starting from Position A relative to E1 and E2, all positions and appropriate combinations, according to Table 1, were measured. All positions and combinations were measured with and without daylight. The measurements were performed on 29-07-2019 under clear sky
conditions without direct sunlight (During morning), with an average global irradiance of \(1855 \pm 372 \text{ W/m}^2\) and an average cloud cover of 35 \(\pm 38\%\) measured at the nearest weather station. Direct sunlight was prevented such that the measurements could be conducted consecutively, without abrupt variations in daylight. Therefore, there was no need to conduct all seven dependent measurements simultaneously.

Two sets, with and without daylight, of 36 luminance maps were
captured; 24 luminance maps from the six virtual users positions (E1-E6) and 12 from ceiling-based positions A, B1, B2, and B3. The luminance range, without daylight, for the virtual users and ceiling-based positions was approximately 1:1750 and 1:700, respectively. During post-processing, the relevant luminance based metrics representing the visual performance, visual comfort and the NIF effects, described in sections 2.1, 2.2, and 2.3, respectively, were extracted from the luminance maps relative to virtual users 1 to 6. The four alternative positions were assessed using the Coefficient of Determination ($R^2$), which is a measure of how well observed data (at eye level) is predicted by a model (ceiling-based), relative to each luminance based metric. High coefficients indicate a high ability to approximate the luminous conditions as experienced by the virtual users.

Additionally, a linear model was developed for each luminance based metric and each position, which relates the predicted luminance for the ceiling-based position to the actual measured luminance at eye level. This model, for the most suitable position, will be verified during the second phase.

### 3.2. Results

The results of the first phase are summarized in Fig. 6 and Table 2. Fig. 6 shows that all ceiling-based positions were able to accurately predict the Desktop Luminance as experienced by the virtual user, for all cases more than 98% ($R^2$) of the variance was explained by the ceiling-based positions. Position A had a slightly lower performance than the variants of position B. However, for the B40 Luminance, position A outperformed the position B variants (Table 2). On average, considering visual performance, visual comfort and NIF effects, the performance of position A and position B3 were very similar. Moreover, position B can measure the Monitor Luminance, which is not possible for position A. The performance of positions B1 and B2 were comparatively low (Table 2). Therefore, based on these measurements, position B3, an aggregate of B3 and B’3, was found to be the most suitable ceiling-based position.
position, this position also has the largest similarities with the FOV and the angle of view of the eye-level measurements.

The coefficients (Table 2) of the linear model (Actual = a \cdot Predicted + b) were generally smaller (closer to 1.0) for the Desktop and Monitor Luminance, due to their simplicity; it is very straightforward to extract these luminance metrics because they are strictly defined. For the B40 Luminance and Retinal Illuminance, the corrections are more distinct because of the high complexity. However, this only had a limited effect on the coefficient of determination, which is subject to the variance which cannot be accounted for by the correction model.

### 3.2.1. Model A

The conditions measured for the virtual users (E1 to E6) were rather different. Therefore, linear models \( y = ax + b \), with \( x \) originating from the ceiling-based measurement) for each individual virtual user, based on two measurements (with and without daylight), were developed as shown in Table 3 only E1, E5, and E6 are shown). From here on these specific models, relating the ceiling-based measurements to the eye level measurements, are referred to as Model A. Model A shows that the coefficients for different virtual users were profoundly different, especially for the B40 Luminance and Retinal Illuminance indicating that each desk requires individual commissioning when a ceiling-based system is applied. In practice, this would mean that the commissioning is relatively simple and straightforward. However, the model might not be suitable for the wide range of conditions that can be exhibited during the day and even during the year.

### 4. Phase 2

#### 4.1. Methodology

During the second phase, four Bee-Eyes were installed in the mockup office environment to assess the performance under varying conditions of the most suitable position, position B3, as found in Phase 1. One Bee-Eye was installed in the ceiling at position B3, which was one of the two locations of position B3. Three Bee-Eyes function as reference measurements at eye level for three virtual users, virtual user one (E1), virtual user five (E5), and virtual user six (E6), respectively (Fig. 1). Continuous measurements were conducted simultaneously from 05:30 to 22:00 on 03-08-2019, which exhibited variable weather conditions (global irradiance of 488 ± 395 W/m² and cloud coverage of 97 ± 7%) and a peak luminance ratio of 1:5200, with a temporal resolution of 10 min resulting in 100 measurements per device. Again, the Desktop Luminance, Monitor Luminance, B40 Luminance, and the Retinal Illuminance were extracted during the post-processing phase, using MATLAB R2019a, using luminance masks analogous to Phase 1. The measurement performance is assessed using the mean absolute percentage error (MAPE), which is an intuitive measure of prediction accuracy.

To achieve acceptable MAPEs, models such as Model A were required to enhance the relation between ceiling-based measurements and eye level measurements. Three models, Model A (Section 3.2.1), Model B, and the Simplified Model B were implemented in the analysis.

#### 4.1.1. Model B

As Model A is only based on two measurements, it was expected that this model is not suitable for all conditions. Therefore, a more elaborate model was developed based on additional measurements in the mock-up office environment to train a new model. Identical measurements were performed from 05:30 to 22:00 on 04-08-2019 with again an interval of 10 min. For each virtual user and luminance based metric 100 data points, originating from the additional measurements, were used to fit new models to \( y = ax + b \), shown in Table 4, independent to the test data (measured on 03-08-2019). Outliers, which were values more than three scaled Median Absolute Deviations (MAD) from the median, as illustrated in Fig. 7 were removed from this dataset because they largely affected the model. From here on this elaborated model is referred to as Model B. In contrast to Model A originating from Phase 1, this model requires more extensive commissioning as reference measurements have to be performed for an entire day; however, this model is suitable for a wider range of conditions than Model A.

#### 4.1.2. Model B - simplified

Additionally, a Simplified Model B has been developed, it only differs from Model B for the B40 Luminance and the Retinal Illuminance representing visual comfort and NIF effects, respectively. Previously, the luminance masks for these luminance based metrics were translated to the ceiling-based position as accurate as possible, described in Sections 2.2 and 2.3, being complex and time-consuming. Therefore, in the Simplified Model B, semi-independent alternative masks (Fig. 8) were applied for the B40 Luminance and the Retinal Illuminance that are not complicated to apply; however, this might go at the expense of the accuracy. The alternative ceiling-based B40 Luminance mask consists of two parallel lines that have an opening angle of approximately 40°. In contrast to the original B40 Luminance mask, the alternative mask does not diverge towards the periphery. The alternative Retinal Illuminance mask was only compressed vertically to avert irrelevant floor and ceiling surfaces, while the horizontal FOV was unchanged. As identical masks are applied for each virtual user, only the model can account for the differences between the virtual users. Therefore, the procedure described in Section 4.1.1 was replicated to develop new models for the B40 Luminance and the Retinal Illuminance, the individual models of the Simplified Model B are shown in Table 5.

#### 4.1.3. Uncertainty

In addition to the MAPE an uncertainty analysis has been conducted, which helps to translate ceiling-based measurements \( L_{\text{ceiling}} \) to eye level

### Table 2

| Position                    | A\(^2\) | a   | b   | B1\(^2\) | a   | b   | B2\(^2\) | a   | b   | B3\(^2\) | a   | b   |
|-----------------------------|---------|-----|-----|----------|-----|-----|----------|-----|-----|----------|-----|-----|
| Visual Performance - Desktop| 0.978   | 1.46| 32  | 0.997    | 1.25| 15  | 0.994    | 1.29| 19  | 0.996    | 1.27| 12 |
| Visual Performance - Monitor| x       | x   | x   | 0.778    | 0.84| –4  | 0.813    | 0.57| –14 | 0.898    | 0.66| –9 |
| Visual Comfort – B40        | 0.730   | 3.19| 48  | 0.603    | 4.54| 94  | 0.638    | 4.10| 95  | 0.701    | 4.61| 80 |
| NIF – Retinal               | 0.955   | 1.42| –51 | 0.697    | 3.98| 231 | 0.899    | 2.20| 106 | 0.969    | 2.79| 135|
| Average                     | 0.888   | 0.769|x   | 0.769    | 0.836|     |          |     |     | 0.891    |     |     |
Table 4
Individual models for Model B. The models are based on 100 independent samples measured from position B’3.

| Position                  | E1           | E5           | E6           |
|---------------------------|--------------|--------------|--------------|
|                           | $R^2$ a b    | $R^2$ a b    | $R^2$ a b    |
| Visual Performance - Desktop | 0.996 1.30 -7 | 0.994 1.27 -3 | 0.999 1.35 -25 |
| Visual Performance - Monitor | 0.988 0.55 8 | 0.947 0.60 14 | 0.992 1.00 -5  |
| Visual Comfort – B40      | 0.933 2.38 -26 | 0.895 6.19 -208 | 0.916 2.32 -9  |
| NIF – Retinal             | 0.995 1.22 -5 | 0.939 3.02 -48 | 0.976 1.10 100 |

Fig. 7. Training data (orange, 04-08-2019) for the model with outliers emphasized by a marker. The black dashed line represents the test data (03-08-2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Individual models for the Simplified Model B. The models are based on 100 independent samples measured from position B’3 while applying alternative easy to apply masks.

| Position                  | E1           | E5           | E6           |
|---------------------------|--------------|--------------|--------------|
|                           | $R^2$ a b    | $R^2$ a b    | $R^2$ a b    |
| Visual Performance - Desktop | 0.996 1.30 -7 | 0.994 1.27 -3 | 0.999 1.35 -25 |
| Visual Performance - Monitor | 0.988 0.55 8 | 0.947 0.60 14 | 0.992 1.00 -5  |
| Visual Comfort – B40      | 0.907 1.53 42 | 0.915 5.59 -116 | 0.916 2.65 -4  |
| NIF – Retinal             | 0.969 7.82 110 | 0.954 41.50 -264 | 0.974 9.63 134 |

Fig. 8. Simplified alternative luminance mask for the B40 Luminance and the Retinal Illuminance.
measurements \( L_{\text{sys}} \) for practical applications. In a first step, the relative uncertainty was calculated according to \( \delta L = \frac{|L_{\text{calc}} - L_{\text{sys}}|}{L_{\text{sys}}} \) for each luminance based metric independent to the virtual users, again extreme outliers were removed. As this value \( \delta L \) is an average relative uncertainty it does not illustrate the potential error. Therefore, the margin of error \( m \), based on the 95% Confidence Interval (CI), was also calculated according to \( m = 1.96 \cdot \sigma \) (\( \sigma \) = standard deviation), as normality was assumed according to the Central Limit Theorem. Finally, the uncertainty of a ceiling-based measurement was indicated by \( L = \delta L \pm m \).

4.2. Results

The overall results are displayed in Fig. 9, each bar represents the MAPE for the different luminance based metrics. It is clear that the Desktop and Monitor Luminance (average MAPE of 3.8% and 4.3%, respectively) were performing significantly better than the more complicated B40 Luminance and Retinal Illuminance with average MAPEs of 22.5% and 25.5%, respectively.

Especially, for Model A these differences were even more distinct. For both the Desktop and Monitor Luminance Model A achieved an acceptable MAPE of 3.7% and 6.2%, respectively, while for the Retinal Illuminance an unacceptable MAPE of 52.1% was found. Also for the B40 Luminance, this error was rather high, indicating that the elementary Model A is not suitable for complex luminance masks. However, when the respective surfaces are strictly defined (e.g. desktop) this model could be applied. Overall, Model B performed significantly better (average error of 9.9% relative to 21.3%), as it captured a wide range of conditions while Model A was only a snapshot of, in this case, two conditions. These gains, relative to Model A, were mainly exhibited for the Monitor Luminance and the Retinal Illuminance. The Desktop Luminance showed a very similar performance while for the B40 Luminance this effect was not found for this model. It performed especially poorly for the desk further away from the window (Desk E6), which also has a large portion of the outside view. This was mainly caused by the applied model and not the luminance mask, as this effect was not found for Model A. Moreover, for the Simplified Model B, this effect was less pronounced. Therefore, it is likely that the conditions during the training of Model B were significantly different compared to the test data for virtual user E6, indicating the importance of relevant calibration conditions.

Table 6 shows the average measurement uncertainty of the ceiling-based position. Similar to Fig. 9 Model B is outperforming Model A as the margins of errors and uncertainties are lower. For instance, the Retinal illuminance, for Model A, has a margin of error over 100% meaning that illuminances twice as big as reality can be measured. Theoretically, according to these results, negative values could also be measured; however, in practice, these values will be truncated to zero, as it is not practically possible. In contrast to the MAPE, the margin of error of the B40 Luminance is lower for the Simplified Model B compared to the original Model B, albeit negligible. Nevertheless, this luminance metric will be very difficult to measure in practice due to a margin of error of approximately 50% for Model B. Fig. 11 gives more insight in the measurement uncertainty of the ceiling-based position relative to virtual user 5 (E5) when applying Model B. Consistently, the B40 Luminance and the Retinal Illuminance exhibit larger uncertainties indicated by the large spread. Nonetheless, the actual Desktop Luminance also monitored as illustrated in Fig. 10 for Model B. Overall, these results indicate that large ratios of daylight openings (Desk E5) result in a lower performance because the luminance for daylight openings is several orders of magnitude higher and can exhibit large irregularities. Only for the B40 Luminance, this effect was not found for this model. It performed especially poorly for the desk further away from the window (Desk E6), which also has a large portion of the outside view. This was mainly caused by the applied model and not the luminance mask, as this effect was not found for Model A. Moreover, for the Simplified Model B, this effect was less pronounced. Therefore, it is likely that the conditions during the training of Model B were significantly different compared to the test data for virtual user E6, indicating the importance of relevant calibration conditions.

![Fig. 9. Mean Absolute Percentage Error for Model A, Model B and the simplified Model B relative to the Desktop Luminance, Monitor Luminance, B40 Luminance, and the Retinal Illuminance.](image)

![Fig. 10. Mean Absolute Percentage Error for Desk E1, Desk E5 and Desk E6 B relative to the Desktop Luminance, Monitor Luminance, B40 Luminance and the Retinal Illuminance for model B.](image)

| Visual     | Performance | Visual Comfort | NIF  |
|------------|-------------|----------------|------|
| Desktop Luminance | 15%       | 15%             | 199% |
| Monitor Luminance | 2.8%      | 2.8%             | 0.2% |
| B40 Luminance | 60%        | 51%             | 32%  |
| Retinal Illuminance | 5.7%     | 0.2%             | 0.2% |

Table 6: The uncertainty of ceiling-based measurement relative to the luminance based metrics and models.

\[ \text{Table 6} \]

|                | Model A | Model B | Model B Simplified |
|----------------|---------|---------|--------------------|
| Visual         | Desktop | −3.9% ± | −0.5% ±          | −0.5% ± 13% |
| Performance    | Luminance | 15%     | 13%                |
| Visual         | Monitor | 1.7 ± 15% | 2.8% ± 7%         | 2.8% ± 7% |
| Performance    | Luminance | −15% ± | −1% ±            | −2% ± 48% |
| Visual Comfort | B40 Luminance | 60%     | 51%               |
| NIF            | Retinal | 5.7% ± | 0.2% ±          | 0.2% ± 30% |
|                | Illuminance | 199%   | 32%               |
occasionally egresses the expected error margin under extreme conditions. In this specific scenario, only one of the 100 measurements falls out of range, which can happen due to the 95% CI that is used to determine the error margin. Nevertheless, this is not necessarily problematic as this occurs only for extreme conditions, which will still be extreme with large measurement inaccuracies.

When looking into the uncertainties of each individual virtual user, as shown in Fig. 12, it becomes clear that lower luminance values are generally overestimated while higher luminance values are generally underestimated (see also Fig. 11). The overestimations are generally limited in magnitude but numerous, while the underestimations can be very large but occur less often. As a result, the average uncertainties are low, even for the B40 Luminance and Retinal Illuminance as indicated in Table 6. Nevertheless, the margin of error can be very large, making it complicated to apply in practice. Even for the well-performing Desktop Luminance virtual user E5 is expected to have an error margin of almost 15%. However, most of the time this is within 5%.

Fig. 11. Absolute luminance measured for virtual user 5 (E5) at eye level (black) and approximated from position B’3 (orange). The orange area represents the margin of error. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 12. Bland and Altman plot for desktop luminance measured using Model B. Each dot represents δL for an individual measurement, with a trend line in orange. The average bias or uncertainty is indicated by the black line, the dotted lines indicate the 95 CI. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
5. Discussion

This study aimed to assess the feasibility of ceiling-based luminance distribution measurements as an alternative measurement position for open office environments. Measuring the luminance distribution from a ceiling-based position allows measurements over a longer period of time as it does not cause interference with daily activities, making it suitable for implementation in lighting control systems. However, it was expected that this goes at the expense of the accuracy.

The study showed that the Desktop and Monitor Luminance were accurately measured using a ceiling-based position above the aisle with a 20-degree angle relative to the ceiling (B3), only minor errors were introduced. Only for extreme conditions, relative high inaccuracies were present. Nevertheless, to our knowledge, this ceiling-based position is not referred to before in literature. The B40 Luminance and the Retinal Illuminance were more complex to measure accurately using this ceiling-based position, even with the elaborate Model B relatively high inaccuracies were found. Moreover, the masking was rather complex, however, the simplified version did not have a significantly lower performance.

In comparison to the partition- or monitor-mounted and vicinity strategy the ceiling-based strategy, originally expected to have to lowest performance, however, it does not perform significantly worse. Direct comparisons to each strategy could not be made due to a difference in methodologies making it impossible to rank the different positions. For the partition- or monitor-mounted strategy a normalized root mean square error (NRMSE) of 11% was found for DGP [16], indicating that this partition- or monitor-mounted position also provides reasonable approximations. For the vicinity strategy [20], relative errors were generally below 25% which was always the case for the Desktop and Monitor Luminance (Table 6). The Retinal Illuminance performed only slightly worse (0.2% ± 30%) but did require a complex model to achieve this.

The luminance masks that were strictly defined by a surface, for the Desktop and Monitor Luminance, performed well. The translation for these luminance masks from eye level to ceiling-based is straightforward, especially when the view is unobstructed. Only minor distortions occur due to the fisheye projection, closer to the periphery these distortions increase. Nevertheless, the effect is limited as the luminance for virtual user 1 (E1), the reference measurement with the largest distortions, was measured rather accurately. The angle of view has an effect, however, the specular reflections in the mock-up office, and most likely in other offices, were limited (specular reflection desktop ≈ 3%). This indicates that similar high accuracies can be achieved for other strictly defined non-transparent predominantly diffuse surfaces such as the background wall. This does not hold for the window area as the angle of view has a large influence due to the directionality of sunlight.

The B40 Luminance and Retinal Illuminance were not easily translated as they do not contain strictly defined surfaces. Their scene independence, at eye level, turns into a disadvantage for ceiling-based positions. Moreover, they contain a large area of the outside view which is sensitive to the angle of view. Fig. 10 indicates, for the Retinal Illuminance, that without a large portion of outside view (E1) relatively high accuracies can be achieved. Also, a complex but accurate translation of the FOV is not necessarily required, simplified semi-independent luminance masks performed practically identical to the accurate but complex luminance masks, making it easier to implement in practice.

The differences in the MAPE between Model A and Model B for the Desktop and B40 Luminance are negligible where the Monitor and Retinal Illuminance show significant increases for Model B. For the Desktop Luminance a high performance was achieved for Model A, indicating a good fit. For the B40 Luminance, both models had a low performance, indicating that a good fit was not possible, which was already shown by the low R² in Section 3.2. Therefore, for visual comfort, it is advised to use another luminance based metric because the performance of the B40 Luminance is very low for ceiling-based measurements, preferably one based on strictly defined surfaces such as luminance ratios between task and background area [34], even though the uncertainty increases for a ratio. As an example, the ratio between the Desktop Luminance and Monitor Luminance was estimated to have an uncertainty of ±30% (15% + 15%) and ±20% for Model A and Model B, respectively, which is still much lower than for the B40 Luminance.

The most suitable ceiling-based position and its performance were based on measurements in August in a Dutch climate. The most suitable position was determined based on two measurements of which one with daylight, without direct sunlight. Of course, this does not represent all relevant conditions. Nevertheless, we do not expect very different findings for a wider range of conditions. For instance, continuous Desktop Luminance measurements using position A resulted in higher inaccuracies, NRMSE of 14% [13], for varying conditions as found during this study for position B3 (NRMSE of 5%). Moreover, the performance of position B3 is assessed only for a single day, sunrise to sunset, with varying daylight conditions. Naturally, this does not cover all conditions during the year. However, it does cover high luminance values, low sun elevations, and variable weather conditions and is, therefore, a reasonable approximation for a wide range of conditions. Nevertheless, some minor deviations, without practical significance, might be expected to the MAPE and error margin for different conditions during the year.

It is advised to limit the number of monitored users by a single luminance camera to four, as was conducted during this research (virtual users E1, E2, E5, and E6 were virtual user E2 was not actively measured during the second phase). Additionally, measurements were only conducted in a single office environment, which was designed to approximate the ‘average’ open office condition. Three virtual reference users were applied to indicate the difference within the office environment, indicating some variability between environmental conditions such as the distances to the window, luminance camera, and the background. The effect of daylight coming through the window was found to be normative to the performance of the ceiling-based measurement. Therefore, it is expected that for office environments with similar daylight conditions the error margins will be of a similar magnitude. However, for a glazed façade at multiple orientations, for instance, it will be highly recommended to perform additional measurements, as the daylight conditions are too different.

Fig. 11 illustrates that the extreme conditions, high luminance values, were not accurately measured, even for the well-performing Desktop Luminance. The luminance and directionality were excessive for these conditions resulting in severe inaccuracies. However, these extreme conditions measured are far outside the comfortable range, with and without the severe inaccuracies introduced by ceiling-based measurements. As an example, both measurements (eye level – ceiling-based) will adjust the blinds in case of a luminance based automated blind system. For this specific reasoning, outliers were removed for Model B and the uncertainty analysis.

The findings of Fig. 12, underestimation for lower luminance values and overestimation for higher luminance values, might indicate that a model based on a third-degree polynomial could have been used to limit the uncertainty. However, initial tests with such a model did not lead to significant improvements that justified the added complexity. Therefore, these models were not deemed appropriate for practical implementation and were, therefore, discarded.

The findings of this study imply that relevant luminance distributions can be measured using the suboptimal ceiling-based positions in open office environments. This strategy prevents interference with daily activities and allows measurements for multiple users at once. Henceforth, luminance cameras can be integrated with lighting control algorithms, which is expected to improve the overall lighting quality in office environments. Luminance based metrics that consist of strictly defined surfaces that are non-transparent and predominantly diffuse are relatively easy to approximate. The commissioning, to capture the required models, during installation is rather limited as only two
reference measurements (Model A) are required per user position. When the office environment has undergone significant changes, for instance due to reorganization, this commissioning should be repeated otherwise irrelevant measurements might be conducted. Slightly higher accuracies can be achieved by extensive commissioning (Model B), incorporating a wider range of conditions, but this gain is limited and, therefore, not advised for luminance based metrics that consist of a strictly defined surface. Moreover, the performance of Model B could be improved further by a longer training period, incorporating an even wider range of conditions, such as seasonal effects. This gain is smaller than the measurement accuracy (5%-15%) of luminance distribution measurement devices and has, therefore, no practical significance.

For more complex luminance based metrics, such as the Retinal Illuminance, extensive commissioning (Model B) is required to develop a correction model and to capture relevant outcomes. Such a model is more important than the luminance mask as it can account for minor misaligns in the mask. Nevertheless, even with extensive commissioning useful approximations are not guaranteed, which was exhibited for the B40 Luminance. Therefore, it is advised to use surface-bound luminance based metrics instead of complex luminance based metrics when available, otherwise extensive commissioning is vital.

6. Conclusion

The objective of this research was to assess the feasibility of ceiling-based luminance distribution measurements in open office environments. A ceiling position above the aisle with a 20° angle relative to the ceiling was found as the most suitable position because its FOV has large similarities with the FOV and angle of view of the user. This position was assessed using four luminance based metrics: Desktop Luminance, Monitor Luminance, B40 Luminance, and Retinal Illuminance, representing visual performance (2x), visual comfort and the NIF effects, respectively. The Desktop and Monitor Luminance achieved an acceptable accuracy, MAPEs of 3.7% and 6.1%, for the elementary Model A. The Retinal illumiance was able to achieve reasonable accuracy (MAPE of 12%) when the elaborate Model B was applied. For the B40 Luminance, inaccuracies >20% were found for Model A and Model B. Therefore, it is advised to use surface-bound luminance based metrics, similar to the Desktop and Monitor Luminance, to replace complex luminance masks such as the B40 Luminance. The findings show that ceiling based measurements are feasible when accounting for the uncertainty; however, a linear correction model is required to capture relevant data, which requires some effort during the commissioning.

For future research, it is advised to translate the conducted measurements to multiple different real office environments under different weather conditions such that the introduced uncertainties have more foundation for different office environments and different weather and climate conditions. Additionally, only four of the numerous luminance based metrics were assessed, it is depending on the application whether these are the most relevant metrics. Finally, an alternative approach would be to apply neural networks to train a ceiling-based luminance camera to extract relevant information on multiple lighting quality aspects relative to the user.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is part of the research program “OPTILIGHT: Mathematical Optimizations for Human Centric Lighting” with project number 14671, which is partly financed by the Netherlands Organization for Scientific Research (NWO), and which is conducted in the context of a bilateral cooperation between TU/e and Signify in the Intelligent Lighting Institute (ILI).

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