Optimizing lighting quality using the luminance distribution

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INTRODUCTION

Lighting is one of the key aspects for a high quality office environment. Lighting influences the visual performance, visual comfort, health, sleep quality, and well-being. Nevertheless, the lighting design strategy is generally to limit the energy costs driven by energy codes and standards, discomfort. Therefore, this strategy can be counter-effective as the wages represent the absolute majority of the costs in office environments. Ultimately, it is more cost-effective to provide high-quality lighting while potentially consuming a little more energy.

High-quality lighting can be defined as "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" [1]. However, lighting quality is not easily quantified as it is highly dependent on time, task and user preference. What we do know, is that the lighting designed with only the requirement of 500 lux on the desktop does generally not provide high quality lighting. The illuminance (in lux) is not the most relevant lighting indicator from a human perspective, however, it is often used because it can be measured easily. Additionally, lighting quality consists of more aspects than the quantity of light on the desktop that is indicated by the illuminance.

This research is part of the OptiLight project that aims to develop an automatic lighting control algorithm for human centric lighting. Currently, these kind of control algorithms are lacking or limited to the visual performance. Additionally, scalability, meaning an easy deployment in different environments without excessive tuning, is an important sub-objective of this research. The focus of this research lies on the practical measurement of lighting quality that will serve as input for the control algorithm. Furthermore, first steps are taken in to develop a quantitative model for lighting quality related to the visual aspects of light. The research is roughly divided in three parts. First, we explore of what lighting aspects make lighting quality based on a literature review. Second, we develop a measurement methodology for practical measurements of lighting quality. Third, based on measurements according to the developed methodology first steps are taken to develop a quantified model for lighting quality.

LIGHT QUALITY

To date, lighting quality does not have a rigorous definition, however, many unsuccessful attempts have been made. Those definitions do not provide any leads which measurable lighting aspects are relevant to the overall lighting quality. Based on a literature review

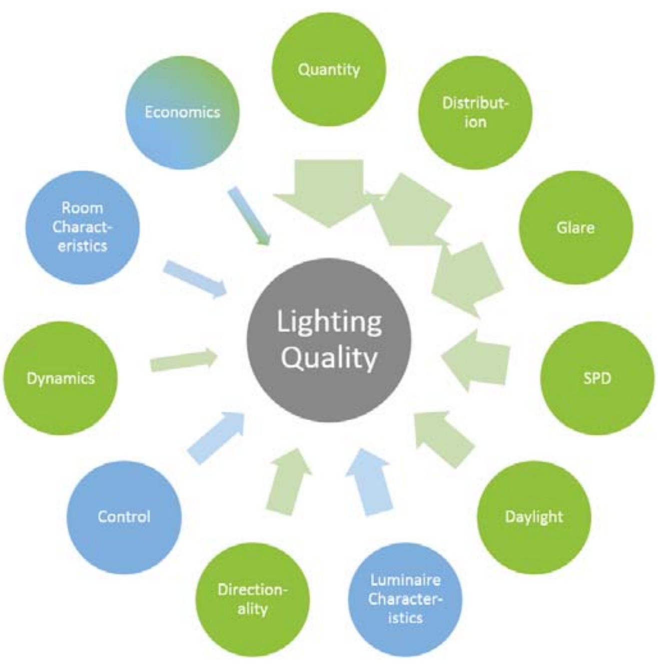

Figure 1. Lighting quality aspects found in literature. The green aspect are variable aspects changing over time, the blue aspects are fixed aspects. The arrows indicate the occurrence in literature.

using forward and backward citation, the different aspects of lighting quality are listed below. The different lighting quality aspects found in literature are indicated in Figure 1.

- The **quantity** of light is an important factor for the acceptability of the lighting for the visual task. Generally, more light, until a certain limit, means a higher satisfaction and improved performance.
- The **distribution** of light is related to the visual comfort. The human eye cannot simultaneously adapt to large difference of light, resulting in discomfort due to continuous movements between contrasting surfaces. However, a completely uniform light distribution is considered dull.
- **Glare**, a subjective sensation of annoyance, discomfort or loss in visibility caused by luminances in the visual field that are significantly higher than the adaption luminance. Discomfort glare is the most relevant glare type in the built environment. Numerous indicators have been developed to quantify this subjective sensation.
- The **spectral power distribution** of light is a complicated aspect. It relates to the color appearance of the light influencing the visual comfort and the light color quality influencing the visual comfort and visual performance. Moreover, the spectral power distribution is of high importance for the non-image forming effects related to health, wellbeing and sleep quality.
- Naturally, **daylight** is a very important lighting quality aspect. Generally, it improves the satisfaction but it is also more desirable for visual comfort. Daylight can also be described by the other lighting quality aspects.
- The **directionality** of light is not often considered, but it helps to distinguish task details, surface textures and faces. Additionally, it relates to the appearance and appreciation of an environment.
- Finally, the **dynamics** of light is a relatively new aspect that can improve the visual performance, but more importantly it is considered more stimulating and pleasant.

The fixed lighting quality aspects are also important; however, they cannot be optimized by a control algorithm. Therefore, these aspects are not considered in this research.

MEASURING LIGHTING QUALITY

Generally, the lighting quality aspects are measured independently of each other using very specific, often very expensive, devices. For a few measurements this can be acceptable; however, for continuous measurements related to a control algorithm, this is not desired. Measurement devices capable of measuring multiple lighting quality aspects at once are desired such that lighting quality can be measured quickly and cheaply. The luminance

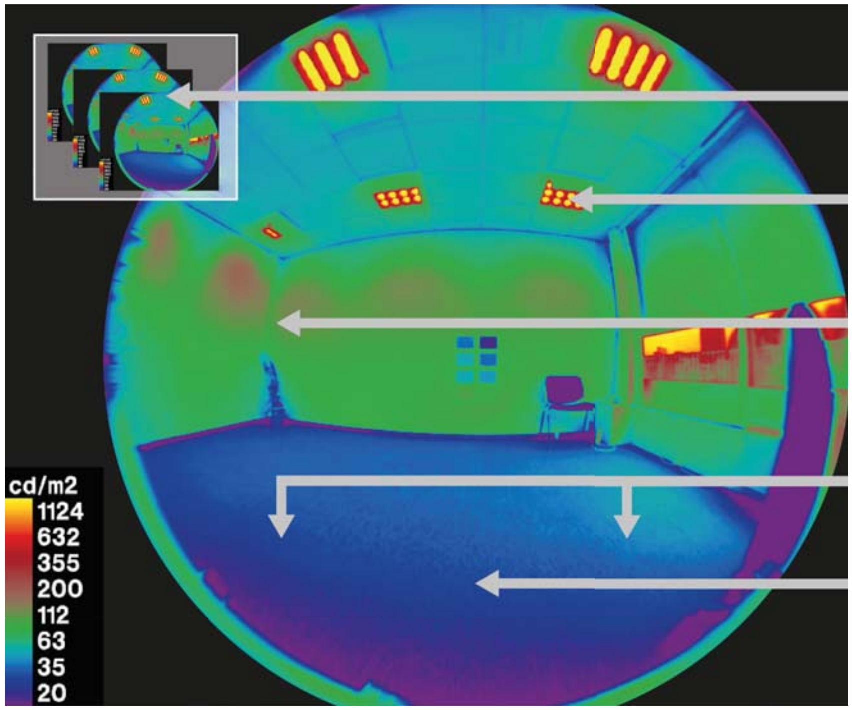

Figure 2. A luminance distribution with indications of location of information

distribution is a parameter that contains a large amount of data that can be used to indicate multiple lighting quality aspects. With a device that measures the luminance distribution we can measure or indicate, as displayed in Figure 2, the quantity, distribution, glare, SPD, directionality and dynamics all at once. Subsequently, daylight can be indicated by these measurable aspects. Only the SPD cannot be measured using such a device. Concluding, a luminance distribution measurement device can be very useful to measure lighting quality. Nevertheless, not all light quality aspects are easily extracted from the luminance distribution, for instance, the directionality and the dynamics, because they are barely used in current practice.

MEASUREMENT DEVICE

As a result, the Bee-Eye, a luminance distribution measurement device, was developed [2]. The Bee-Eye uses a low cost single-board computer, camera and fisheye lens to autonomously measure the luminance distribution. The High Dynamic Range (HDR) technology is essential for the measurement of the luminance distribution because HDR images allow to capture the luminance range occurring in the real world, while standard 8-bit images have a very low dynamic range; typically from 0 to 255 [3]. The HDR images are made using a sequential exposure change technique, in which seven 8-bit images are captured by sequentially varying the shutter speed.

Figure 3. The Bee-Eye

Subsequently, the exposures are merged into one single HDR image. Within this process, the essential camera response curve is approximated using radiometric self-calibration. The response curve is a camera-specific function, which relates the pixel values directly to the scene radiances while also accounting for corrections administered in the proprietary imaging pipeline.

Based on the floating point RGB values of the HDR images, the luminance is calculated. Therefore, the RGB color space is translated to the XYZ color space because the color matching function $\bar{y}$ is equal to the sensitivity of the human eye for photopic vision. Consequently, the luminance is calculated by extracting the Y tristimulus according to equation 1, including a calibration factor to improve the accuracy.

$$\mathrm{L} = k \cdot (0.2125 \cdot R + 0.7125 \cdot G + 0.0721 \cdot B)$$

Equation 1. Equation for Luminance

Finally, the vignetting effect is accounted for being a non-linear effect of light fall-off at the periphery of the lens due to internal scattering, which can be approximated by a polynomial function. Especially, fisheye lenses can exhibit significant light fall off, up to 73%, at the periphery of the lens.

Ultimately, the calculation of the luminance based on the HDR images results in a luminance value for each individual pixel as displayed in Figure 2 with a practical accuracy. To indicate the accuracy 10 samples, varying from dark gray to white, were repeatedly measured with the Bee-Eye and a Konica Minolta LS-100 luminance meter. The results of this measurement are displayed in Figure 4. An average relative difference of 3.6% with a standard deviation of 2.2% was found between the Bee-Eye and the luminance meter. It should be noted that the relative difference is expected to be slightly higher for colored samples.

The measurement steps are all automated on the single-board computer such that the luminance distribution is measured autonomously at a predefined measurement interval. Moreover, the Bee-Eye is remotely controlled using Wi-Fi. Additionally, the measurement results are send to a server such that the results can be sequenced from distance.

MEASUREMENT PROTOCOL

Conducting relevant measurements using the Bee-Eye is not straightforward. Preferably, the luminance distribution is measured from the eye position of the user. Especially in field studies this is not feasible, so the Bee-Eye needs to be installed at the ceiling and/or a suboptimal position in the vicinity of the user. Recommendations or best practice examples are not widely available yet. Moreover, the measurement interval is of importance when including daylight. Maintaining a very high interval might result in a sheer amount of data, while a lower interval might miss relevant data. Finally, using the Bee-Eye in field studies might arise privacy issues because the device uses images captured at relative short interval. We aim to give recommendations on how to extract the individual lighting quality aspects from the luminance distribution, suitable measurement positions, and suitable measurement intervals based on a combination on measurements and simulations in the form of a measurement protocol that can be widely applied.

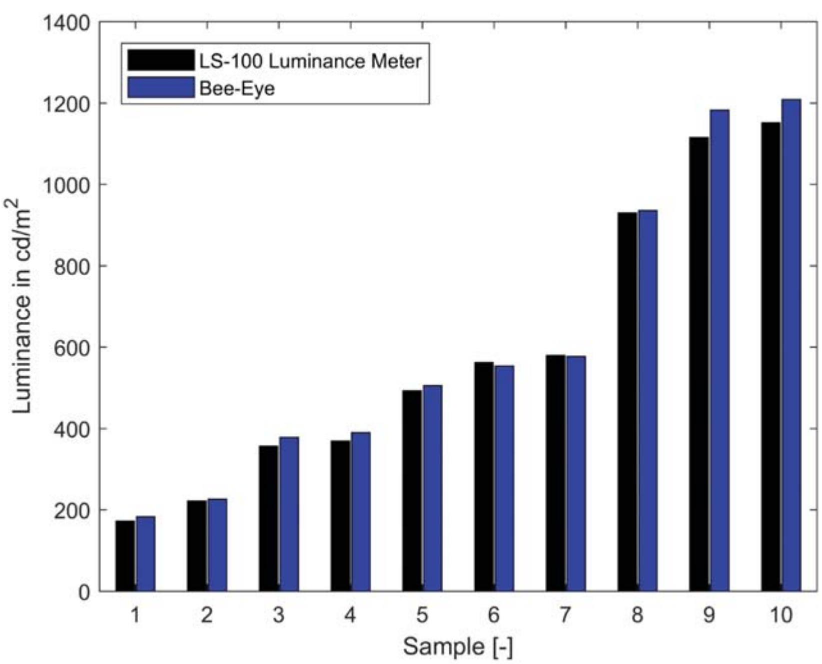

Figure 4. The average measurement results of the Bee-Eye compared to the Konica Minolta LS-100 luminance meter

QUANTIFIED MODELS

To develop quantified models the Bee-Eye and the measurement protocol are applied in field studies. During these field studies, spanning a few weeks, the luminance distribution will be measured using the Bee-Eye and the participants lighting quality ratings will be gathered using experience sampling. Experience sampling is a research methodology were participants are frequently, typically using 1 hour intervals, asked to report their, in this case, lighting quality rating. Using methodologies originating from data science, the luminous conditions are related to the participants lighting quality ratings. Based on this, the relation of the individual lighting quality aspects and their interactions to the subjective lighting quality are explored to improve the understanding of lighting quality and provide the control algorithm with quantified models.

SUMMARY

Current lighting strategies in offices do not necessarily provide high quality lighting. To provide high quality lighting aspect, such as the quantity, distribution, glare, SPD, daylight, directionality, and dynamics of light should be considered. Most of these aspects can be measured using the luminance distribution. Therefore, we developed the Bee-Eye, a practical and autonomous luminance distribution measurement device. With the Bee-Eye we are able to measure the individual aspect of lighting quality continuously such that it can serve as input for a control algorithm. Additionally, we can improve the understanding of lighting quality by relating the measured luminance distributions to the subjective responses of lighting quality. ■

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[3] Reinhard E, Heidrich W, Debevec P, Pattanaik S, Ward G, Myszkowski K. High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting. San Fransisco: Morgan Kaufmann; 2010.