

Photometric measurements of lighting quality

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Photometric measurements of lighting quality: an overview

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Abstract

This paper aims to provide an overview of various aspects used to measure the overall lighting quality, instead of solely focusing on a single aspect. Lighting quality is a concept that allows excellent vision while providing high comfort. However, it cannot be measured directly; although, it can be indicated by measuring different aspects of lighting quality individually. By reviewing thirty eligible studies, based on forward and backward citation, eleven lighting quality aspects were determined that influence the overall lighting quality. Preferably, control algorithms for high quality lighting implement all these aspects; however, current control algorithms generally have a limited focus on energy or one or two specific aspects. Consequently, these control algorithms do not necessarily provide high quality lighting. This paper reviews measurement methodologies for the variable aspects of lighting quality, namely quantity, distribution, glare, spectral power distribution, daylight, directionality, and dynamics. We distinguish ad hoc and continuous measurements for each aspect. Ad hoc measurements are single measurements that provide a high accuracy “snapshot”; continuous measurements have a lower accuracy but provide a good overview over time that is relevant as input for lighting control algorithms optimizing the lighting quality. This overview shows that luminance distribution measurement devices are highly suitable for measuring lighting quality for both ad hoc and continuous measurements. Except the spectral power distribution, all variable aspects of lighting quality can be measured using such a device although the aspects directionality and dynamics still require more suitable luminance based indicators. Hence, it can be concluded that a luminance distribution measurement device is very suitable device to provide relevant input for lighting quality control algorithms.

Keywords:

Lighting quality; Photometric measurements; Luminance distribution; Continuous measurements

1. Introduction

Lighting is an important requirement that can improve the comfort in the modern office environment. With wages representing the majority of costs in offices, enhancing the user comfort by improving the light, thermal, air and sound quality, is a more efficient strategy to limit the costs [1,2]. Limiting the energy use, often driven by energy codes and standards, can be counter effective as this can cause significant discomfort [3]. In addition to performance and comfort, lighting can also affect alertness, wellbeing, health and sleep quality [4,5]. Two types of light effects can be distinguished: image forming effects and non-image forming effects. The image forming effects relate to the rods and cones within the eye, enabling vision. Additionally, in the early 2000s, a new photoreceptor, which is non-image forming, was found that affects the human health and wellbeing [6], opening a new field of research.

Lighting quality, a term related to the image forming effects of light, is one of the least understood aspects in the building lighting field [7]. There is no consensus of what lighting quality exactly consists of as it is a very wide and ambiguous concept [8]. Originally, it was “a term used to describe all of the factors in a lighting installation not directly connected with the quantity of illumination” (Stein et al. cited in [9]). However, after this a number of definitions have been proposed, such as “good-quality lighting 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” [5]. These definitions do not provide leads on how lighting quality can be measured. Achieving consensus on an objective methodology to determine lighting quality is the first step in an improved understanding of lighting quality, enabling future studies to relate photometric measurements of lighting quality to subjective responses [10]. Subsequently, recommendations can be developed, based on an improved understanding, for high quality lighting that can be implemented in requirements or standards.

To optimize the lighting within a building, an increasingly number of lighting control algorithms have been developed. These control algorithms can have very different characteristics and levels of

complexity [11]. The most commonly used control algorithms aim to limit the energy use by daylight harvesting [12] or occupancy-based sensing [13]. Moreover, control algorithms are available that aim to improve the visual comfort, visual performance [14], and possibly wellbeing and health if the non-image forming effects are also considered [15]. These kinds of optimizations require a control algorithm as they are dependent on varying aspects such as daylight, time, and occupancy. Limitations of the currently existing control algorithms are that they generally focus on one or two specific aspects, while multiple other lighting aspects are also affected as the different aspects of light are interrelated [3]. Optimizing one single aspect can negatively influence other aspects, potentially decreasing the lighting quality. Therefore, these control algorithms do not necessarily provide high comfort and high visual performance [11]. To optimize the lighting, all relevant aspects that together make lighting quality need to be considered. It is not straightforward to determine all these aspects, as this research is extensive and complex; therefore, this kind of research is limited. The first step in optimizing the lighting quality is measuring all relevant photometric aspects, related to the understanding of lighting quality. An abundance of piecemealed information is available on measuring different lighting aspects, but overviews are scarce. Gentile et al. [16] developed a measurement protocol to assess lighting quality with the objective to assess the overall performance of building retrofits. However, this assessment is performed based on the comparison of two ad hoc measurements on similar days before and after the retrofit. Nevertheless, there is no protocol available for the continuous measurement of lighting quality; hence, no suitable input can be generated to optimize the lighting quality using control algorithms. Additionally, a measurement protocol suitable for the implementation in control algorithms should be administered automatically without interactions with the users, and devices used should be economical and robust. Consequently, control algorithms that aim to optimize the lighting quality cannot be developed.

In this article, we provide an overview, based on existing literature, of how lighting quality can be measured objectively. Therefore, direct and indirect objective measurements of lighting quality are explored. Direct measurements use one single metric to describe the overall lighting quality. Indirect

measurements use multiple metrics to describe lighting quality, as lighting quality can also be considered a construct [7]. Moreover, ad hoc and continuous measurements are reviewed as they are relevant for lighting quality research and control algorithms, respectively. Ad hoc measurements are generally more accurate and may help to improve the understanding of lighting quality. Continuous measurements generally have a lower accuracy, but they are relevant as input for control algorithms, which require continuous input on the lit environment, that aim to optimize the lighting quality. Based on this overview, recommendations can be developed on how to measure lighting quality as input for control algorithms. The related research is part of an interdisciplinary research effort that aims to develop such a control algorithm that is able to optimize the lit environment. Therefore, measuring the variable aspects of lighting quality is emphasized, as these are aspects that can be optimized in contrast to the fixed aspects of lighting quality.

After a description of the criteria on which the literature is selected, the remainder of the paper focuses on lighting quality metrics. In a first part of the review, lighting quality metrics aiming to measure lighting quality directly are explored. In a second indirect approach, this article focuses on literature sources in which lighting quality is considered a construct [7], indicating that lighting quality can be described and measured by a series of aspects. Finally, in the concluding section recommendations are made on measuring lighting quality as input for control algorithms.

2. Method

The different lighting quality aspects are based on studies that were systematically collected using backward and forward citation. A timeframe from 1990 until present was selected, as lighting quality received significant attention in the 1990s, as evident by numerous lighting quality conferences and publications. Two articles were chosen as starting point. The study by Veitch and Newsham [7] was selected as this highly cited work emphasizes the meaning of lighting quality. Moreover, the study was published at the beginning of the selected time frame. The second study, by Gentile et al. [16], was selected as this recent work emphasizes the measurement of lighting quality aspects. Together

these studies cover the scope of this overview. Based on these two studies, using backward and forward citation, additional eligible studies were selected (Figure 1 and Figure 2). A study was deemed eligible when lighting quality or the luminous environment was researched as a whole, using at least 3 aspects, and when originating from the selected time frame. The eligible studies were categorized in three classifications as displayed in Table 1. Only, the references of the highest rated articles (***) were analyzed to find new eligible studies. Additionally, a Web of Science search was performed using “lighting quality” as search term for title, abstract and keywords, for the period of 2015 until present during which no new eligible articles were found. Ultimately, 30 studies were deemed eligible for this overview [3,5,7,8,16–41].

Rating	Relevance	Publisher
***	Very High	Relevant Journal or High Impact Report (e.g. CIE publication)
**	High	Journal, Report or Thesis
*	Medium	Conference

*Table 1. Eligibility criteria for forward and backward citation. Studies ranging from a very high relevance to a medium relevance are included in the overview, only references from *** rated studies are analyzed to find new eligible studies.*

Based on the eligible studies, a list of quantifiable and objective aspects was developed. Different studies used different sets of aspects that often coincide or similar aspects with different terminology; therefore, some subjective binning was required to prevent a multitude of unique aspects. Requirements for this binning were that different aspects have a clear distinction and that each aspect has at least two components. Nevertheless, interrelations between aspects are inevitable.

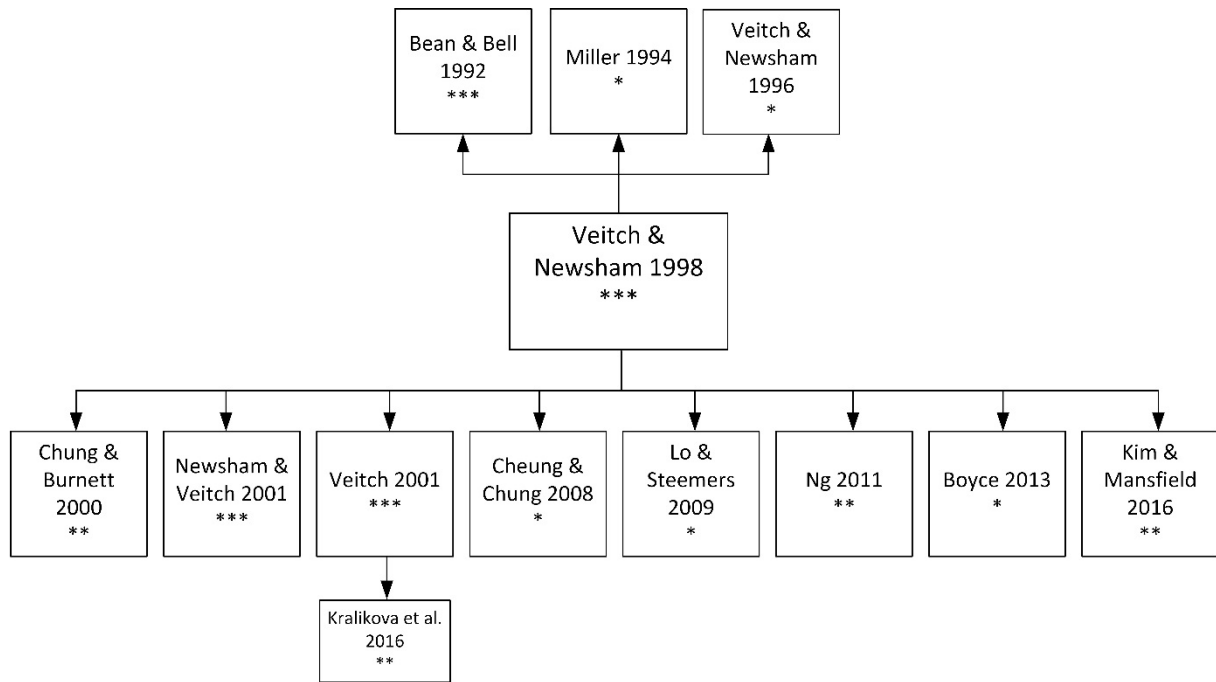


Figure 1. Flow diagram displaying the selected articles that were deemed eligible originating from a backward and forward citation method starting with the selected article of Veitch and Newsham (1998) [7]. Only articles rated with *** are analyzed to find new eligible studies.

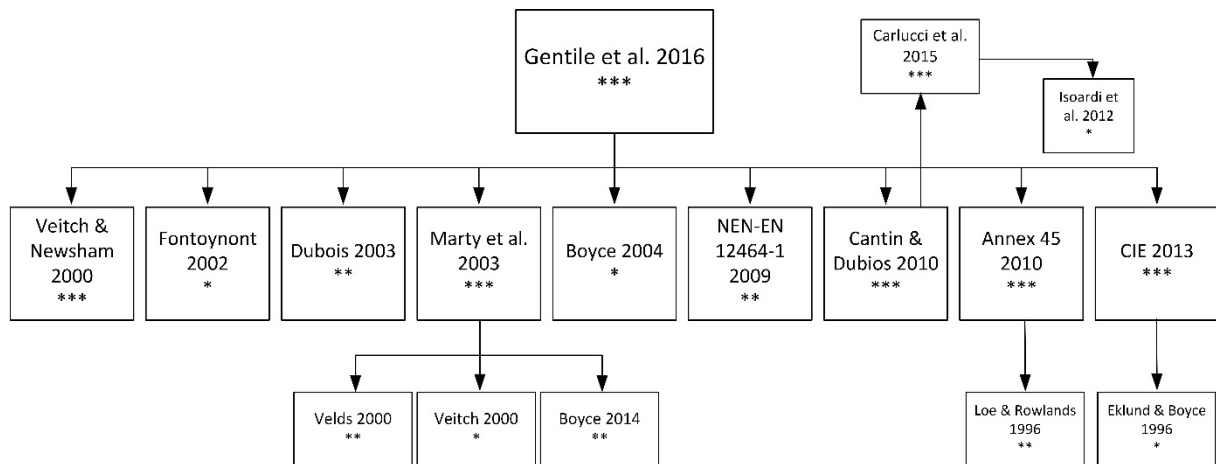


Figure 2. Flow diagram displaying the selected articles that were deemed eligible originating from a backward and forward citation method starting with the selected article of Gentile et al. [16]. Only articles rated with *** are analyzed to find new eligible studies.

3. Direct measurement of lighting quality

Several attempts have been made to develop single indicator models to assess and describe lighting quality [7,8], including the Visibility Level Model, Lighting Quality Index, the Comfort, Satisfaction and Performance index, Interior Lighting Evaluation System, and the Ergonomic Lighting Indicator.

3.1. Visibility Level Model

The Visibility Level Model (VL), measuring the effectiveness of the visual performance, was originally developed by Blackwell but adopted and improved by the CIE [7,42]. In this model, visibility is “associated with the perception of objects and visual details of interest” [42]. The model considers quantity as well as quality of lighting. The author stated [42] that the visual performance approach should consist of photometric aspects, physiological aspects and mental conditions of the observer. The visibility level is described by four aspects: reference visibility level (VL), contrast rendering factor (CRF), disability glare factor (DGF) and transient adaptation factor (TAF). However, the DGF and TAF are not easily measured outside the laboratory [7,42].

3.2. Lighting Quality Index

As an alternative for the visibility level model, Herst and Ngai suggested the Lighting Quality Index (LQI). The LQI is based on a combination of the equivalent sphere illuminance (ESI) and the visual comfort probability (VCP). The LQI is described as the percentage of the space meeting the criteria, set by the designer, for both ESI and VCP. The ESI relates to “the level of sphere illumination which would produce task visibility equivalent to that produced by a specific lighting environment”(cited in [7]) and the VCP relates to discomfort glare. However, this method was not widely accepted due to the inherent ESI system [7].

3.3. Comfort, Satisfaction and Performance index

Similar to the VL and LQI, the Comfort, Satisfaction and Performance (CSP) index has some limitations in applicability, considering that the maximum correlation between the CSP index and subjective response was only 0.54 [17]. Additionally, a replication of the CSP index by Perry et al. [43] found even lower correlations. The CSP is “an attempt to produce an indicator for the effectiveness of a lighting installation, as perceived by the workers who use it” [17], assuming that there are three visual quality elements that determine the effectiveness: the comfort, satisfaction, and performance level. The CSP describes comfort as a linear equation including the British glare index [44], satisfaction was described

as the ratio between cylindrical and horizontal illuminance and performance was described as a combination of the illuminance, uniformity and color rendering. Each element is weighted similarly with a maximum score of 10 [17].

3.4. Interior Lighting Evaluation System

In contrast to the previous models, the Interior Lighting Evaluation System (ILES) [45] uses a multifaceted concept to assess lighting quality, directly as well as indirectly, based on measurements and surveys, respectively. In addition to photometric parameters, it also includes economic parameters and human behavior. The direct photometric component uses a cost function to calculate a quality value number, which evaluates a selection of important photometric aspects. The cost function consists of a weighing factor, indicating the importance of the parameter, and the scaling factor representing the effective value of the parameter compared to the recommended or optimal value of the parameter. The weighing factors, which are variable depending on the specific case, are based on surveys or polls [45,46]. Additionally, ILES consists of a subjective component indirectly assessing the lighting quality. As this must be easy to administer and understand for uninformed users, a survey was designed containing 11 questions that are rated on a two or five point scale.

3.5. Ergonomic Lighting Indicator

Analogous to ILES, the Ergonomic Lighting Indicator (ELI) is based on a combination of objective and subjective components [47]. ELI uses five criteria important for the assessment of lighting quality: visual performance, view, visual comfort, vitality and control; all rated on a scale of 1 to 5. According to the author, this method is especially useful for communication during lighting design. ELI is based on input gathered by a questionnaire with 38 questions having an objective or subjective character. It was shown that ELI has an objectiveness level of 70%; therefore, it can be almost considered objective [48]. Nevertheless, large scale field tests are required to confirm the performance [48].

4. Indirect measurement of lighting quality

As indicated in the previous section, direct measurements of lighting quality have significant limitations. Therefore, the indirect measurement of light quality is explored. Based on the method described in section 2, a list of 11 lighting quality aspects was developed as displayed in Table 2. The aspects are ranked from 1 to 11 based on the percentage of studies that incorporate that specific aspect. Additionally, Table 2 indicates whether aspects are variable or fixed. In the following sections, all variable aspects of lighting quality are described because these are aspects that can be optimized by a control algorithm.

Aspect	Components	% of studies	Variable
Quantity of light	Illuminance; Luminance	100%	Yes
Distribution of light	Uniformity; Luminance Distribution	90%	Yes
Glare	Disability glare; Discomfort glare; Veiling reflections	77%	Yes
Spectral power distribution of light	Appearance; Color quality	58%	Yes
Daylight	Daylight penetration; View out	45%	Yes
Luminaire Characteristics	Luminous intensity distribution; Flicker	42%	No
Directionality of light	Direction; Modelling	39%	Yes
Control	Automatic control; Individual control	29%	No
Dynamics of light	Variability; Rhythm	19%	Yes
Room Characteristics	Objects; Reflectances	19%	No
Economics	Energy efficiency; Investment	16%	Partly

Table 2. Eleven lighting quality aspects based on literature. Each lighting quality aspects consists of at least two components that are used to describe the lighting quality aspect. It is indicated what percentage of the thirty eligible studies consider the specific lighting quality aspects; additionally, it is indicated whether this aspects are variable.

4.1. Quantity of light

The quantity of light is a lighting quality aspect that is considered in all eligible studies; it indicates the amount of artificial light or daylight that falls on the surfaces of a space. The quantity of light is, to a large extent, responsible for the acceptability of the lighting for the visual task [49]. Generally, the satisfaction and performance increases with an increasing amount of light. As the amount of light

increases, to a certain limit, the lighting becomes “more pleasant, more comfortable, clearer, more stimulating, brighter, more colorful, more natural, more friendly, more warm and more uniform. It also becomes less hazy, less oppressive, less dim and less hostile” [50]. However, for very high quantities, satisfaction decreases while the performance remains constant [16]. It is an important aspect of lighting quality because the quantity of light influences the satisfaction and visual performance.

Photometric indicators for the quantity of light are the illuminance and luminance [49]. Additionally, for the quantity of daylight the daylight factor is often used, described as the ratio between internal and external horizontal illuminance for overcast sky conditions [51].

4.1.1. illuminance

The illuminance, the areal density of the luminous flux, is measured by calibrated illuminance meters including a cosine correction [52]. The horizontal illuminance is only an adequate criterion for working environments where the working plane is actually horizontal [53]; especially in the current working practice with extensive use of computers, this is not the case anymore. Therefore, the working plane illuminance is generally used, whether this is horizontal, vertical or tilted [5]. The working plane illuminance is the most used indicator for lighting quantity because it is easily measured and used in multiple studies, and also recommendations in this regard are available.

During ad hoc measurements, the illuminance is measured for one point at the time; therefore, a measurement grid is often established to cover the overall lighting of the space [54]. The European standard [35] provides guidelines for an appropriate grid approximating squares. Moreover, alignment of the measurement grid with the luminaire layout is to be prevented. Additionally, a zone of 0.5 m from the wall is excluded from the grid. In a simplified method, the illuminance is only measured for relevant task positions [16].

A measurement grid, according to the previously stated guidelines, is not feasible for continuous measurements. For continuous measurements, the space should be divided into daylighted zones. Daylighted zones are established based on the distance from the window and the activity in the zone.

In each daylighted zone one measurement point is placed at a location that is critical or represents the typical illuminance of that zone. In offices, each workstation should have at least one measurement point, at the working plane level [55].

4.1.2. Luminance

The luminance is the only photometric measure that is directly related to the illuminance on the retina and therefore most closely related to the human visual perception of brightness [33,56]. The luminance is increasingly recognized as an important factor for visual comfort [33]. It is, therefore, advised to use the luminance to address the quantity of light. However, the interpretation is complex; thus studies examining the luminance or recommendations are limited [16,56].

Previously, the luminance was measured by a (spot) luminance meter. However, with the current High Dynamic Range (HDR) technology [57], it is possible to determine the luminance based on pixels values. This measurement methodology is further explained in section 4.2. The luminance emphasizes the light reaching the viewer from the seating position [40]. It is, therefore, measured from the viewer's position, and for completeness for potentially extreme situations [16].

4.2. Distribution of light

Twenty-eight of the eligible studies considered the distribution of the light, indicating how and to what extent the light is distributed within the space and influences the visual comfort. The human eye can adapt to large variations of light levels, but it cannot simultaneously manage large differences of light. A poor distribution of light may result in visual stress and fatigue due to the continuous eye movements between contrasting surfaces. On the other hand, it is not desirable to have a completely equal light distribution. Because this causes dull lighting, which is unpleasant and can lead to tiredness and lack of attention. It is, therefore, important to have some variations to provide a stimulating environment [33]. Generally, a poorer distribution is accepted when daylight enters from the side. Indicators for the lighting distribution are the illuminance uniformity and the luminance distribution.

4.2.1. Uniformity

The uniformity is the ratio between the minimum and average illuminance on a surface [35], based on the illuminance measurement elaborated in section 4.1.1. There are also examples that use the ratio between the minimum and the maximum illuminance to determine the uniformity. The uniformity is an indicator that is frequently used because it is easily determined based on illuminance measurements. Moreover, the uniformity can be translated to the luminance [58], for instance, to indicate the uniformity of a wall.

4.2.2. Luminance Distribution

The luminance distribution is the pattern of luminance in a space bounded by surfaces [40] and is often simplified to luminance ratios. The luminance distribution is measured using HDR cameras (i.e. luminance distribution measurement devices) [59,60]. The pixel values, after some transformations, represent the luminance values. The HDR technology is essential as it allows to capture the luminance ranges occurring in real scenarios [59]. Fisheye lenses are used to capture the entire luminance distribution of a room as experienced from the camera position; therefore, it is advisable to measure from the viewers' position. Theoretically, the luminance distribution can also be measured by a (spot) luminance meter, but this is an imprecise and tedious process subject to major and rapid changes in the luminous conditions.

For ad hoc measurements, the luminance distribution is measured from the seating position at a height of 1.2 m, representing the view from the eye. As potential users in the room are not constantly looking at the same direction, some extreme situations need to be measured as well [16].

Continuous measurements of the luminance distribution are problematic because the respective space is occupied by the users. Two strategies can be distinguished to measure the luminance distribution while a space is occupied. For lab studies, two identical rooms located directly besides each other can be used [61,62]. In the first room, the participant is seated; in the second room, the appropriate measurement devices are set-up. This strategy is not feasible for field studies; so in field studies the

measurement devices needs to be placed at a suboptimal position. Then, the measurement device is placed at a position as close as possible to the optimal position. Fan et al. [63] provide a methodology to determine this suboptimal position; in their study this position was rotated 30° at a distance of 0.3 to 0.5 meters from the optimal view point.

4.3. Glare

The third lighting quality aspect is glare. Glare is defined as “the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility” [64]. Three types of glare are defined: (i) disability glare or physiological glare, (ii) discomfort glare or psychological glare, and (iii) veiling reflections [36,38,65]. Disability glare and discomfort glare can occur simultaneously but are distinctively different phenomena [66].

4.3.1. Disability glare

Disability glare, although rarely occurring in buildings[67], is stray light in the eye that disrupts vision due to intraocular light scatter [20,65]. It immediately reduces the visual performance and the ability to see [38], but it does not necessarily induce discomfort [68].

4.3.2. Discomfort glare

Discomfort glare causes discomfort by high luminance contrasts or unsuitable luminance distributions within the visual field, without necessarily reducing visual performance or visibility [66]. Compared to disability glare, it is relatively difficult to identify as it is a visual sensation, which cannot be measured directly, with a subjective character [67]. Thereby, there is no complete theoretical understanding of discomfort glare [69]. Discomfort glare does not necessarily influence the visual performance immediately, but over time negative effects such as headaches, fatigue and decreased concentration can occur [70].

A number of glare indices have been developed that describe the subjective magnitude of discomfort glare [62]; nevertheless, a practical and effective discomfort glare predictor, with a high correlation to

the subjective response, is still lacking [66,71]. Generally, these indices consist of the following four quantities: luminance of the glare source, solid angle of the glare source, displacement of the glare source relative to the line of sight, and the adaptation luminance [62].

Among the many glare indices, the Unified Glare Rating (UGR)[72], Daylight Glare index (DGI)[73], and Daylight Glare Probability (DGP) [62,66] are most commonly used. The different indices cannot be simply compared to each other [69]. Glare indices that are developed for electrical lighting (e.g. UGR) are not suitable for daylight and vice versa because daylight openings have a significant higher solid angle. Moreover, discomfort glare from daylight seems to be accepted to a higher extent [65]. Merits and demerits of these indices are displayed in Table 3.

Indices	Applications	Merits	Demerits
UGR	Electrical	Simple. Composed based on best parts previous formulae. Established method	Only standard light sources
DGI	Electrical/Daylight	Suitable for daylight and electrical light; however, the interpretation is slightly different. Similar to UGR	Low correlation. Only suitable for uniform light sources. Based on electrical light measurements. Does not include adaptation.
DGP	Daylight	High correlation. Including observer variability. Based on daylight measurements	Only valid for DGPs between 0.2 and 0.8

Table 3. Merits and demerits of the commonly used glare indices separated by their application for electrical light or daylight.

Generally, simulations or measurements are required to assess glare using the previous stated indices. Previously, measurements were conducted using spot luminance meters, a time consuming process which is problematic due to the dynamic character of daylight [66]. In this process most quantities are measured, but the displacement of the glare source relative to the line of sight is in all methods based on position indices as proposed by Luckiesh and Guth [74] and Iwata and Tokura [75]. A limitation is that all glare indices are based on well-defined sources. When the scene becomes complex, it is unclear

which areas represent the light source and the background. Some rules to clarify this have been developed, but they lack validation [69].

In contrast to the tedious spot measurements, the required data can also be generated quickly using luminance distribution measurement devices [59,60], similarly to the methodology described in section 4.2.2. Wienold and Christoffersen [62] used this technology to develop the DGP under actual daylight conditions. They also developed the pre-processing tool *evalglare* for RADIANCE to calculate not only the DGP, but also the other commonly used glare metrics, based on HDR images originating from luminance distribution measurements or simulations [62,76].

4.3.3. Veiling reflections

Veiling reflections are “specular reflections that appear on the object viewed and that partially or wholly obscure the details by reducing contrast” [68]. As a result, veiling reflections reduce the visibility and may cause discomfort [77].

The contrast rendering factor (CRF), the ratio of the relative visibility under actual conditions to the relative visibility under reference conditions, is used to indicate veiling reflections. The reference condition is a completely diffuse field with the same task background luminance. Theoretically, the CRF is measured using a visibility meter. However, even under laboratory conditions it is subject to considerable problems [77]. The CRF can also be estimated using a luminance meter [40], but this is a tedious process. Therefore, the CRF is rarely used in field measurements.

4.4. Spectral Power Distribution of light

The Spectral Power Distribution (SPD), a quality aspect considered by 58% of the eligible studies, represents “the radiant power emitted by a light source at each wavelength or band of wavelengths in the visible region of the electromagnetic spectrum” [78]; the light source can be daylight, a luminaire, a reflecting surface or a combination of these. The SPD indicates which colors are represented within the emitted light; therefore, it influences the color appearance and the color quality of the light (for details see section 4.4.2). Theoretically, the SPD can also be used to calculate photometric quantities,

but dedicated metrics and devices that do not lose any information are available. It should be noted that the SPD is also very important regarding the non-image forming effects [79]; however, this is outside the scope of this overview.

The SPD of daylight is preferred as it covers the full spectrum [80]; hence, it displays a great variety of colors, helps to distinguish slight shades of colors and makes colors look natural [81]. The SPD is a complex metric of which the effects are not completely understood and that is not easily communicable. Therefore, the effects of the SPD are separated in two concepts: color appearance and color quality. Using this simplification, we are better able to describe the resulting effects of the SPD.

4.4.1. Color appearance

The color appearance relates to the apparent color of the emitted light independent of the context [35] caused by available wavelengths within the visual spectrum, and has the attributes brightness, hue and colorfulness [82]. The visual effects of color appearance can be controversial, but there is some consensus that the color appearance does influence the comfort level [83–86]. However, the preferred color appearance is completely dependent on the activity. Some studies concluded that the color appearance influences the room appearance [85,87], while others did not find this effect [50]. Finally, it is suggested that the color appearance influences the perceived brightness [50,86,88–90].

The color appearance of the light source is generally indicated by the correlated color temperature (CCT), which is the temperature of a black body radiator having a chromaticity associated with the chromaticity of the SPD of the light source [68]. It should be noted that different SPDs with different appearances can result in the same CCT, due to the information loss by translating from the multidimensional SPD to the one dimensional CCT.

Preferably, the CCT is based on spectral measurements. It is best measured using a spectroradiometer focused at a white Lambertian reflector such as Spectralon or BaSO₄. The Lambertian reflector is placed horizontally, perpendicular to electric light source, at the measurement location and is measured from a 45° angle [83]. Based on the chromaticity coordinates extracted from the SPD, the

CCT can be calculated based on methods developed by multiple scientists ranging from simple equations to complex algorithms [91–95]. Alternatively, devices (e.g. Chroma meters) are available that directly measure the chromaticity coordinates using three sensors sensitive to the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ color matching functions, respectively [96]. However, the accuracy is expected to be lower as spectral response errors (f_1') are introduced. Finally, alternative low-accuracy methods to estimate the CCT, for instance using digital cameras [97], are available. It is advised to perform the measurement of the CCT in the middle and for key positions of the considered space [98].

4.4.2. Light color quality

The concept of light color quality consists of different dimensions that influence the color perception of the observer in an environment. Six dimensions are identified: color fidelity, color discrimination, visual clarity (brightness), color preference, color harmony and color acceptability [99]. The color fidelity, or rendering, is the effect of the light (source) “on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant”[68]. Color discrimination is the ability to distinguish between colors [100]. Visual clarity relates to the feeling of contrast [99]. Color preference and color harmony are both aesthetic judgements for the individual objects and relationship between objects [99], respectively. Finally, the color acceptability relates to making a judgement about the whole environment [99]. Good light color quality helps to improve the visual performance, comfort and wellbeing [35].

Table 4 displays a selection of commonly used color quality metrics indicating the dimensions covered by these metrics. The Color Rendering Index is the most widely used and the only internationally accepted metric for color quality [100]. However, except the Color Quality Scale all metrics consider only a limited number of dimensions. It is, therefore, advised to always use at least two metrics [81,83,101]. A metric for color acceptability is not available as the mathematical modelling of the color acceptability is unsolved [99]. For an extensive review of all metrics, we refer to the work by Houser et al. [102]. In all cases the metrics are based on the SPD; it is, therefore, recommended to measure SPD

similarly as described for CCT measurements. Based on the measured SPD and data on the reference illuminants and color samples, the metrics can be calculated according to the provided equations in the references of Table 4.

	Abbreviation	Color Fidelity	Color Discrimination	Visual Clarity	Color Preference	Color Harmony	Color Acceptability	Reference
Color Rendering Index	R _a	X						[103]
Flattery Index	R _f				X			[104]
Color Preference Index	CPI				X			[105]
Color Discrimination Index	CDI		X					[106]
Color Rendering Capacity	CRC	X						[107]
Pointer's Index	PI	X						[108]
Colour Quality Scale	CQS	X	X	X	X			[100]
Feeling of Contrast Index	FCI			X				[109]
Memory Colour Rendering Index	MCRI	X			X			[110]
Color Harmony Rendering Index	R _{hr}					X		[111]

Table 4. Commonly used light color quality indices, including their abbreviations and reference. In the table it is indicated, by X, which lighting quality dimensions can be assessed by the light color quality indices.

4.5. Daylight

The fifth rated lighting quality aspect is daylight; two components are distinguished in the aspect daylight: daylight penetration and view out, relating to daylight entering the room and the quality of the view outside through the daylight openings, respectively.

Humans evolved under daylight conditions; therefore, access to daylight generally improves the satisfaction, and it “is more desirable for the psychological dimensions of visual comfort, environmental appearance and amenity”[112]. Additionally, all previously mentioned aspects (i.e. quantity, distribution, glare and SPD) are influenced by daylight, as the light is generally composed of daylight and electrical light. Moreover, daylight and electrical light can be controlled independently. However, as daylight is not always available, lighting quality should also be achieved without daylight.

Moreover, a surplus of daylight can lead to discomfort. Often daylight penetration is a given, depending on the fixed window openings, weather and time. However, there are possibilities to optimize daylight penetration on the run. An increasingly number of buildings are applied with dynamic sun shading (sun screens), brightness control (blinds) and/or smart glazing integrated in the façade. Sun shading and smart glazing can be used to block direct solar radiation, prevent glare or overheating. Often, these kind of systems are fixed, but dynamic systems that follow the trajectory of the sun are also available. Additionally, brightness control generally has a dynamic character as blinds are easily adjusted, manually or automatically, permitting optimizations. Hence, daylight penetration can be optimized by a control algorithm.

4.5.1. Daylight penetration

Daylight penetration is often indicated with measures such as the daylight factor or useful daylight illuminances (UDI) [113]. “The daylight factor is the ratio of internal illuminance related to the external illuminance of an overcast sky” [51]. The daylight factor is measured for a similar grid as described in section 4.1.1., and it can be measured in actual spaces, scale models and simulation models. The UDI is developed to account for the limitations of the daylight factor introducing varying conditions, and it is represented as a percentage of the time in which the illuminance is in a useful range. The UDI is determined using simulations adopting the previously defined grid. In addition to these specialized indicators, daylight can also be described with the previously mentioned aspects and their accompanying indicators (e.g. illuminance).

4.5.2. Outside view

A high quality outside view and visual contact with the world can influence the work performance and job satisfaction and can even result in improved general health [35]. Moreover, it has been indicated that the outside view might be essential to have beneficial effects of daylight [114]. View outside is bipartite: it is influenced by the size of the widow opening, and the quality of the view, having a subjective character. A high quality view generally consists of natural aspects rather than aspects of

the built environment [115]; additionally, a view with a high information content can be rated as a high quality view [116]. The quality of view is largely dependent on the fixed location. However, the outside view can be obstructed by the previously mentioned sun shading, brightness control and smart glazing. Hence, the quality of the view can be decreased drastically; therefore, it should be considered in a lighting quality optimization.

The window size is often indicated relative to the external wall area [117]. These indicators do not incorporate the different seating positions of different users; the users all experience the window size differently depending on their location. We suggest to use the solid angle assessed from the seating position, as this incorporates view direction. The quality of the outside view is largely subjective, but Hellinga and Hordijk developed a method to assess the subjective view quality objectively [118]. They developed an assessment method for quality of view, which correlated well with the extensive quality of view surveys they conducted, but further validation is still required.

4.6. Directionality of light

The directionality is a lighting quality aspect that is accounted for in twelve of the thirty eligible studies. The directionality of a light scene can be described by the flow of light. The concept of the flow of light consists of two aspects: the direction of the light flow and the strength of the light flow. Another definition for the strength of the light flow, also called modelling, is the balance between diffuse and directional components of the lit environment [119].

Adequate directionality helps to distinguish details of a task, surface textures and three dimensional objects including faces [16,119]. As a result, it influences communication, the appearance and the appreciation of an environment [120]. Moreover, the directionality of light can influence health and wellbeing because of a non-homogeneous distribution of the non-image forming cells in the eye [121]. The directionality of light can cause three distinct patterns on objects: the illumination pattern, the shadow pattern and the highlight pattern [120].

4.6.1. Direction and modelling

Theoretically, the directionality of a point within a room is determined based on an infinitesimal sphere that is met by an infinite number of luminance rays from all directions [122,123]; consequently, these rays can be described as three dimensional bound vectors. The vectorial sum is also a vector with the illuminance as magnitude, “hence the terms vectorial illuminance or illumination vector”[123]. The magnitude of the illumination vector is described by the difference between the “maximum difference across diameters of an infinitesimally small sphere at that point” [124]. The direction of the illumination vector is the altitude angle between the maximum and minimum luminance ray [120,123]. The strength of the flow of light is described by relating the magnitude of the illumination vector to the total amount of incident light on this infinitesimal sphere [120], also called scalar illumination [124]. Practically, it is not feasible to measure this theoretical concept, and simplifications are required to assess the directionality. Indicators for the direction of light are limited to the direction of the illumination vector. For the strength of the flow of light, or modelling, several indicators are developed as listed in Table 5. The vector to scalar ratio is used most commonly, representing the relation between the approximated illumination vector and the approximated scalar illumination.

Indicator	Reference
Vector to Scalar Ratio	Cuttle [120]
Cylindrical to Horizontal Illuminance Ratio	Hewitt et al. [125]
Vector to Cylindrical Illuminance Ratio	Bean [126]
Vertical to Horizontal Illuminance Ratio	Love and Navvab [127]
Flow of Light Ratio	Cuttle [128]
Illuminance Contrast Energy (ICE)	Morgernstern et al. [129]
Side Forward Ratio	Veitch et al. [130]
Light Factor to Density of Light Ratio	Xia et al.[131]

Table 5. Indicators to determine the strength of the light flow or modelling, including reference for original study.

Traditionally, these indicators are determined based on cubic illumination or similar technologies. Methods to measure the cubic illumination range from using a single photocell to successively measure the illuminance on the six faces of a theoretical cube to using a six-cell cubic photometer adopting a measurement grid similar to the horizontal illuminance [128]. Subsequently, the scalar, cylindrical, horizontal and vertical illuminance are calculated by summing the relevant sensor pairs [128]. The first method is tedious and complicated while the six-cell cubic photometer is vulnerable for calibration errors [132]. The cubic photometer is sensitive to orientation, because only six faces are available; therefore, a maximum variance of 33% can occur in the scalar illumination. For office lighting this is typically no concern [123], as most offices are designed in the three perpendicular directions.

Recently, methods have been developed to evaluate the directionality based on HDR imaging. Dubois et al. propose a method using a Lambertian white sphere and a HDR camera to determine the vector to scalar ratio for one selected point within a space [98]. The white sphere, divided in 24 evenly distributed sections, is monitored by two HDR cameras, each at one side of the sphere. Based on the 24 luminances or illuminances, the illumination vector and scalar are calculated according to the cubic illumination method [16,98]. Disadvantages are that two cameras are required; it is suggested to use one camera and successively measure both sides while using a grey reference surface to calibrate these measurements [98].

The method proposed by Howlett et al. [133] was able to indicate directionality, while also measuring other indices, using only one HDR camera. The authors developed the Ambient Light Directionality Indicator (ALDI), which consists of a white square-based pyramid and a reflective gnomon. The directionality is measured based on the ratio between the average luminance of two faces of the pyramid, depending on being sidelit or toplit. The gnomon provides visual evidence on the direction of the light flow and indicates whether light was coming from a diffuse source or a point source [133,134]. A disadvantage is that the directionality is only measured in a two-dimensional plane.

All methods described, except the one proposed by Howlett et al., are only used as ad hoc measurements only encapsulating one single moment. ALDI is used to measure the directionality at an hourly interval, and also to indicate the temporal variation of the directionality.

4.7. Dynamics

The final lighting quality aspect considered in this article is the dynamics of light. The dynamics of light consist of the variability of light and the rhythm of light, indicating the amount of change and the character of change, respectively, in the luminous environment over time. Dynamic lighting leads to an improved quality of visual performance, it is considered more stimulating, more pleasant, and leads to higher levels of arousal [4,36,135]. The dynamics of light in a lit environment are caused by daylight or by electric lighting with dynamic output. Theoretically, all previously mentioned aspects can have a dynamic character, but generally, only illuminance, luminance and the correlated color temperature are considered in dynamic lighting.

4.7.1. Variability and rhythm

Rockcastle and Andersen [136] developed a metric to describe the annual variation in luminance for daylight. This method calculates the variability based on luminance pictures and accounts for the cumulative difference in pixels as they vary over time. Results are represented in a cumulative annual luminance variability map, similar to a luminance picture, and a temporal luminance variability map. The annual variability is the “average difference between adjacent hourly and monthly instances”. This metric is able to indicate the degree of change in luminance during a year, location of this change (annual cumulative map) and the rhythm of change (temporal map). Depending on the interest, this method could be alternated to indicate dynamics over a shorter period of time or to indicate dynamics of other lighting quality aspects. To indicate the dynamics of light, multiple measurements are needed. Depending on the indicator of interest, the appropriate measurements are conducted as described in the earlier sections.

5. Conclusions and Recommendations

The objective of this study was to review current literature regarding methodologies to measure lighting quality, preferably in a continuous manner such that it can be used as input for control algorithms aiming to optimize lighting quality. In this study, lighting quality is considered a construct because it does not have a suitable definition; therefore, different lighting aspects are included that influence the lighting quality. Subsequently, lighting quality can be determined by measuring each individual aspect independently.

Nevertheless, a number of single indicator models exist that aim to describe lighting quality directly. However, all models have significant limitations such as measurement difficulties, low correlations with the subjective responses and limited validation; as a result none of the models is widely used. Nonetheless, these models provide insight into potential lighting quality aspects and methodologies to aggregate different aspects into one final lighting quality score.

During the literature study, it was found that the methodology section in multiple studies is often incomplete. It occurs that the characteristics of the measurement devices and measurement locations are not mentioned, but also indicators are used that are not suitable for the specific interests (e.g. CCT as a numeric indicator instead of describing the spectral power distribution). Moreover, the focus is often on illuminance-based indicators, while the luminance is more relevant as it relates to how humans experience the light. Illuminance is still being used because it is relatively easy to measure; however, luminance cameras provide the opportunity to measure luminance more practically. These both might be reasons that illuminance preference studies are not able to achieve consensus about what illuminance is generally preferred.

In this overview, ad hoc and continuous measurements of the different lighting quality aspects are distinguished. Ad hoc measurements are “snapshots” of reality measured with a high accuracy, typically achieved by using state of the art devices and optimal measurement locations. It is possible to achieve a high accuracy because for one individual measurement it is usually acceptable to disturb

occupants or to clear the specific space. As opposed to ad hoc measurements, it is not acceptable to disturb occupants or clear a space for continuous measurements. Additionally, the measurement conductors cannot be present during all measurements. Therefore, the measurement device is fixed, mostly at a suboptimal location to not disturb the occupant; furthermore, as the conductors are not present, for safety reasons no state of the art measurement devices are used. As a result, continuous measurements generally have a lower accuracy but provide a good overview over time; therefore, continuous measurements are useful for the integration in control algorithms.

It can be concluded that not all lighting quality aspects are equally matured because some of them are used less often. Especially, directionality and dynamics are aspects where indicators exist, but with limited applicability and without consensus. Also, the outside view component for the daylight aspect, having a large subjective character, is less matured.

In this overview, eleven lighting quality aspects are distinguished; to do so, some subjective binning was required to form aspects relevant for the scope of this study. Therefore, it does not mean that these specific aspects only form an accurate construct for lighting quality; for instance the IEA [36] provides slightly different lighting quality aspects because the scope of the study is slightly different.

The overview shows that for all aspects, measurements can be conducted using luminance distribution measurement devices. Only the SPD cannot be measured by such devices although algorithms exist that are able to estimate the correlated color temperature based on image data. More than an estimation is not possible as cameras generally only have three different channels (R, G, and B), where SPD measurements require a multitude of channels, preferably for each individual wavelength. Nevertheless, the luminance distribution can be seen as a suitable device to measure lighting quality because this device enables us to measure multiple lighting quality aspects continuously at once, where other devices have a limited applicability. Additionally, it has been shown that these luminance distribution measurement devices are able to achieve a practical accuracy using low cost components [59], allowing these devices to be fixed without significant safety issues. Therefore, it can be concluded

that a luminance distribution measurement device is a very suitable tool to be implemented in control algorithms that aim to provide high quality lighting.

5.1.1. Recommendations

Most aspects of lighting quality can be measured individually; however, it remains unknown how to combine and rate different aspects related to each other. In this overview, the different aspects are rated according to the percentage of occurrence. This does, of course, not directly indicate the importance of certain aspects; it only indicates which aspects researchers believe are important. A complication is that the relation between aspects is dependent on various factors, including the task, people's preferences, and cultural differences. Weighting factors can be determined, based on surveys or comparative research, to indicate the importance of different lighting quality aspects. However, more research and data are required to optimize the lighting quality in control algorithms as these weightings are highly case specific. Ultimately, the lighting quality measurements and their associated weighting factors can be combined into, for instance, a cost function that can be implemented in a control algorithm as the optimization criteria for the overall lighting quality. A number of metrics are available for the outside view, directionality and dynamics; however, they are not necessarily suitable for measuring using luminance distribution measurement devices. Most of these indicators are not developed for a luminance camera but are in some cases fitted to the use of luminance cameras. Developing indicators specifically for the use of luminance distribution measurement devices, which are potentially applied at suboptimal positions, using the immense powers of image processing might result in more suitable and practical indicators for lighting quality measurements.

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