Section A-Research Paper
ISSN 2063-5346

Daylight and its indices: a review

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DOI: 10.48047/ecb/2023.12.si4.1793

Abstract: Sunlight is a multi-dimensional occurrence that has the potential to improve the well-being, health, and interaction of occupants with the external surroundings due to its dynamic qualities in terms of both illumination and temperature. It is gift to human from Mother Nature, it have wide range of spectrum which cannot be replaced by artificial light. Daylight exhibits dynamism, with its intensity, colour, and temperature undergoing continuous fluctuations over time. To measure daylight various metrics are being used. The concept of daylight metrics has emerged as a pivotal aspect in architectural and interior design, offering a systematic approach to quantifying and optimizing the utilization of natural light within built environments. Daylight metrics encompass a range of measurements and calculations that evaluate the quality, quantity, distribution, and performance of natural light in indoor spaces. This comprehensive review paper focuses on the metrics related to daylight quantity, light uniformity, and direct sunlight, elucidating their advantages and constraints through their mathematical formulations. It provides guidance on their application, along with identifying areas that require enhancement to facilitate their utilization within optimization processes for building design.

1. Introduction

The primary objective of both natural and artificial lighting is to ensure optimal visibility for indoor and outdoor activities, regardless of external weather conditions [1]. Daylighting involves integrating natural light into indoor spaces to reduce the reliance on artificial lighting and lower energy consumption within buildings [2][3]. Adequate and high-quality illumination plays a crucial role in facilitating effective indoor tasks, especially during night time, thereby enhancing productivity and overall quality of life. Literature suggests that artificial lighting is responsible for, up to 40%, of the annual electricity utilization in buildings, presenting a major challenge in achieving the sustainable development goals outlined by the United Nations [4].

Diverse energy performance rating systems are employed to monitor the efficiency of building energy usage, attributing scores, stars, or other indicators based on their performance. Globally recognized building rating frameworks, such as Leadership in Energy and Environmental Design (LEED) [5], underscore the significance of lighting in attaining elevated performance benchmarks. LEED, for instance, allocates specific points to daylighting. The assessment criteria for gauging the effectiveness of energy-efficient lighting, encompassing both natural and artificial sources, are subjects of continuous research [6]. Moreover, “electricity consumption and energy-efficiency are not the only topics to consider when it comes to designing appropriate lighting scenarios for buildings: good visual comfort is of course equally important” as per Scartezzini and Linhart[7].

Therefore, the thorough analysis and classification of metrics designed to assess visual comfort play a pivotal role in setting overarching standards for lighting efficiency in building design. Furthermore, the formulation of standardized criteria proves beneficial in shaping the creation of energy-efficient systems, capable of delivering exceptional environmental performance in terms of visual quality while maintaining minimal energy usage.

2. Visual Comfort

Definition of visual comfort by European standard EN 12665 is "a subjective state of visual well-being induced by the surrounding visual environment" [25]. This concept is influenced by several factors: (i) the physiological characteristics of the individual’s eye, (ii) the characteristics related to the quantity of light and its spatial distribution, and (iii) the light source’s spectral characteristics. The assessment of various factors has traditionally been used to investigate visual comfort, encompassing aspects such as (i) light quantity, (ii) light distribution, (iii) direct sunlight penetration the, and (iv) the calculation of potential glare risks for habitants. This paper targets indices used in measurement of quantity of daylight, light distribution (uniformity) and penetration of light in the indoor space.

3. Indices for Assessing Daylight Quantity

Characterizing interior daylight poses a challenge due to numerous design variables influencing it, including factors like views, window size, room dimensions, and glass properties [8]. Nonetheless, assessing illuminance levels within structures can be achieved through diverse methods, including experimental, numerical, and simplified approaches. In the early 1980s, BRE introduced simplified metrics to evaluate indoor lighting effectiveness [9]. Table 2 presents daylight quantity indices.

Table 1: Daylight quantity indices

Indices	Representation	Source of light	Space discretization	Duration of time	Acceptability criterion	Threshold value	Ref.
Illuminance	E_p	Daylight, Electric light	Confined	Point of time	One term	200-300-500 lx [10]	-
Daylight factor	DF	Daylight	Confined, Zone	Point of time	One-tailed	DFavg > 3% ∩ DFmin/DFmax > 0.16 [12] DFavg > 5% ∩ DFmin > 2% [13]*** DF > 2% on at least 80% of the room [14]	Hopkinson [11]
Daylight Autonomy	DA	Daylight	Confined	Annual	One-tailed	-	Reinhart and Walkenhors [15]
Continuous Daylight Autonomy	cDA	Daylight	Confined	Annual	One-tailed	-	Rogers and Goldman [16]
Spatial Daylight Autonomy	sDA	Daylight	Zone	Annual	One-tailed	Preferred: $sDA_{300/50\%}$ > 75% on occupied area [17][18] Acceptable: $sDA_{300/50\%}$ > 55% on occupied area [17][18]	IES [17]
Useful Daylight Illuminance	UDI	Daylight	Confined	Annual	Two-tailed	$UDI_{100-2000}$ [20] $UDI_{100-2500}$ [21] $UDI_{500-2000}$ [22] $UDI_{300-8000}$ [23]	Carlucci [19]
Frequency of Visual Comfort	FVC	Daylight	Zone	Annual	Two-tailed	-	Sicurella, Evola [24]
Intensity of Visual Discomfort	(IVD)	Daylight	Zone	Annual	Two-tailed	-	Sicurella, Evola [24]

***In the calculation, it is recommended to leave a 0.5 m zone around the classroom perimeter.

Many research studies explain the penetration of daylight into a space using illuminance, a measurable physical quantity in lux at a designated point P on a surface (Ep), as indicated by the following equation 1. Illuminance refers to the measurement of light that reaches a surface per unit area. This is surface's brightness whuch is measured in lux. It signifies a physical measurement at a particular point P on a surface, quantifying the amount of light per unit area, and is expressed in lux. This value is obtained by dividing the luminous flux that reaches a small area around point P by the area (Arec) of that surface.

$$E_p = \frac{df}{dA_{rec}} \; [lx] \qquad (1)$$

Illuminance is a metric used to measure the amount of light in a particular area, and it is specific to that location and short-term in nature. In office environments, the European standard EN 12464-1 [25], along with other studies, suggests that an optimal workspace should have an illuminance level of 500 lux [26]. However, differing opinions exist, with some researchers considering 425 lux [27] or even 300 lux [23] to be acceptable levels for office lighting. The illuminance metric reflects the amount of daylight at a specific point during each hour, but it may not accurately represent the overall sufficiency of daylight in a space throughout the year. To address this, the Daylight Factor (DF) has been commonly employed as a measure to assess the adequacy of daylight in a given space. Trotter introduced the term "Daylight Factor" (DF) in 1895. *DF is "the ratio of the daylight illumination at a given point on a given plane due to the light received directly or indirectly from the sky of assumed or known luminance distribution to the illumination on a horizontal plane due to an unobstructed hemisphere of this sky. Direct sunlight is excluded for both interior and exterior values of illumination"* [28] & "*the ratio of the internal illuminance at a point ($E_{p,obs}$) in a building to the unshaded, external horizontal illuminance ($E_{p,unobs}$) under a CIE overcast sky*" as the most unfavourable situation [29],

$$DF = \frac{E_{p,obs}}{E_{p,unobs}} \qquad (2)$$

$E_{P,obs}$ = horizontal illuminance at a point P due to the presence of a room that obstructs the view of the sky

$E_{P,unobs}$ = horizontal illuminance at the same point P if the view of the sky is unobstructed by the room.

Additionally, the absence of accounting for the dynamic aspects of climate has motivated researchers to develop metrics that take into account specific sun radiation and climate conditions, as well as adaptable systems like shading devices, within a scheme. In response to this, the introduction of climate-based daylight modelling (CBDM) has provided a means to assess daylight sufficiency and instances of surpassing design goals. The primary metric within CBDM is Daylight Autonomy (DA), which was initially introduced by the Swiss Association of Electricians in 1989 [30], and later refined by Walkenhorst & Reinhart [15].DA is "*the percentage of the occupied hours (t_i) of the year when a minimum illuminance threshold (E_{limit}) is met by the sole daylight ($E_{daylight}$)"* (eq.3).

$$DA = \frac{\sum_i (wf_i \,.\, t_i)}{\sum_i t_i} \in [0,1]$$

$$with \; wf_i = \begin{cases} 1 & if \; E_{Daylight} \geq \mathrm{E_{Limit}} \\ 0 & if \; E_{Daylight} < \mathrm{E_{Limit}} \end{cases} \qquad (3)$$

The DA metric measures the percentage of annual occupied hours when the illuminance at a specific point in a room exceeds a specified threshold, often set at 500 lux (E_{limit}), as suggested by Olbina and Beliveau [22].

Rogers and Goldman [16] introduced Continuous Daylight Autonomy (cDA) as an enhancement of the Daylight Autonomy (DA) metric which incorporate partial modifications linked to time intervals when the horizontal illuminance from daylight falls under the specified limit (eq. 4). This approach acknowledges the benefits of even a small amount of daylight contribution.

$$cDA = \frac{\sum_i (wf_i \,.\, t_i)}{\sum_i t_i} \in [0,1]$$

$$wit\square\ wf_i = \begin{cases} 1 & if\ E_{Daylig\square t} \geq \mathrm{E_{Limit}} \\ \frac{E_{Daylig\square t}}{E_{Limit}} & if\ E_{Daylig\square t} < \mathrm{E_{Limit}} \end{cases} \tag{4}$$

cDA is a long-term metric that assesses the quantity of daylight that reaches a particular point within a building during its operational hours. This indicator focuses on a single direction and considers the constant availability of daylight. The Illuminating Engineering Society (IES) [17] enhanced the concept of Daylight Autonomy (DA) by eliminating its limitations. They introduced a refined version called Spatial Daylight Autonomy (sDA), which also takes into account occupant satisfaction. sDA is *"the annual percentage of occupied hours (y) where at least 50% of the floor area (P_i) reached to a certain illuminance threshold (x)"* (eq. 5)

$$sDA_{X/y\%} = \frac{\sum_i (wf_i \,.\, DA)}{\sum_i p_i} \in [0,1]$$

$$wit\square\ wf_i = \begin{cases} 1 & if\ DA \geq \mathrm{DA_{Limit}} \\ 0 & if\ DA < \mathrm{DA_{Limit}} \end{cases} \tag{5}$$

The $sDA_{300/50}$ metric is recommended by the Illuminating Engineering Society (IES) for daylight analysis. This means that the analyzed portion should have an illuminance level of 300 lux or more for at least 50% of the occupied time, which typically spans from 8 am to 6 pm local time[17]. While this equation generates a value specific to an area or zone, using a single value as a daylighting metric for pooled workspaces might not be suitable.To overcome this Useful Daylight Illuminance (UDI) is introduced. UDI represents the portion of the year during which the horizontal internal daylight illuminance at a specific location remains within an acceptable range [19]. This metric categorizes periods into three bins based on proposed illuminance limits: the upper bin represents the proportion of period when daylight exceeds comfortable levels, perhaps causing visual discomfort. The middle bin represents the percentage duration when the desired light intensity is achieved. The bottom bin reflects the percentage of hours when there is inadequate daylight. (eq. 6).

$$UDI = \frac{\sum_i (wf_i \,.\, t_i)}{\sum_i t_i} \in [0,1]$$

$$\begin{cases} UDI_{overlit} & wit\square \quad wf_i = \begin{cases} 1 & if\ \ E_{Daylig\square t} > \mathrm{E_{Upper\ limit}} \\ 0 & if\ \ E_{Daylig\square t} \leq \mathrm{E_{Upper\ limit}} \end{cases} \\ \mathrm{UDI_{useful}} \quad \text{with} & \mathrm{wf_i} = \begin{cases} 1 & \text{if } \mathrm{E_{Lower\ limit}} \leq \mathrm{E_{Daylight}} \leq \mathrm{E_{Upper\ limit}} \\ 0 & \text{if } \mathrm{E_{Daylight}} < \mathrm{E_{Lowerr\ limit}} \vee \mathrm{E_{Daylight} > E_{Upper\ limit}} \end{cases} \\ \mathrm{UDI_{underlit}} & \text{with} \quad \mathrm{wf_i} = \begin{cases} 1 & \text{if } \mathrm{E_{Daylight}} < \mathrm{E_{Lower\ limit}} \\ 0 & \text{if } \mathrm{E_{Daylight}} \geq \mathrm{E_{Lower\ limit}} \end{cases} \end{cases} \tag{6}$$

In addition to, Reinhart and Wienold [31]aimed to address the limitation of higher DA criteria by combining Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) into a unified metric termed Daylight Availability (DAv). This metric use to classify buildings into four parts: 'fully daylit' (corresponding to $sDA_{300,50\%)}$, 'partially daylit' (corresponding to $sDA_{150,50\%)}$, 'overlit' (corresponding to $sDA_{25000,50\%}$), and 'non daylit' (corresponding to $sDA_{0,50\%}$).

Comparable to the UDI concept, the Frequency of Visual Comfort (FVC) pertains to the fraction of time (t_i) within a designated timeframe for the period of which illuminance values ($E_{daylight}$) fall within a defined range, ensuring visual comfort solely in relation to daylight conditions (eq. 7). FVC expressed as [24] "*a percentage of the time during a specific period during which daylight alone produces suitable levels of illuminance*." When the average illuminance remains within the range of two specified threshold levels, it is presumed that visual comfort is exclusively achieved through daylight illumination.

$$FVC = \frac{\sum_i (wf_i \, . \, t_i)}{\sum_i t_i} \in [0,1]$$

$$with \; wf_i = \begin{cases} 1 & if \quad \mathrm{E_{Under}} \leq \mathrm{E_{Daylight}} \leq \mathrm{E_{Over}} \\ 0 & if \quad E_{Daylight} < \mathrm{E_{Under}} \vee \mathrm{E_{Daylight}} > \mathrm{E_{Over}} \end{cases} \qquad (7)$$

The attention wasn't solely on the average daylight illuminance in the context of Frequency of Visual Comfort (FVC) . Sicurella et al. [24]also introduced the concept of Intensity of Visual Discomfort (IVD). It is defined as "*the time integral of the difference between the spatial average of the current daylight illuminance and the upper limit of visual comfort (E_{over} = 750 lux) as IVD_{over} or the lower limit of visual comfort (E_{under} = 150 lux) as IVD_{under}" (eq. 8).* IVD can serve as a tool to evaluate both visual outcomes and daylight infiltration. However, achieving zero IVD consistently over an extended period is challenging.

$$IVD = \int_P \Delta E(t) dt$$

$$\begin{cases} IVD_{Over} \quad with \quad \Delta E(t) = \begin{cases} E(t) - E_{Over} & if \; E(t) \geq E_{Over} \\ 0 & if \; E(t) < E_{over} \end{cases} \\ IVD_{Under} \quad with \quad \Delta E(t) = \begin{cases} 0 & if \; E(t) \leq E_{under} \\ E_{Under} - E(t) & if \; E(t) > E_{Under} \end{cases} \end{cases} \qquad (8)$$

4. LIGHT DISTRIBUTION INDICES

Visual comfort is determined not just by the quantity of daylight available in a given place, as well as by how that light is distributed across the area. This aspect holds significance across various types of buildings, including office spaces, schools, libraries, and more. A uniformly illuminated environment not only minimizes the risk of glare but also correlates with the frequency at which occupants feel the need to turn on artificial lighting. However, within the existing literature, there is only one metric associated with the distribution of daylight, known as Illuminance Uniformity (U_O). This metric is defined as the proportion of the least illuminance intensity ($E_{minimum}$) and the mean illuminance intensity ($E_{average}$) over a certain work plane (eq. 9a). It's also feasible to employ the ratio of the minimum and maximum illuminance values (E_{max}) on the designated surface, although this approach requires clear specification (eq. 9b) [32]. The respective formulations for these metrics are as follows:

$$U_{0,average} = \frac{E_{min}}{E_{average}} \qquad (9a)$$

$$U_{0,max} = \frac{E_{min}}{E_{max}} \qquad (9b)$$

Furthermore, various uniformity thresholds have been proposed, such as 0.8 [33], or within the range of 0.4 to 0.7 as per the visual job [34]. This underscores the inconsistency in the recommended criteria. Notably, there is a lack of correlation between the prescribed calculation methods and factors related to occupancy.

5. INDICES FOR SUNLIGHT PENETRATION

To overcome the limitation of the daylight autonomy (DA) definition caused by the absence of an upper limit, the IES committee [17] introduced an additional measure designed to evaluate the potential for both visual and thermal discomfort in spaces illuminated by daylight. This metric, known as Annual Sun Exposure (ASE), is not focused on glare but serves as an indicator of discomfort. ASE is an illuminance-based and dynamic metric designed to evaluate the extent of direct natural light infiltration. It calculates the percentage of occupied points receiving direct daylight exceeding 1000 lux for at least 250 hours annually (abbreviated as $ASE_{1000,250h}$). Currently, ASE is not deemed a robust daylight metric for evaluation due to several notable uncertainties. These uncertainties include things like how accurately the sun is shown and how results are affected by the resolution of the analysis array. [35][36].

A novel metric named 'Sunlight duration' has been recently presented by [37] for the purpose of describing an environment illuminated by daylight. This metric is defined as the portion of each day in which incident sunlight enters a space through windows or openings, expressed either in hours or as a dimensionless parameter. The measurement of sunlight duration is influenced by nearby obstacles in an urban setting that might obstruct direct sunlight exposure. The sunlight duration (s) for various sun azimuth angles, taking into account the sun's altitude (γ_s) and the height of obstacles (γ). In this equation, if the sun's altitude (γ_s) is lower than the height of obstructions (γ), the reference point on the window pane is shaded by surrounding buildings. Conversely, if the sun's altitude (γ_s) is greater than the height of obstructions (γ), the reference point is shaded from overhead elements like overhangs.

$$s = \int_{t_{s.i}}^{t_{e.i}} s_i \, dt$$

$$\begin{cases} t_{s.i} & starting\ time\ of\ the\ sunny\ period \\ t_{e.i} & end\ time\ of\ sunny\ period \\ i & number\ of\ sunny\ period \end{cases} \tag{10}$$

An additional measurement, as proposed by [74], involves the evaluation of the cross-sectional dimension of the sunlight beam that traverses a window. This metric relies on factors like the portion of the window exposed to sunlight, the duration of sunlight exposure, and the cosine of the angle at which sunlight strikes the window. Remarkably, it can be adapted to various scales and computed annually as the Annual Sunlight Beam Index (S_{tot}). Specifically, S_{tot} compiles the cumulative SBI (Sunlight Beam Index) for every glazed openings over the course of a year, accounting for situations where the sun's altitude (γs) exceeds zero.

$$S_{\Delta t} = A_i cos\theta \Delta t = (A_g - A_u) cos\theta \Delta t \tag{11}$$

$$S_{tot} = \sum\nolimits_{\gamma s>0} (A_i cos\theta \Delta t) \tag{12}$$

6. CONCLUSION

Numerous visual comfort metrics have been proposed over time to evaluate various aspects of a well-lit environment and how humans perceive it. This study compiles and reviews the primary visual comfort indices. The primary contribution of this investigation is to present a comprehensive overview of the subject, aiding professionals and scholars working in diverse domains of building performance evaluation and design. This broader perspective enhances understanding of the intricate and diverse nature of visual comfort, guiding them towards more detailed and specialized resources. To quantitatively measure visual comfort across daylight level, distribution, and direct sunlight, a compilation of different metrics has been amassed from existing literature, each accompanied by its distinct mathematical expression.

The key visual comfort indices are systematically categorized and their primary characteristics are outlined in table 1. Consequently, the secondary achievement of this study is the development of a decision support tool for designers and analysts. This tool aids in the effective selection of the most appropriate visual comfort index for specific visual assessments.

The prevailing metrics employed by researchers encompass sDA (Spatial Daylight Autonomy) and ASE (Annual Sun Exposure) and Useful daylight illuminance (UDI) . According to LEED v4 standards, a threshold of up to 10% for ASE is considered acceptable, while maintaining sDA above 50% is a standardized requirement for simulation-based modelling approaches aimed at evaluating daylight performance. For comprehensive and extended assessments, UDI appears to be a suitable choice. It encompasses a broad range of essential information from the illuminance time-series. Being two-tailed, UDI has the capacity to quantify instances of both excessive and deficient lighting conditions. It not only provides insights into the levels of useful daylight but also indicates the potential for excessive daylight that might lead to issues such as glare and excessive solar heat gain.

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