Building and Environment 81 (2014) 320–333

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Measuring the dynamics of contrast & daylight variability in architecture: A proof-of-concept methodology

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ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form
28 May 2014
Accepted 12 June 2014
Available online 25 June 2014

Keywords:
Daylighting design
Spatial contrast
Light variability
Visual effects
Dynamic lighting
Lighting perception

ABSTRACT

Unlike artificial light sources, which can be calibrated to meet a desired luminous effect regardless of latitude, climate, or time of day, daylight is a dynamic light source, which produces variable shadow patterns and fluctuating levels of brightness. While we know that perceptual impacts of daylight such as contrast and temporal variability are important factors in architectural design, we are left with an imbalanced set of performance indicators – and few, if any, which address the positive visual and temporal qualities of daylight from an occupant point-of-view. If visual characteristics of daylight, such as contrast and spatial compositions, can be objectively measured, we can contribute to a more holistic analysis of daylit architecture with metrics that complement existing illumination and comfort-based performance criteria. Using image processing techniques, this paper will propose a proof-of-concept methodology for quantifying contrast-based visual effects within renderings of daylit architecture. Two new metrics will be proposed; annual spatial contrast and annual luminance variability. Using 56 time-step instances (taken symmetrically from across the day and year) this paper will introduce a method for quantifying local contrast values within a set of rendered images and plot those instances over time to visualize hourly and seasonal fluctuations in contrast composition. Using the same 56 instances, this paper will also introduce a method for quantifying variations in luminance (brightness) between instances to measure fluctuations in brightness. This paper pre-validates each of the proposed methods by calculating annual spatial contrast and annual luminance variability across ten abstract digital models and comparing those results to the authors' own intuitive ranking.

1. Introduction

Daylight offers both functional and aesthetic value to architecture, providing natural and energy-efficient illumination for interior tasks and infusing interior space with light, shadow, and texture. Unlike artificial light sources, which can be adjusted to meet a desired luminous effect regardless of latitude, climate, or time of day; daylight is sensitive to a number of dynamic conditions. The latitude of a given location affects the length and intensity of daylight hours across the year while climatic factors affect its strength and variability on an hourly scale. These variable conditions result in a highly dynamic source of illumination and perceptual phenomena. While many architects have expressed the importance of these phenomenological effects on our perception of space [1–4] we are left with disproportionally few, if any, daylight design metrics that can evaluate the positive impacts of luminous variability within the visual field.

A preoccupation with electricity consumption, brought about by the oil crisis of the 1970s and strengthened through contemporary trends in energy conservation, encourages architects and engineers to place value in daylight as an energy-efficient alternative to artificial light. In an effort to reduce energy consumption, daylighting research has gravitated toward the widespread development of task-based illumination metrics [5] as a means of offsetting a building's reliance on electric light. Visual comfort metrics, especially those pertaining to glare, have also gained predominance within the last two decades, as the emphasis on daylight integration has led to an increase in glazed facades and complex shading systems that can trigger occupant discomfort during visual tasks. Advances in computational power have helped to facilitate time-intensive simulations, allowing us to transition from point-in-time glare risk-assessment to dynamic annual metrics [6,7]. Perceptual performance indicators such as contrast and

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http://dx.doi.org/10.1016/j.buildenv.2014.06.012

variability, on the other hand, are traditionally defined as qualitative design factors and quantitative methods to explore their impact or relevance have been limited. Although subjective in nature, the perceptual performance of space is central to architectural design and often ranks above other more concrete evaluation criteria (like task-plane illuminance and visual comfort) within the design process. With this in mind, it is important to consider perceptual performance criteria alongside illumination and visual comfort metrics to develop a more holistic evaluation of daylight in architecture. A brief review of existing daylight performance metrics will help situate this paper and underline the need for new metrics that address the positive impacts of daylight within our field-of-view.

1.1. Task-driven performance metrics

The most common daylight metrics used today typically focus on task performance, whether in regard to illumination (work-plane task illumination) or to visual comfort (eye-level glare evaluation). A third, less established category, but one of particular relevance to this paper, relates occupant preferences to perceptual factors such as brightness and luminous diversity within an established view position.

Over the past several decades, there have been significant improvements in our understanding of daylight as a dynamic and variable source of illumination. We have transitioned from static metrics such as Daylight Factor DF [8] to annual climate-based metrics like Daylight Autonomy DA [5] or Useful Daylight Illuminance UDI [9], as well as Acceptable Illuminance Extent AIE [10] when dealing with whole areas of interest over time, that all account for a more statistically accurate method of quantifying internal illuminance levels [11]. While DF may be the most widespread task-based illumination metric currently used in practice, it limits our understanding of daylight as a dynamic source of illumination, assuming a more-is-better attitude regardless of the sky type or intended programmatic use of the space under consideration [5]. Dynamic illumination metrics, such as DA, UDI or AIE, can evaluate annual illumination thresholds, taking into account building orientation and climate-driven sky type to provide a more accurate assessment of task-plane illuminance.

Unlike task-based illumination metrics that rely on illuminance, visual comfort metrics (typically pertaining to glare) tend to rely on luminance [12]. Of the four photometric quantities (luminous flux, intensity, illuminance, and luminance), luminance is most closely related to how the eye perceives light, and as such, appears as the only quantity capable of expressing visual discomfort. As luminance, brightness, and contrast are subjectively evaluated, methods to analyze glare discomfort are fragmented across no less than seven established metrics [7,13,14]. While these indices do not always agree, partly due to the fact that some were developed for electric lighting sources and others for daylight, most are derived from the same four quantities: luminance, size of glare sources, position of glare source, and the surrounding field of luminance that the eye must adapt to [15]. Glare-based visual comfort metrics, such as Daylight Glare Probability DGP [7], considered the most reliable index for side-lit office spaces under daylight conditions, have also evolved into dynamic annual metrics such as DGPs [15] which provides a comprehensive yearly analysis of glare, with limited computational intensity [6].

Task-driven illumination metrics such as DF and DA can be used to determine whether an interior space is sufficiently illuminated for the performance of visual tasks, whereas comfort-based luminance metrics such as DGP allow us to evaluate the visual field for sources of glare-based discomfort. While the shift toward climate-based metrics such as DA and UDI represents a significant improvement in daylight analysis, this data is limited to a two-dimensional task-surface and does not correspond to the three-dimensional view of space that is perceived by an occupant. Although dynamic glare metrics such as DGPs evaluate a three-dimensional view position, they also only establish that high levels of contrast negatively impact visual comfort. Of the many established glare indices, not one addresses the notion of contrast as a positive visual effect.

Furthermore, task-driven illumination and visual comfort metrics are only applicable in spaces where visual tasks are frequently carried out. For spaces where visual tasks are less indicative of lighting performance, we have few, if any, broadly accepted metrics to help guide designers. In the absence of quantitative criteria, architects are tasked with creating acceptably bright or visually engaging environments, based on subjective criteria [16]. For many architects, this task is made difficult by the dynamic nature of sunlight and the challenges associated with predicting the range of visual effects that will occur across the day and year.

1.2. Perceptual daylight metrics

Two factors that are widely accepted to impact the field-of-view in daylit architecture are average luminance and luminance variation [17]. The former has been directly associated with perceived lightness and the latter with visual interest [18]. To evaluate the visual impacts of luminosity within interior architecture, existing research has relied on average luminance or “brightness,” threshold luminance, and luminance variation (or standard deviation) in line with occupant surveys to establish trends in preference. Survey-based studies most commonly rely on high-dynamic-range HDR images, digital photographs or renderings produced through Radiance, which provide an expanded range of photometric information, allowing us to evaluate characteristics such as brightness and contrast [19,20]. Some studies have found that both mean luminance and luminance variation within an office environment contribute to occupant preference [21], whereas others have discovered that luminance distribution across an occupant's field-of-view [22] as well as the strength of variation are factors of preference [23].

In a study conducted by Cetegen et al., the authors discovered a positive trend between increased average luminance levels and satisfaction for the view in an office setting, but they also saw a trend between increased luminance *diversity* and the participant's impression of excitement [21]. In a second study, also conducted in an office setting, Tiller and Veitch concluded that a non-uniform lighting distribution increased an occupant's perception of brightness and preference [22]. Along the same lines, Wymelenberg & Inanici conducted a study on occupant preferences toward light distribution in an office setting with horizontal blinds. The authors of the study concluded that adequate variations in luminance tended to create a stimulating visual environment, while excessive variability tended to create uncomfortable spaces [23].

The problem with those studies that rely on average luminance, luminance range, and standard deviation, is that they do not address the *spatial* diversity of luminance values within an occupants' field-of-view. In a daylight classification system proposed by Claude Demers, she categorizes digital images of architecture in terms of average brightness and standard deviation. While this method produces a typological language to codify lighting ambiance, she acknowledges that it cannot account for the spatial distribution of perceived light, which is central to the visual experience of architecture [24]. To address the importance of light distribution, Parpairi et al. developed the Luminance Difference (LD) index, which proposes a spatially dependent method for measuring luminance diversity across a selected view direction.