Theory Behind Photometric Measurements

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Abstract

Photometric measurements are vital for understanding and quantifying light in architectural spaces. This whitepaper examines the theoretical foundations of photometric measurements, explains the relationship between photometry and radiometry, and underscores the importance of a comprehensive understanding of photometric principles for designing lighting systems that prioritize human well-being and environmental sustainability.

Introduction

Photometric measurements are quantitative assessments of light as perceived by the human eye [1]. Illuminance, a key photometric measure, is widely used in the lighting industry to evaluate whether light levels in spaces are appropriate. However, discussions of photometric measurements are often limited to what is necessary for general industry applications. For example, illuminance is defined as "the luminous flux that falls on a surface per unit area," while luminance is defined as "the amount of luminous flux per unit area of a surface in a specific direction per unit solid angle" (Fig. 1). While the definitions stand, a constrained understanding may arise, leading many individuals to associate illuminance exclusively with light levels on a surface and to perceive luminance as representing light levels from a specific direction.

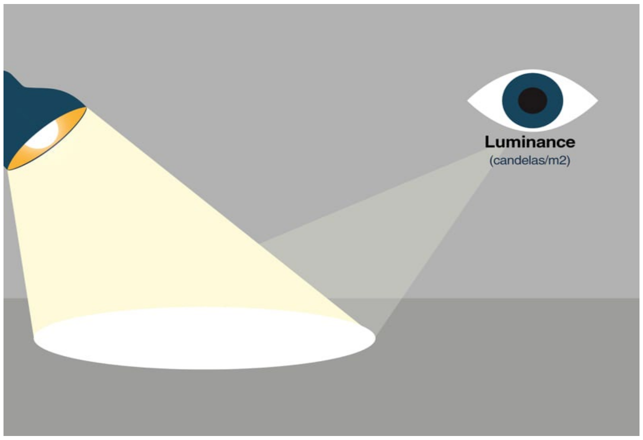

Fig. 1. Photometric measurements: illuminance and luminance

As awareness of human comfort in relation to electric lighting increases—particularly regarding circadian rhythms [2] and human-centric lighting [3]—several pertinent questions emerge. Key considerations involve how to incorporate the factors during the design phase and how to achieve the technical integration within lighting systems. The theory underlying human comfort in relation to electric lighting cannot be adequately explained by the definitions of photometric measurements alone [4]. Consequently, there is an increasing demand for a more comprehensive understanding of the measurements.

Radiometry

A thorough understanding of radiometry is foundational for the study of photometric measurements. Radiometry is the scientific discipline concerned with the measurement of optical radiation, encompassing all forms of electromagnetic radiation across the spectrum (visible light is part of it) [5]. It focuses on quantifying the physical properties of light without regard to human perception. Some of the key components of radiometric measurements include radiant flux, irradiance, and radiance.

Radiant flux refers to the rate at which radiant energy is emitted, transmitted, or received and is measured in watts (W). In contrast, irradiance is characterized as the power of radiant energy incident on a surface per unit area and is measured in watts per square meter (W/m^2). Radiance is described as the amount of radiant flux traveling in a specific direction per unit solid angle per unit area, measured in watts per steradian per square meter ($W/sr{\cdot}m^2$).

Spectral power distribution (SPD) of light sources is defined as the emitted power from a light source per unit area per unit wavelength and is represented in radiometric terms. It refers to the representation of the power of light at different wavelengths across the electromagnetic spectrum. The SPD can vary significantly between different light sources (Fig. 2). For instance, a cool white fluorescent lamp exhibits several peaks in its SPD, while an incandescent bulb shows a more continuous increase across the visible spectrum.

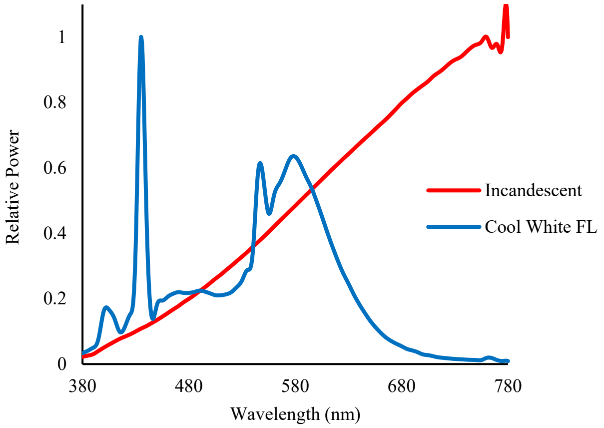

Fig. 2. SPDs for two different light sources

To measure radiometric quantities, a variety of equipment can be selected. A device frequently utilized by researchers is called spectroradiometer (Fig. 3). It is an instrument used to measure the intensity of electromagnetic radiation across different wavelengths and it provides detailed information about the spectral distribution of light.

Fig. 3. Spectroradiometer and its displaying platform

Photometry

Photometry is the study of measuring light based on its perceived brightness to the human eye [6]. Unlike radiometry, it focuses on visible light and how it affects human visual perception. To convert radiometric quantities to photometric quantities, the following equation is needed.

$$\phi_v = K_m \int_{380}^{780} \phi_e(\lambda)\, V(\lambda)\, d\lambda$$

Where,

ϕ_v is the photometric quantity (luminous flux, luminous intensity, illuminance and luminance).

ϕ_e is the radiometric quantity (radiant flux, radiant intensity, irradiance and radiance, respectively).

K_m is a constant ($K_m = 683$ lm/W)

$V(\lambda)$ is the CIE standard observer.

Standard Observer (Luminous Efficiency Function)

Pioneers did experiments to capture the human eye sensitivity to brightness along the visible spectrum [7-9]. While CIE combines all of the studies and adopted the $V(\lambda)$ (standard observer) in 1924 (Fig. 4) [10]. It also goes by 1924 2-degree luminous efficiency function.

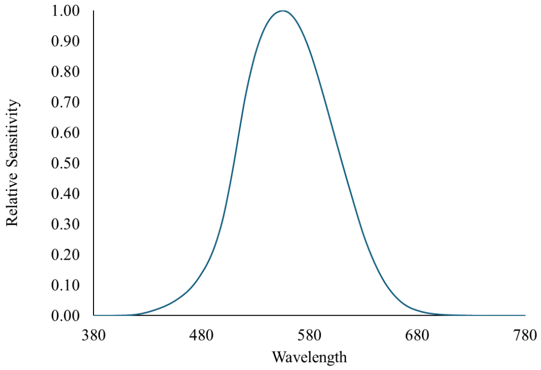

Fig. 4. CIE 1924 2-degree luminous efficiency functions (standard observer) (V(λ))

Normalized to a maximum of 1 at 555 nm, the standard observer measures the human eye's sensitivity to various wavelengths of light in architectural lighting conditions, and it remains applicable in today's lighting industry. Tools like illuminance meters and luminance meters measure radiometric quantities and use the standard observer to derive photometric measurements.

However, since the conception of standard observer, several studies suggested that the standard observer maybe inaccurate due to limitations of experimental protocols, such as small field of view and low light levels [11-13]. New luminous efficiency models have been proposed, but the cost-effectiveness has not been systematically discussed.

Conclusion

In conclusion, the theoretical foundations of photometric measurements are essential for accurately optimizing lighting in architectural spaces. However, the practical implementation often requires a more nuanced understanding of the complex ways in which light interacts with human vision, particularly in the context of SPD and luminous efficiency function.

As lighting systems evolve to address human-centric design principles, it becomes increasingly important to refine the measurement models. Ultimately, advancing the theoretical framework of photometric measurements will be instrumental in shaping lighting systems that not only enhances the visual appeal of buildings but also improves human well-being and supports environmental sustainability in the built environment.

About Wangyang Song, Ph.D:

Wangyang is dedicated to developing creative, state-of-the-art, energy efficient lighting solutions, in keeping with the rapidly evolving lighting and control technologies and the budgetary constraints of our clients. He stresses the importance of the innovative application of technology and science to lighting design, while recognizing the aesthetic standards and the needs of the end users. He is in tune with the needs and requirements of the MEP built environment, and works closely with other trades to deliver an integrated lighting design to our clients.

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Figure 1: [https://faro.es/en/blog/luminance-illuminance-difference/]

Figure 3: [https://internationallight.com/blog/what-difference-between-spectrometer-spectroradiometer-and-radiometer]