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Introduction

The technology of electrical light sources started in 1880 with the development of the tungsten lamp based on the thermal radiation principle by Thomas Edison. From the beginning of the twentieth century until 1990, a variety of light source types for indoor and outdoor lighting such as fluorescent lamps, compact fluorescent lamps, sodium and mercury high pressure lamps, and halogen metal lamps have been manufactured. Parallel to light source development, the disciplines of lighting science and illuminating engineering have been established by the use of conventional photometry and conventional illuminating design methods, which are based on the spectral luminous efficiency function $V(\lambda)$.

The $V(\lambda)$-function is valid for photopic vision in order to evaluate light sources from the point of view of illumination quality. In this process, quantities such as glare metrics, detection and identification probabilities, contrasts, luminance level and illuminance level, and illuminance uniformity have been developed in order to evaluate the illumination quality of light sources. These parameters have found their way to lighting and technological standards for the development of lighting products for international trade and lighting design. The use of $V(\lambda)$ is, however, misleading because it "represents only one of the possible responses of the retina of the eye to stimulation by electromagnetic radiation" [1], the response of the luminance channel with a spectral sensitivity limited to the central band of the visible spectrum around 555 nm, thus ignoring or underweighting rays of reddish and bluish wavelengths that are important to render or emphasize the colors of the colored objects in the lit environment.

With the appearance of modern triband fluorescent lamps, technological development has led to the necessity of defining a more color-related figure of merit: the color rendering index (CRI R_a) was introduced in 1965. It was based on the numeric evaluation of color differences and used test color samples to describe the color appearance change under a test light source in comparison to a reference illuminant of similar correlated color temperature (CCT). (More recently, the color rendering property has been called *color fidelity*.) The general CRI uses eight desaturated Munsell colors and the visually nonuniform $U^*V^*W^*$ color space and the aim was to optimize light source spectra so as to cause small color differences compared to a reference light source of the same CCT. But this color difference has to be computed independent of the direction of the

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color shift between the test light source and the reference light source mixing lightness, chroma, and hue shifts between them.

Although the definition and the calculation method of the CRI have been improved during the last three decades, color rendering has remained the only internationally recognized metric to evaluate the color quality of light sources and its deficiencies turned out to be relevant as more and more flexible light source spectra became available for the advanced illuminating systems of lighting practice.

Since 1994, with the development of white LED light sources based on very bright and efficient blue LED emission and novel phosphor-converting materials, lighting industry and users of lighting systems have obtained a new technological platform for varying the spectral power distribution of a certain light source with previously unknown flexibility. This new era of spectral design is characterized by previously unknown possibilities to optimize the wavelength of the blue LED chips between 405 and 465 nm and a huge variety of broadband phosphor systems between 510 nm (cyan-green) and 660 nm (deep red).

Since about 2000, several types of optimal LED light sources have been combined in modern, so-called multi-LED light engines with separately addressable and optimizable LED channels including white phosphor-converted LED channels, colored partially phosphor-converted LED channels as well as colored pure semiconductor LEDs in the most recent so-called hybrid multi-LED illuminating systems.

The result of the above-described LED revolution has been a plethora of different spectral power distributions with very different color quality properties (including not only the variation of color fidelity but also of color harmony, color vividness, color naturalness for a wide range of white tones between warm white and cool white) from the same, flexible LED light engine. But a system of unambiguous numeric metrics starting from the spectral power distribution of the light source and providing indices for the different color quality properties available for lighting practitioners (lighting engineers, developers of LED light sources and LED lighting systems, lighting architects, lighting designers, scientists and students, facility managers, and system planners) to systematically evaluate and consciously design the color quality properties of these illuminating spectra by considering different applications (e.g., shop lighting or museum lighting) and different users (e.g., according to region of origin or age) is currently missing.

But from recent literature (from the twenty first century) it is well known that it is the color quality of high-quality illumination that mainly determines its user acceptance. Accordingly, from about 2000 on, new models to describe color perception have arisen (including the CIECAM02 color appearance model and the CAM02-UCS color space) and this knowledge has been used to develop more advanced metrics and indices to describe the different aspects of color quality, including new ways to describe color fidelity and color preference.

With the above new possibilities of LED spectral design in mind, industry and research need a *system* of practically relevant color quality metrics in order to rank, optimize, and select the color semiconductor LED light sources and phosphor-converted LED light sources to be used in the future's LED light engines and LED illuminating systems (as well as other, conventional light sources such as fluorescent lamps or other discharge lamps). Light source spectra should be adapted to the actual lighting application such as shop lighting, high-quality lighting of colored museum objects in galleries, or hotel, conference hall, restaurant, and retail lighting.

In the last few years, new lighting applications of increasing importance have emerged and have given rise to human centric lighting (HCL) considerations concentrating on the various properties of the human users and their interpersonal variations – for example, for hospitals, schools, and homes for elderly light source users. In such applications, the comprehensive modeling of color quality needs to be co-optimized with dynamic lighting control and the modeling quantities of nonvisual effects (including the so-called circadian effect).

Lighting engineers need a new, single criterion parameter or spectral optimization target parameter (similar to the concept of Perceived Adequacy of Illumination, PAI [2]) constructed from multiple measures for general lighting practice. This parameter should combine the following items: illuminance level, a measure of chromatic visual performance, CCT dependence, nonvisual factors, and a generally usable color quality measure possibly consisting of a color fidelity index and another, usable measure that describes how *saturated* object colors appear under the given light source.

The task of color quality research is to develop color quality (color rendition) metrics that correlate well with the visual assessments of the users of lighting systems and the designers of light sources and luminaires regarding the criteria "color preference," "color naturalness," and "color vividness." If high color vividness, high color preference, or high color naturalness should be ensured by the light source illuminating the colored objects, then a saturation term must be added according to the current development of lighting technology (at the time of writing at 2016). Concerning CCT, this parameter (as an important parameter for HCL design) has a strong influence on the comfort, well-being, and visual performance of the light source users. Combined with different types of colored objects (e.g., bluish objects or reddish objects), the CCT of the light source also influences subjective color preference assessments.

If a usable model of lighting quality is at the lighting engineers' disposal, this will allow a more efficient, human centric optimization of the illuminating system fostering user acceptability and the turnover from the sales of such modern and acceptable lighting systems. This gain, in turn, leads to the possibility of further technological improvements to be described by more developed models and lighting quality metrics. This cyclic nature of technological development and the scientific development of modeling lighting and color quality aspects is illustrated in Figure 1.1, together with the factors of the optimization of illuminating systems.

As suggested in Figure 1.1, the technological development of light sources (especially the occurrence of high spectral flexibility, e.g., instead of fluorescent lamps with fixed spectra, the emergence of spectrally tunable multi-LED engines) results in the development of new concepts and models of lighting engineering and color science, enabling a better description of visual perception, color quality, and visual performance. These advanced models, in turn, allow for new possibilities of spectral design for better user acceptance, for example, by

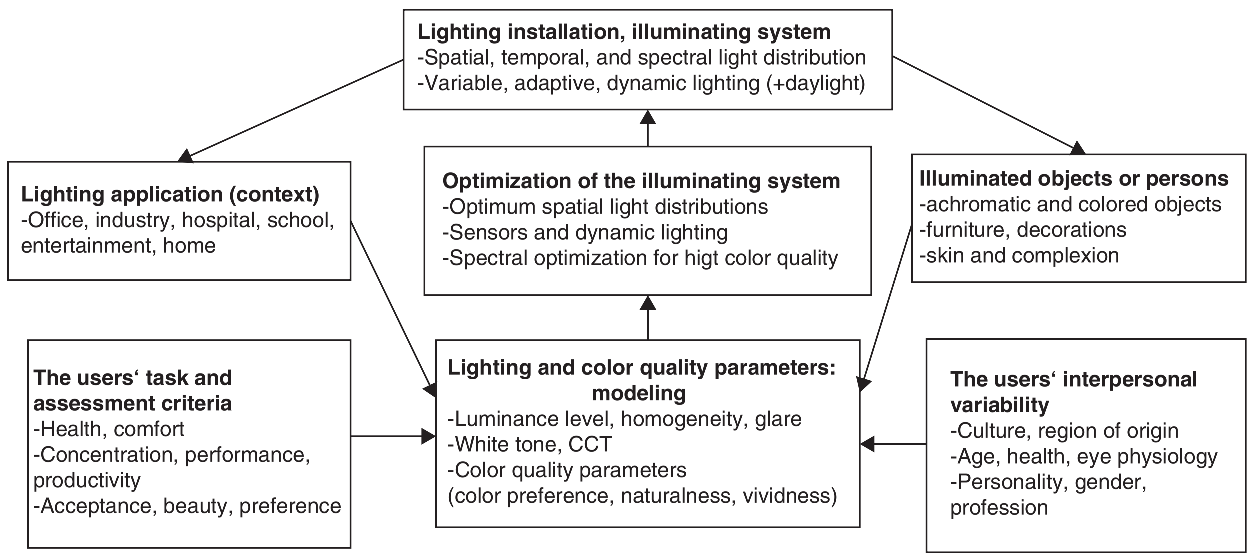

Figure 1.1 Development of illuminating system technology by the use of a comprehensive optimization scheme that considers both the users' human aspects (for human centric lighting) and the objective, technological features (application dependence and the type of illuminated objects).

ensuring an appropriate level of object oversaturation by the use of appropriate color quality metrics.

To help understand the concepts necessary to accomplish the comprehensive lighting quality optimization scheme of Figure 1.1, the present book will describe in the systematic view of its chapters, the following *visual* aspects of lighting and color quality evaluation and design:

1) Appreciation and preference of the *white tone* of the light source including metameric white light for different observers and field sizes.
2) *Illuminance level and visual clarity:* in order to ensure good visual performance at a workplace, illuminance levels of $> 500\,\mathrm{lx}$ are needed but visual clarity depends on CCT. Brilliantly lit scenes represent an important color quality effect, for example, in high-quality shop lighting.
3) *Color temperature:* the preference of white light in warm, neutral, or cool (daylight) tones between 2500 and 7000 K depends on the individual user's characteristics and also the type of colored objects being illuminated (e.g., bluish objects only).
4) *The so-called "color quality" (or "color rendition") properties:* besides the color fidelity (earlier it was called *color rendering*) aspect of color quality that describes the realness and truth of a lit arrangement of colored objects, other aspects of color quality like vividness (colorfulness), naturalness, attractiveness, preference, and object color discrimination ability come into play and need to be taken into account (depending on the lighting application) if the aim of the lighting engineer is a modern, highly qualitative lighting design.

In the last 10 years, the above aspects have been the subject of intensive discussions and several psychophysical color quality experiments in many lighting laboratories all over the world. The resulting new descriptor quantities (color quality metrics) have given rise, according to the above-mentioned cycle, to significant technological developments driven by the dynamic development of LED light source technology. Many of these psychophysical experiments indicated that the general color rendering index, CIE CRI R_a, in its currently standardized and recommended form, cannot account for the visual scaling results of users in terms of color preference, color naturalness, or color discrimination. Therefore, a systematic analysis of all color quality aspects is needed together with a set of specific and usable principles to *optimize* the spectral power distributions of LED lighting systems, correspondingly. According to the above intentions, the present book deals with the issues to be described below.

The human visual system's relevant properties will be summarized in Chapter 2 together with all important visual color phenomena to understand how color appearance comes into existence and behaves, including human eye physiology, chromatic (opponent) channels and the color attributes lightness, brightness, colorfulness, chroma, and hue. Subjective aspects of color quality and their objective descriptor quantities (naturalness, preference, color gamut, color vividness) will also be described in Chapter 2 together with cognitive color effects such as color memory and color semantics. Cognitive color aspects are relevant to developing decision criteria in terms of limits of continuous lighting quality variables or color quality indices for lighting practice (e.g., limits of an index to distinguish between "acceptable"/"not acceptable"; or among "excellent," "moderate," or "bad" color quality).

The issues of white lighting, whiteness perception, white tone acceptance, and white tone preference will be dealt with in detail in Chapter 3. The reason is that the white point (white tone) of the light source is an important visual prerequisite to ensure good color quality in a lit environment with arrangements of colored objects. The interaction between light source spectral power distributions and the spectral reflectance of colored objects causes color appearance distortions in color space in comparison to the most natural light source for human beings, that is, daylight. To quantify these distortions affecting color discrimination and color gamut properties, different sets of colored objects from the real world (skin tones, flowers, paint colors, etc.) have been analyzed and grouped after their spectral reflectance in a systematic manner in Chapter 4.

A detailed study of scientific literature will summarize the main tendencies of visual experiments on color quality including the observers' scaling results and their correlation with existing color quality metrics. The aim of this part of the book (Chapter 5: literature review) is to demonstrate the nature and the importance of color quality issues for lighting practitioners by the brief presentation of these experiments (research questions, hypotheses, questionnaires, light sources, colored objects, and results) in a usable way for lighting practitioners.

Research questions include, for example, which figure of merit should be the second color quality metric besides the color fidelity metric if the perceived color quality of a lit scene could be described by the aid of two-color quality metrics. A systematic characterization of all color quality metrics discussed in recent literature (metrics of color fidelity, color gamut, color preference, color naturalness, and color memory) and the correlations among the different color quality metrics (including color preference and naturalness metrics as functions of two-metrics combinations) will be elaborated in Chapter 6.

In the analyzed literature, several pieces of missing information have been identified by the authors of the present book. Therefore, a series of own visual color quality experiments were carried out (at the Laboratory of Lighting Technology of the authors and other coworkers at the same laboratory) with different LEDs and other light sources at different CCTs and object saturation levels. These results will be presented in a systematic way in Chapter 7 with the final aim of establishing a novel color quality metric and finding a relevant semantic interpretation of the acceptable value ranges for this metric. This is essential to supply lighting practitioners with a concrete, numeric guidance to optimize their light sources, possibly the multi-LED light engines of the future.

The visual experiments on color quality presented in Chapter 7 include studies on the role of the illuminance level above which good color quality comes into play, brightness matching in a comparative study between different, metameric light sources, the effect of the chromaticity (white tone) of the light source and the effect of the changing relative spectral power distribution of the light source that causes the interaction between the emission spectra and the spectral reflectance of the illuminate objects, and the visual effects of changing color quality in the user's human visual system. Results from color preference experiments at different color temperatures (2700–6500 K) including white points at different chromaticities on the Planckian locus (and also below and above it, with different spectral power distributions) will be described in Chapter 7.

In our color quality experiments described in Chapter 7, different contexts such as beauty product lighting (skin tones and cosmetics) and food (grocery product) lighting have been investigated by selecting a set of representative colored objects for the above-mentioned applications (e.g., makeups or fruits). Some of the experiments were designed to find out the critical amount of chroma enhancement (ΔC^*) at which color preference or naturalness are rated to be maximal and above which these two subjective attributes are rated to be "no more acceptable." Experiments have been performed partially in a viewing booth but also in a real experimental room with three-dimensional immersion, observation, and visual color quality assessment.

Using the current color quality metrics obtained from literature and also the novel color quality metrics derived from the own experiments, a systematic and detailed guidance including workflow diagrams will be provided for the lighting practitioner about how to design and optimize the LED light engine's spectra by selecting different blue chips, colored semiconductor LEDs, and phosphor systems in Chapter 8. The aim of Chapter 8 is to help design such LED spectra (as a result of a comprehensive spectral optimization) that exhibit the best compromise between color fidelity, colorfulness, and color preference including the effects of long-term color memory, color discrimination, and the avoidance of unacceptable color gamut distortions.

By the use of all-inclusive, advanced LED modeling, color quality for different lighting applications can be co-optimized with HCL aspects including circadian optimization. This will be shown in Chapter 9 of the book. Finally, Chapter 10 recapitulates the lessons learnt from the book for the practice of lighting engineering including Figure 10.1 summarizing all color quality aspects and their optimization. As these spectral design and color quality optimization principles are not LED specific, they can also be applied to any light source including conventional (e.g., fluorescent lamps) or the future's OLED-based light engines.

According to the above-described aims and content, Figure 1.2 summarizes the chapter structure of the book.

As can be seen from Figure 1.2, the introduction, the foundations, and the conclusions are located at the first (upper) level of the structure. White point issues, the prerequisite of successful color quality design, constitute an individual level, the next intermediate one. After ensuring a correct white point, the block of four chapters (within the dashed line frame) dealing with color quality experiments and color quality metrics (including the most important issue of the colored objects to be illuminated by the light source) follow. Based on this knowledge, it is possible to carry out the spectral optimization of the light source, the

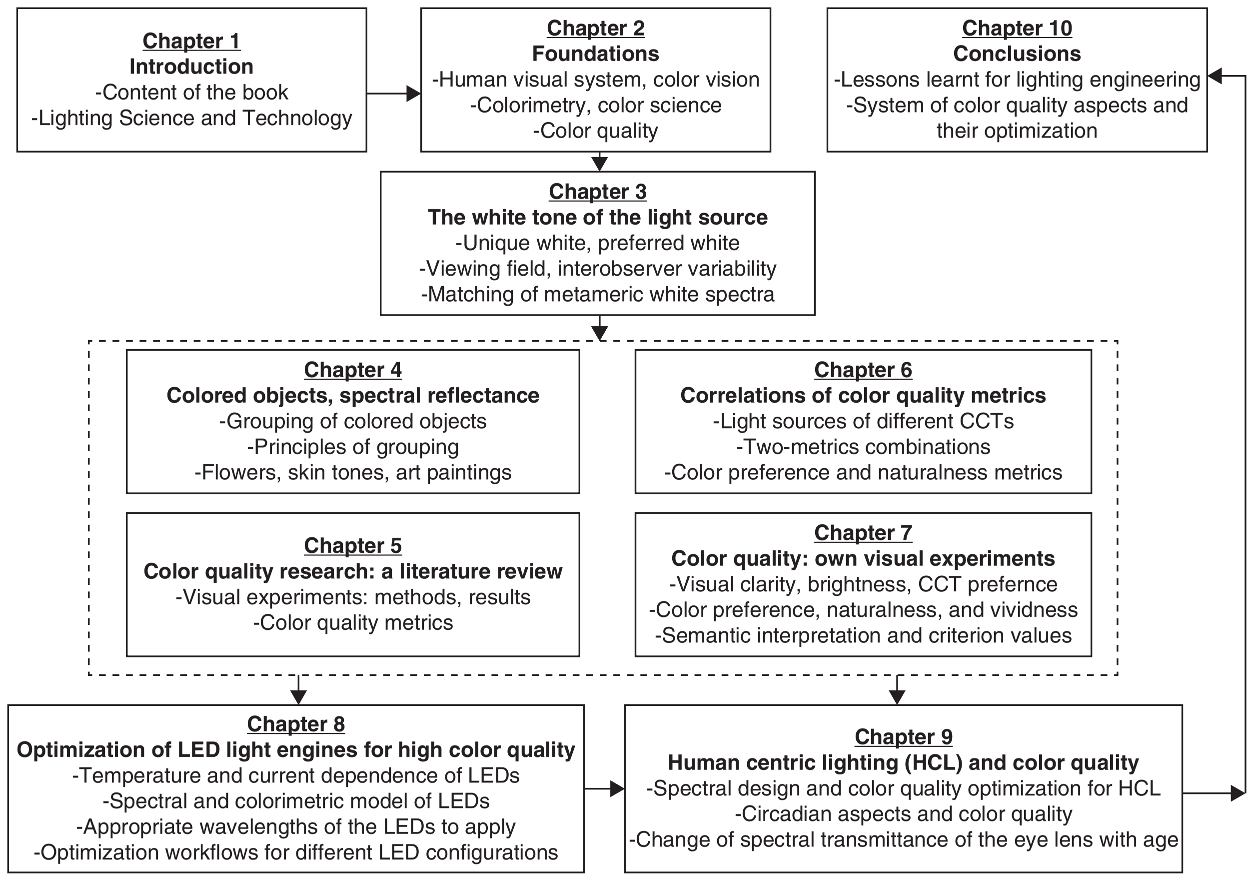

Figure 1.2 Chapter structure of the book.

final aim of the present book. The corresponding two chapters are situated at the lowest level of Figure 1.2, with an arrow pointing toward the conclusions, located, in turn, at the upper level of the book's framework.

References

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2 Cuttle, K. (2010) Opinion: lighting criteria for the future. *Light. Res. Technol.*, **42**, 270.