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Human Centric Integrative Lighting

Technology, Perception, Non-Visual Effects

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Preface

Since the introduction of LED technology at the turn of the century and the discovery of a new light-sensitive receptor, whose signals play a key role in the control of human biorhythms, there has been a new dynamic in colour and light quality research, coupled with intensive research in the fields of neurobiology, sleep research, psychology, human medicine and occupational science, with the aim of qualitatively and quantitatively exploring the relationship between radiation properties and mechanisms of action in the brain as well as in physical organs.

Based on the conviction that such valuable scientific findings, which will certainly continue to be collected over the next few years, should already be implemented in lighting design, lighting product development, and lighting planning, the authors saw the need to combine and bundle these scientific findings with technological and systems engineering advances, such as the Internet of Things, networking of communication systems, and sensor systems. This book is aimed at scientists, lighting designers, lighting engineers, psychologists, engineers, as well as students.

The first German language book was written in an unexpectedly difficult time with the COVID-19 pandemic in winter 2020–2021. The present English language book is an extended and updated version of the German one written in the not-less-difficult year 2022. The authors would like to thank the scientific staff of the Technical University of Darmstadt, especially S. Beck, J. Klabes, Dr. S. Babilon, and B. Zandi for the literature collection. The authors would like to thank the research assistants S. Klir and S. Benkner, whose lecture slides on *Smart Lighting* formed part of the content of Chapter 11 for the students of lighting technology. The authors would like to thank W. Truong, who is doing his doctorate at the TU Darmstadt at this time, for jointly developing the concepts of measuring circadian-effective metrics and for the joint publication with the main author of this book on the health of early-shift workers, the results of which were included in a section of this book.

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1

Introduction and Motivations

1.1 Introduction: A Historical Review. Current Issues

The International Commission on Illumination (CIE) defined the 2° standard colour matching functions in September 1931, more than 90 years before the publication of this book: the so-called $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ functions for visual colour matching with a visual field of view of 1–4°. This made it possible to calculate the tristimulus values and chromaticity coordinates for any colour stimulus of any spectral composition in the visible wavelength range, to characterise *perceived colours* and communicate them in scientific and industrial processes. In addition, from the end of the nineteenth century until today, the following steps of development have taken place in lighting technology:

(a) *In lighting technology and photometry*: from the end of the nineteenth century until around the 1980s, some parts of the world experienced a steadily growing development of the industrialisation process (e.g. mechanical engineering, shipbuilding, electrical engineering, and construction), so that research in lighting technology concentrated on formulating the requirements for workplaces in offices and manufacturing on the basis of physiological visual performance such as contrast perception ability, visual acuity, reading speed, or error rate of the work performed, using the parameters *illuminance* (in lux) or *luminance* (in $\mathrm{cd\,m^{-2}}$) as a basis. The results of research in this field up to the end of the twentieth century formed the basis for today's international and national lighting standards [1–3].

(b) *In light source technology*: from 1879 to 1999, there were several important developmental steps from incandescent lamps to high-pressure discharge lamps, halogen incandescent lamps, three-band fluorescent lamps, and compact fluorescent lamps (see Table 1.1). From 1994 to the present day, light source technology has undergone enormous progress with the new development of high-power LEDs. The luminous efficacy of white LEDs exceeds the values of commonly used discharge lamps (e.g. T5 lamps, Cosmopolis lamps, and HMI lamps). The high luminous efficacy of the LEDs, rated according to the $V(\lambda)$-function for daytime vision, contributes positively to the worldwide effort to save energy and protect the environment.

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Table 1.1 Major milestones in the development of light source technology.

Year	Contents
1854	Goebel: Light bulb with bamboo fibre
1879	Edison: Incandescent lamp with carbon filament
1900	Cooper, Hewitt: Patent on mercury vapour lamp
1906	Introduction of the tungsten metal filament lamp with nitrogen filling
1934	Introduction of the low-pressure discharge lamp with phosphors
1959–1960	Introduction of the tungsten halogen lamp
1971	Fluorescent lamps with a three-band concept
1980	Introduction of the CFL-i (energy-saving) lamp
1994	White LED based on InGaN material

Source: TU Darmstadt.

(c) *In CIE – colorimetry*: the history of CIE – colorimetry is characterised by the constant efforts to define perceptual colour attributes (brightness, lightness, hue, chroma, and saturation) and to arrange them in a perceptually equidistant colour space. If these perceptually equidistant colour spaces are created, the colour differences between different colours can be calculated there and used for industrial quality control. One benefit of accurate colour difference calculation is the colour rendering index. This task was carried out at several levels of knowledge over the last decades (see Table 1.2 as well as [6, 7]). The research results of colour science have been used in the colour industry (display technology, film technology, printing technology, and textile industry), and more intensively since about 2010 in lighting technology and light source technology (LED, OLED).

Since the beginning of the twenty-first century, some development trends relevant to lighting technology have intensified as follows:

- Societies in large parts of the world (North America, Europe, China, Japan, and South-East Asia) have been oriented towards information technology. The way of working, the work processes (day and night rhythms), as well as the work equipment (monitors, data, and display devices), have reached a new quality. In addition to quality features such as illuminance or uniformity and glare, other discussions about light and health, well-being during office work, stress reduction, and increased concentration through lighting have been added.
- The previous light source technologies had the decisive disadvantage that the spectrum and colour of the lamps could only be varied to a small extent. Today's high-power and mid-power LEDs with their high luminous efficacies and with a few advantages such as dimmability, controllability, and integrability also have the great advantage that they can be formed from coloured and white LEDs into a *lighting system* of variable spectral composition (chromaticity, colour temperature). The *dynamic light* formed in this way enhances the colour

Table 1.2 Major milestones in the development of CIE colorimetry.

Year	Contents
Year	Contents
1931	Definition of the 2° – standard colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$
1960	Definition of the UCS diagram (*Uniform Colour Scale*)
1964	Definition of the CIE 1964 ($U^*V^*W^*$) colour space
1964	Definition of the colour matching functions $\overline{x_{10}}(\lambda)$, $\overline{y_{10}}(\lambda)$, and $\overline{z_{10}}(\lambda)$ for 10° field of view
1976	Definition of the 2 colour spaces CIE $L^*a^*b^*$ (or CIELAB) and CIE $L^*u^*v^*$ (or CIELUV)
2004	CIE Publication: a colour appearance model for colour management systems: CIECAM02, Publication No. 159 (Vienna: Central Bureau of the CIE, 2004) [4]
2006	Definition of the CAM02-UCS colour space based on the colour appearance model CIECAM02 [5]

Source: TU Darmstadt.

and light quality of *interior lighting*, for the evaluation of which non-visual, colour-technological, and photometric approaches are now increasingly expected to come into play.

This makes it clear that the three important components of lighting technology (photometry, colorimetry, and light source technology) should be used much more intensively and closely together in current and future research for the evaluation of the colour and light quality of workplaces and in the lighting industry for the development of new lighting products. In addition – in the period between 2000 and today – the *non-visual effects of light* have been investigated by various international research groups. Despite numerous efforts in the experimental field, these findings are only partially implemented in the practice of lighting product development and lighting design in a comprehensible and interpretable way.

According to the above considerations, the authors elaborated on the present book to answer the following questions:

1. How do the visual and non-visual mechanisms in the brain and in other physiological areas function during night-time hours and during the day?
2. Which influencing parameters and which initial parameters with which metrics in the physiological and psychological – emotional area are decisive for the description of the subjective and objective characteristics of health, well-being, and work performance of human beings? To what extent can scientists and product developers control these parameters – according to the findings to date? Where is there still a need for research?
3. What findings are known so far about the effects of light at night? The focus will be on the relationship between irradiation and its effects on humans.
4. What findings have been made so far for the time during the day? Can some of them be scientifically established to the extent that the long-awaited

recommendation values for lighting designs as well as for the development of intelligent lighting products can be put up for discussion?

5. How to record, measure, and interpret the visual and non-visual parameters of lighting with daylight and electric light? Such measurements should be carried out not only with laboratory measuring devices but also with portable, inexpensive, and accurate measuring units to plausibly record the effects of light in alternating and dynamically changing workplaces and places where people stay.

Derived from these important questions, this book (except for this chapter) is divided into the thematic blocks summarised in Figure 1.1.

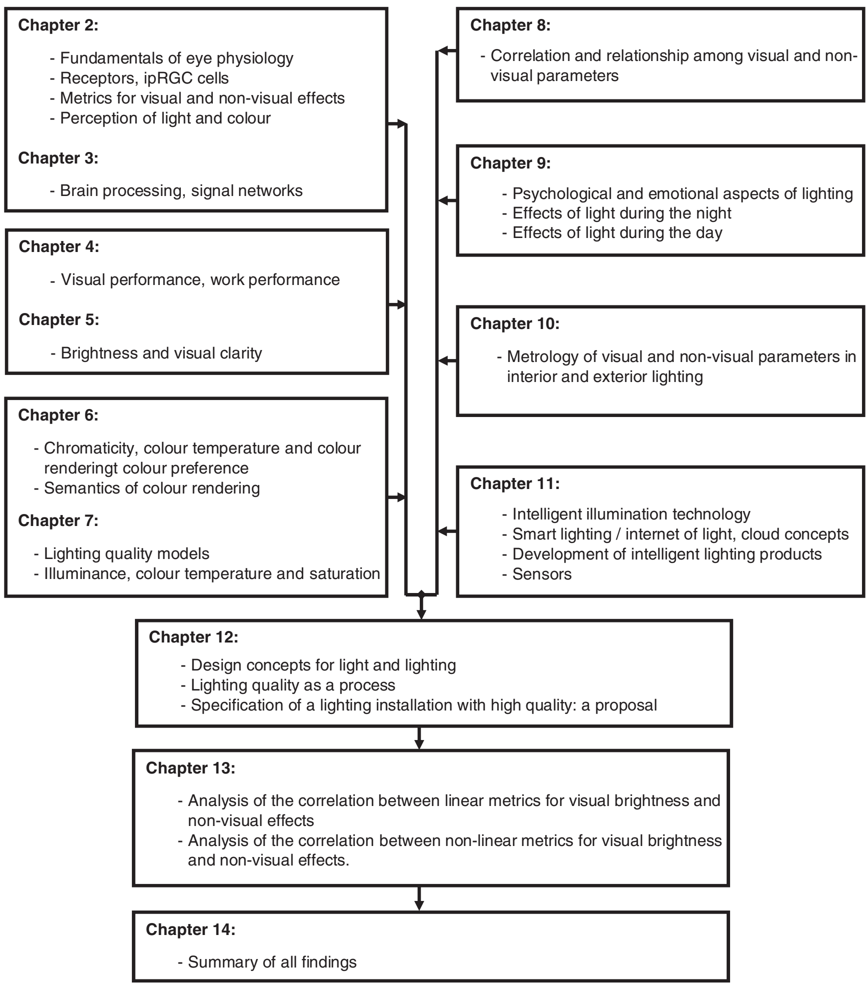

Figure 1.1 Contents of the present book. Source: TU Darmstadt.

References

1 DIN EN 12464 (2011). Licht und Beleuchtung, Teil 1: Beleuchtung von Arbeitsstätten in Innenräumen (Light and Lighting, Part 1: Lighting of Indoor Workplaces), German version EN 12464-1:2021). Beuth, Berlin.

2 Schmits, P.W. (2002). Innenraumbeleuchtung – Tendenzen und Reaktionen, Tagung Licht (Interior Lighting – Trends and Reactions, Conference Light), Maastricht, 34–47.

3 CIE (1981). An analytical model for describing the influence of lighting parameters upon visual performance. CIE Publication No. 19/2.1.

4 Commission Internationale de l'Eclairage (2004). A colour appearance model for color management systems: CIECAM02 CIE TC8-01. Technical Report. CIE Publication No. 159. https://cie.co.at/publications/colour-appearance-model-colour-management-systems-ciecam02.

5 Luo, M.R., Cui, G., and Li, C. (2006). Uniform colour spaces based on CIECAM02 colour appearance model. *Color Res. Appl.* 31: 320–330.

6 CIE (2004). Colorimetry. C. I. E. "Report No: CIE Pub No 15." *Vienna: CIE Central Bureau*. https://cie.co.at/publications/colorimetry-3rd-edition.

7 Commission Internationale de l'Eclairage (1995). Method of measuring and specifying colour rendering properties of light sources. Technical Report. CIE 13.3-1995.

2

Fundamentals of Lighting Technology – Basic Visual and Non-visual Aspects

This chapter summarises the basics of modern lighting technology (including colorimetry), with special emphasis on the connection between the visual and non-visual components of the human visual system to understand the most important aspects of Human-Centric Lighting. Section 2.1 deals with the structure of the eye and the retina to illustrate the mechanisms of visual and non-visual signal processing. Section 2.2 presents the basic photometric and colorimetric parameters and the modelling of colour appearance. The basics of non-visual aspects such as melatonin suppression at night, their modelling as well as the spectral activity functions and the metrics for the consideration of non-visual influencing variables are discussed in Section 2.3.

2.1 The Human Visual System. Visual and Non-visual Signal Processing

To understand the basic concepts of Human-Centric Lighting, the structure, and functioning of the human eye, including the retina (the '*biological image receptor*'), should first be understood. Figure 2.1 illustrates the structure of the human eye.

As can be seen in Figure 2.1, the human eye is an ellipsoid with an average length of about 26 mm and a diameter of about 24 mm. The eye is rotated in all directions with the help of eye muscles. The outer layer is called the sclera. The sclera continues in front as a transparent cornea. The choroid supplies the retina with oxygen and nourishment. The retina is the photoreceptive layer of the eye, containing both the photoreceptors and those cells that pre-process the signals from the photoreceptors through neuronal connections (ganglion cells, amacrine and bipolar cells, and horizontal cells), see Figure 2.2.

The vitreous body is responsible for maintaining the ellipsoidal shape of the eye. It consists of a suspension of water (98%) and hyaluronic acid (2%). The optical system of the human eye is a complex, slightly decentered lens system that projects an inverted and reduced image of the surroundings onto the retina. The cornea, anterior chamber, and iris form the front part of this optical system, followed by the posterior chamber and the biconvex lens of the eye. The lens is held in place by the zonula fibres.

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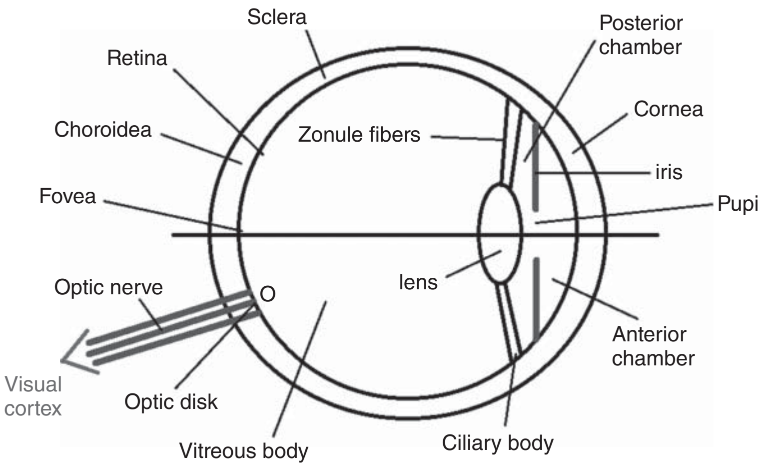

Figure 2.1 Structure of the human eye. O (optic disk): blind spot – the point where the optic nerve crosses the eye and transmits the pre-processed neuronal signals from the retina towards the visual cortex. Source: Reproduced with permission from Wiley-VCH [1].

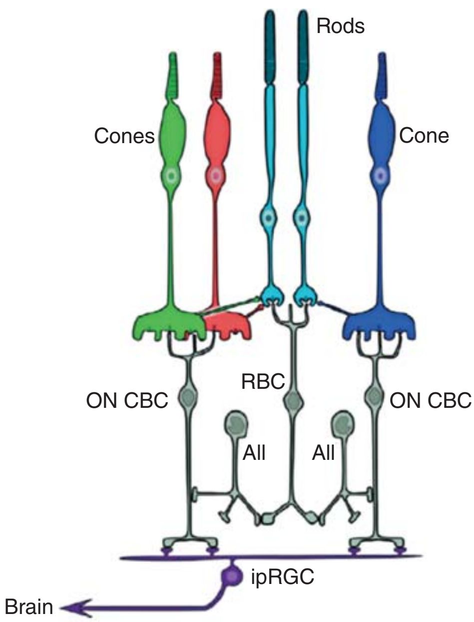

Figure 2.2 Schematic representation of the retinal circuits in humans. Photoreceptor connections via the cone bipolar cells (ON CBCs), amacrine cells (AII), and rod bipolar cells (RBCs), ipRGC: intrinsically photosensitive retinal ganglion cell with the pigment melanopsin. Source: Reproduced from Lucas et al. [2] with permission from Trends in Neurosciences.

By tensing the ciliary muscles, the focal length of the lens can be changed. The angle of vision intersects the retina at the *fovea centralis*, the site of the sharpest vision. The most important optical parameters of the components of the ocular medium include the refractive indices (which typically range from 1.33 to 1.43) and the spectral transmission factors. All parameters vary considerably in different individuals and are subject to significant changes with age. In particular, accommodation, visual acuity, and pupillary responses are impaired with age. The spectral transmission of the ocular media decreases significantly with age, especially for short wavelengths (see Section 12.6.1 for details).

After light rays reach the retina, they pass through the retinal layers and, in the central retina, also through the so-called *macula lutea* (a yellow pigment layer that protects the central retina) before reaching the photoreceptors, which are located on the back of the retina. The blind spot is the location (labelled O in Figures 2.1 and 2.3) where the optic nerve passes through the eye. The retina is blind at the O spot because the density of rods and cones is zero there.

The retina (a layer with an average thickness of 250 μm) is part of the optical system of the eye and with its photoreceptor structure also part of the visual brain. The retina contains a complex cell layer with two types of photoreceptors, rods and cones. Both the rod and cone receptors are connected to the nerve fibres of the optic nerve via a complex network of the pre-processing cells mentioned above, which calculates further neuronal signals from the receptor signals. The retina contains about 6.5 million cones and 110–125 million rods, while the number of nerve fibres is about 1 million. The density of the rods and cones varies and depends on the position of the retina (see Figure 2.3).

There is also a third type of photosensitive cell, the so-called ipRGC (*intrinsic photosensitive retinal ganglion cell*, which contains the pigment melanopsin), which is responsible for regulating the circadian rhythm, see Section 2.3. Figure 10.3 illustrates the distribution of ipRGCs on the retina. According to the illustration

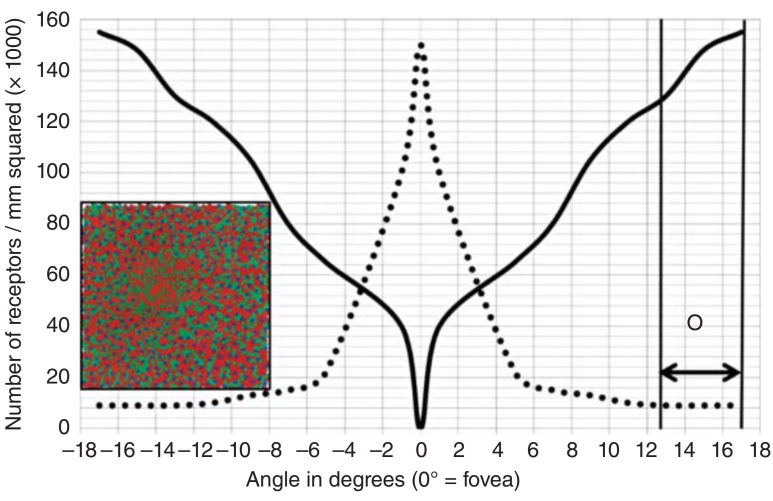

Figure 2.3 Rod density (solid curve) and cone density (dots) as a function of retinal position (abscissa: in degrees) drawn according to Oesterberg's data [3]. O: Blind spot; inset diagram: cone mosaic of the rod-free inner fovea with an extension of approx. 1.25 °, i.e. approx. 350 μm. Red dots: long-wavelength-sensitive cone photoreceptors (L-cones). Green dots: medium-wavelength-sensitive cones (M-cones). Blue dots: short-wavelength sensitive cones (S-cones). Source: Reproduced with permission from Wiley-VCH [1], except for the inset diagram. Source of inset diagram: Figure 1.1 from Sharpe, L. T., Stockman, A., Jägle, H., & Nathans, J. (1999), Opsin genes, cone photopigments, colour vision, and colourblindness, pp. 3–51 in [4]. Reproduced with permission from Cambridge University Press.

in Figure 2.2, which reflects current knowledge of neurophysiology, the signals from the cones and rods are also transmitted not only to the 'normal' ganglion cells but also to the *photosensitive* ganglion cells ipRGCs. The signals of the ipRGCs in turn flow into both *visual* and *non-visual signal processing channels*, whereby the visual and non-visual channels are strongly interconnected in the human brain, see Figure 2.2, Figure 10.6 as well as Chapter 3 of this book.

Due to the photopigment melanopsin, the ipRGCs (which represent only approx. 1–5% of the retinal ganglion cells [2]) are *directly sensitive to* light and can therefore also respond to light in isolation from the rest of the retina [2]. They are connected *in situ* to the rod and cone photoreceptors via the retinal circuits, see Figure 2.2. As a result, the ipRGC signal can be influenced by both intrinsic melanopsin photoreception and extrinsic rod and cone signals [2], see also Figure 2.13. Figure 2.3 shows rod and cone density as a function of retinal position, while the inset diagram of Figure 2.3 shows the long, medium, short (LMS) cone mosaic (which is similar to a digital camera) of the rod-free inner fovea.

As can be seen in Figure 2.3, there are no receptors at the site of the blind spot because the optic nerve exits the eye at this point (labelled O). The fovea is in the centre of the *macula lutea* region. A characteristic value to show the diameter of the fovea is 1.5 mm, which corresponds to a visual angle of about 5°. The fovea is responsible for the best visual acuity due to the high cone receptor density, see the cone density maximum in Figure 2.3. Outside the fovea, cone diameter increases to about 4.5 μm, cone density decreases, and rod density (diameter of rods: 2 μm) increases to reach a rod density maximum at about 18–20°.

Rods are responsible for night vision, also called *scotopic vision*, at a luminance lower than 0.001 cd m^{-2}. Rods are more sensitive than cones, but they become completely inactive above about 60–100 cd m^{-2}. Cones are responsible for daytime vision or *photopic vision* (at a luminance of about 10 cd m^{-2} or higher). The transitional area between scotopic (rod) vision and photopic (cone) vision is called the twilight or *mesopic area*, where both the rods and cones are active. Acceptable *colour quality* (see Section 6.7) can only be expected in the photopic range.

In addition to pupil contraction, the transition between rod and cone vision in the mesopic area represents a second important adaptation mechanism of the human visual system to changing light conditions (so-called *adaptation*). There is a third adaptation mechanism, the *gain control* of the receptor signals.

Photoreceptors contain pigments (opsins, certain types of proteins) that change their structure when they absorb photons and generate neural signals that are pre-processed by the horizontal, amacrine, bipolar, and ganglion cells of the retina to provide neural signals for later processing through the various visual and non-visual channels of the visual system. There are three types of cones (see the cones labelled red, green, and blue in Figure 2.2 as well as Figure 2.3) with pigments of different spectral sensitivity, the so-called L- (long-wave sensitive), M- (medium-wave sensitive) and S-cone (short-wave sensitive) cones. L-, M-, and S-signals for the perception of homogeneous colour fields and for coloured spatial structures (e.g. a red-purple rose with fine colour shadings).