TECHNICAL REPORT

ISO/TR 9241-610

First edition
2022-10

Ergonomics of human-system interaction —

Part 610:
Impact of light and lighting on users of interactive systems

Ergonomie de l'intéraction homme-système —

Partie 610: Impact de la lumière et de l'éclairage sur les utilisateurs de systèmes interactifs

Reference number
ISO/TR 9241-610:2022(E)

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Foreword

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This document was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 4, *Ergonomics of human-system interaction*.

A list of all parts in the ISO 9241 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

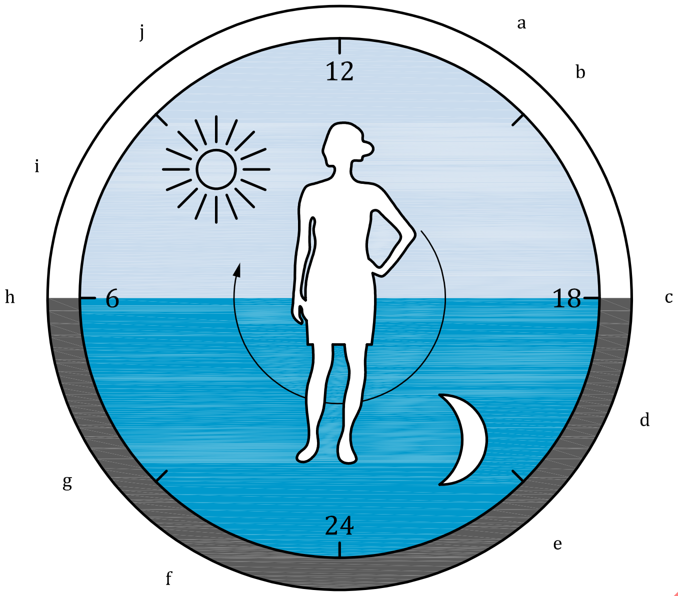
ISO 9241-6 was developed to give guidance on the work environment, including lighting to support vision. Since the discovery of a third sensor in the human eye, ample research has demonstrated that ocular light exposure, besides supporting visual perception, influences many aspects of human physiology and behaviour, including circadian rhythms, alertness and sleep, mood, neuroendocrine and cognitive function.

Users of interactive systems that mostly incorporate at least one visual display are likely to be affected both by the light generated by their work equipment and by lighting as an environmental factor. New scientific evidence establishes the fact that light exposure by the work equipment can reach levels of the same magnitude as ambient lighting[1].

Lighting has been defined as the use of light for making things visible since the International Lighting Vocabulary of the CIE was published in 1938.[2] In the 4th edition published in 1987, its definition was "application of light to scene, objects or their surroundings so that they may be seen".[3] The role of lighting has been thoroughly reconsidered in the light of the scientific evidence in the last two decades so that the internationally acknowledged definition was changed in the last version.[4] The definition now reads "application of light to a scene, objects, or their surroundings" (E-ilv 17-29-001).

"… so that they may be seen" has been dropped because of the new, additional role of light. It is required by scientists as well as practitioners that the design of lighting be performed in consideration of health effects. Currently, "Light and Health" has become a slogan pointing to the new goal. This can be characterized as considering and supporting human circadian rhythms governed by the circadian clock. Although such rhythms have been studied for decades, the discovery of molecular mechanisms controlling them was awarded the Nobel Prize for Medicine in 2017. The illustration by the Nobel Prize Committee can also serve as a short description for this document: "This clock [circadian] helps to regulate sleep patterns, feeding behaviour, hormone release, blood pressure and body temperature.

A large proportion of our genes are regulated by the clock." (Figure 1)[5].



a Best coordination.

b Fastest reaction times.

c Highest body temperature.

d Highest blood pressure.

e Melatonin secretion.

f Deep sleep.

g Lowest body temperature.

h Cortisol release.

i Fastest increase in blood pressure.

j High alertness.

SOURCE The Nobel Committee for Physiology or Medicine. 'The 2017 Nobel Prize in Physiology or Medicine' press release[5]. Reproduced with permission of the copyright holder.

Figure 1 — The circadian clock (also known as the circadian oscillator) and its impacts on our physiology

It should be noted that the first Nobel Prize in Medicine was awarded in 1903 to Niels Ryberg Finsen for his contribution to the treatment of diseases with optical radiation.

The new role of light has been considered not only by scientists but also by various institutions that deal with ergonomics, work organization, safety and health. Due to a high variety of sources that can be of relevance, this document has been prepared on the basis of documents representing the published outcome of expert evaluations of literature with a good general agreement, although published with a time difference of more than a decade. This document has been prepared after studying References [1] and [6] to [11] and the literature reviewed by their respective authors.

Ergonomics of human-system interaction —

Part 610: Impact of light and lighting on users of interactive systems

1 Scope

This document provides users of interactive systems with a summary of the existing knowledge about ergonomics considerations for the influence of artificial (electric) and natural lighting of environments on humans other than on vision, with a focus on non-image-forming effects.

The document can furthermore be used as guidance on the specification of use environments in consideration of non-visual effects of lighting, also called non-image-forming (NIF) functions.

Therapeutic use of light and optical radiation is not part of this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
correlated colour temperature
CCT
temperature of a black body (Planckian) radiator whose perceived colour most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions

[SOURCE: IEV 723-08-34]

3.2
chronobiology
field of biology pertaining to periodic rhythms that occur in living organisms in response to external stimuli such as photoperiod

3.3
chronotype
phase relationship of the circadian clocks to the zeitgeber

Note 1 to entry: A person's chronotype is the propensity for the individual to sleep at a particular time during a 24-h period.

3.4
circadian
biological process that displays an endogenous, entrainable oscillation of about 24 hours

3.6
circannual
biological process that displays oscillation of about a solar year

3.7
colour rendering
<of a light source> effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant

[SOURCE: E-ilv 17-22-107,[4] modified — Notes to entry removed.]

3.8
colour rendering index
CRI
R
measure of the degree to which the psychophysical colour of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation

[SOURCE: E-ilv 17-22-109,[4] modified — Notes to entry removed.]

3.9
cone
photoreceptor in the retina containing light-sensitive pigments capable of initiating the process of photopic vision

[SOURCE: E-ilv 17-22-002,[4] modified — Notes to entry removed.]

3.10
daylight
part of global solar radiation capable of causing a visual sensation

Note 1 to entry: This definition is used for the purposes of lighting engineering. In physics, daylight is solar radiation in the range of optical radiation.

[SOURCE: E-ilv 17-29-105,[4] modified — Notes to entry replaced.]

3.11
daylight factor
D
quotient of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution and the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded

[SOURCE: E-ilv 17-29-121,[4] modified — Notes to entry removed.]

3.12
intrinsically photosensitive retinal ganglion cell
iPRGC
cells in the human retina that are intrinsically photosensitive due to the presence of melanopsin, a light-sensitive protein

3.13
light at night
LAN
exposure to artificial light during the dark hours of the day

3.14
light
<physics> radiation within the spectral range of optical radiation

Note 1 to entry: This definition also covers the use of the term in most disciplines, e.g. medicine, chemistry, biology.

3.15
light
<lighting engineering> radiation within the spectral range of visible radiation

Note 1 to entry: Visible radiation is optical radiation capable of causing a visual sensation directly (see E-ilv 17-21-003[4]).

3.16
luminous colour
colour perceived to belong to an area that appears to be emitting light as a primary light source or that appears to be specularly reflecting such light

[SOURCE: E-ilv 17-22-045,[4] modified — Notes to entry removed.]

3.17
luminous intensity
I_v, I
density of luminous flux with respect to solid angle in a specified direction

$$I_v = \frac{d\Phi_v}{d\Omega}$$

where

Φ_v is the luminous flux emitted in a specified direction;

Ω is the solid angle containing that direction.

Note 1 to entry: Luminous intensity is measured by candela, which is one of the seven SI base units.

[SOURCE: E-ilv 17-21-045,[4] modified — Notes to entry revised.]

3.18
melatonin
hormone that is produced by the pineal gland

3.19
optical radiation
electromagnetic radiation at wavelengths between the region of transition to X-rays ($\lambda \approx 1$ nm) and the region of transition to radio waves ($\lambda \approx 1$ mm)

Note 1 to entry: The lower end of the range begins in some regulations and standards at 100 nm. The difference is irrelevant for this document because both $\lambda \approx 1$ nm and $\lambda \approx 100$ nm are in the range of UV-C radiation.

[SOURCE: E-ilv 17-21-002,[4] modified — Notes to entry revised.]

3.20
photopic
relating to or denoting vision in daylight or other bright light, believed to involve chiefly the cones of the retina

3.21
rod
photoreceptor in the retina containing a light-sensitive pigment capable of initiating the process of scotopic vision

[SOURCE: E-ilv 17-22-003,[4] modified — Notes to entry removed.]

3.22
spectrum
display or specification of the monochromatic components of the radiation considered

[SOURCE: E-ilv 17-21-015,[4] modified — Notes to entry removed.]

3.23
use environment
generic term for the physical environment where light and optical radiation is present or intentionally used

Note 1 to entry: In industrial areas, use environment is called work environment. Since the physical environment outside the working space is also effective for the items under consideration, the term use environment has been introduced for the purposes of the ISO 9241 series.

3.24
zeitgeber
environmental cue, such as a change in light or temperature, that entrains or synchronizes an organism's biological rhythms, usually naturally occurring and serving to entrain to the Earth's 24-h light/dark and 12-month cycles

Note 1 to entry: From the German "zeit" (time) and "geber" (giver).

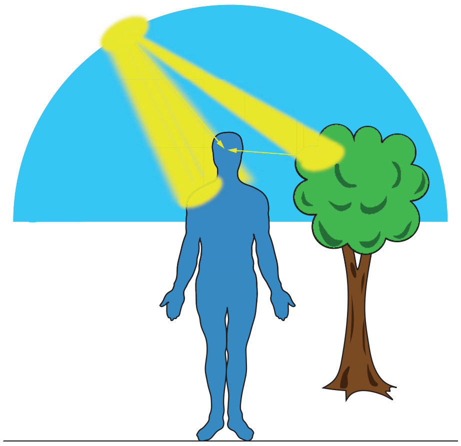
4 Light and lighting — more than just vision

4.1 How radiation impacts the human body

Radiation, in general, can generate effects in any material if absorbed by it. Radiation or parts of it reflected or transmitted do not cause any effect, for example a transparent material does not warm up independently from the level of energy passing through. Cells, tissues and organisms can be affected by two different categories of radiation, ionising and non-ionising. The distinction is based on the energy level of the radiated particles. Light, IR, UV and radio waves belong to non-ionising radiation.

NOTE Extraterrestrial UV radiation capable of ionising does not penetrate the atmosphere, whereas electric sources emitting similar wavelengths are only used for special purposes and are, therefore, not relevant for this document.

The relevant parts of the spectrum for this document are light (see Figure 3, Figure 4), (non-ionising) UV and IR. They can cause a variety of responses after entering the body through three pathways (Figure 2).[12]



Source Çakir, G. *Tageslichtnutzung und Sonnenschutzmaßnahmen an Büroarbeitsplätzen*.[13] Reproduced with permission of the copyright holder.

Figure 2 — Pathways for the solar radiation

A plethora of biological effects are caused by optical radiation hitting the skin and the eyes. Depending on the wavelength, energy can penetrate the skin to a different depth. While vision for which light is responsible is considered in most publications, generating vitamin D is of vital interest for human health, not only for the bones but also for the communication between cells (see also 4.5).

4.2 The role of light for life

Light[1)] is part of the radiant energy that fills the universe. Almost all life on Earth has evolved accompanied by light. No wonder that most living species have developed biological processes as a response to the natural light, the availability of which is governed by the rotation of the Earth and its motion around the sun.

Thus, light is central to the biological history of the world, both as a fuel for photosynthesis and as an environmental signal. As a fuel for photosynthesis light produces all green life from sea level up to the highest places where plants can survive, but also all tropical coral reefs deep down to where sunlight carries sufficient energy. As a signaller, light carries much of the information that enables life to adapt to its environment, and improved ability to receive that information is responsible for numerous evolutionary adaptations.

The importance of visible-light signalling for humans is demonstrated, for example, by the exquisiteness of the eye as an optical instrument; the large fraction (half) of the human brain devoted to visual signal processing; and our extreme dependence on visual technologies[14]. In fact, the human eye is not a sensor that conveys information from the environment to the brain like the ear; it is part of the brain.

At a very early stage of human history, artificial lighting was developed as one of the first human technologies. It expands the productive day into non-daylight hours and during the day it expands the productive space into the non-daylight areas of enclosed spaces. Bringing daylight into built space was one of the main objectives of architecture for thousands of years. Doing so, daylight was manipulated in different ways even when the “built” environment was a cave.

For the longest part of history, workrooms were built such that artificial lighting served as an auxiliary means to the main source, daylight. The availability of fluorescent light changed the architecture of buildings thoroughly, and it was believed that industrial work could be performed even completely without daylight. But the current notion is that “since the introduction of electric lighting, there has been inadequate light during the day inside buildings for a robust resetting of the human endogenous circadian rhythmicity, and too much light at night for a true dark to be detected; this results in circadian disruption and alters sleep/wake cycle, core body temperature, hormone regulation and release, and

1) Light in this sense is optical radiation.

patterns of gene expression throughout the body." [15] Although in the first half of the 20th century the light inside buildings was less adequate than now, fewer people spent fewer hours in such environments.

With electric lighting becoming ubiquitous, the daily pattern of the light/dark cycle which existed even in artificially lit interiors to a certain extent has disappeared or can be shifted to other parts of the 24-h day depending on working hours or personal preferences. However, it is well-known that the light/dark cycle incident on the retina regulates the timing of the human circadian system. Disruption of a regular, 24-h pattern of light and dark can significantly affect our health and well-being[16].

4.3 Non-visual effects of radiation

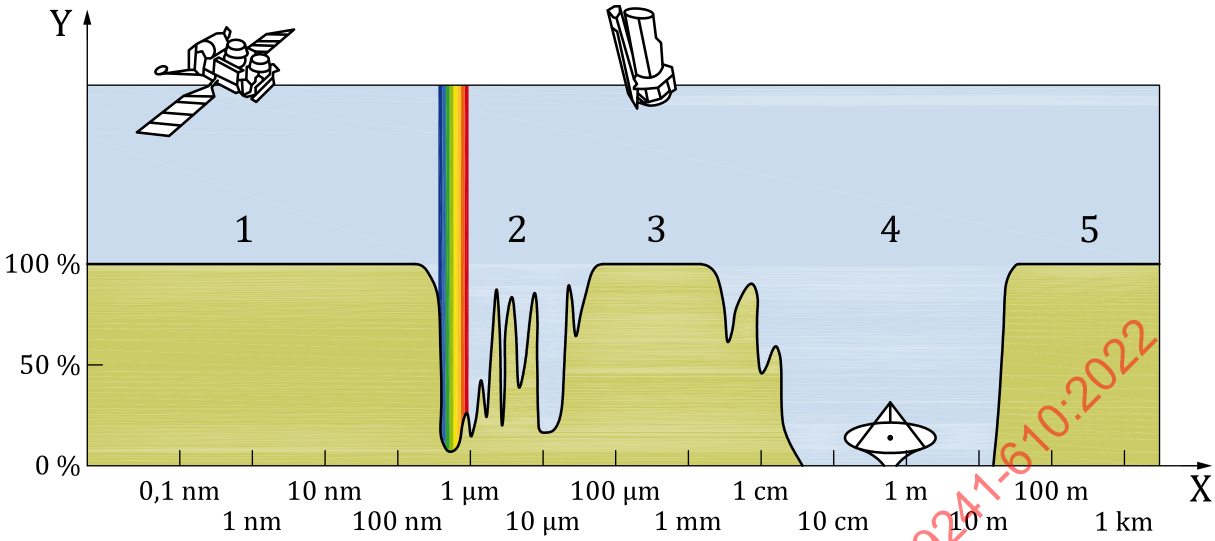
The solar energy received on the surface of the Earth is part of the radiant energy after being filtered by the atmosphere. The overall range of wavelengths measurable on Earth extends over a range of wavelengths from 10^{-16} m to 10^{5} m (electromagnetic spectrum). Only a limited range of wavelengths of radiation from 380 nm to 780 nm is considered light by definition in lighting engineering because these enable the eye to form images by exciting visual sensation, a process called vision. In contrast to these, some other effects of radiant energy are called "non-visual".

NOTE There is some confusion in the naming of effects caused by optical radiation other than vision. Since the 1920s, when disciplines dealing with the impact of "light" on humans became separated, various effects that did definitely not relate to vision were attributed to photobiology. Thus, some researchers used the phrase "biological effects" until it was acknowledged that also vision is biological. Before the discovery of the ipRGC in 2002, NIF effects of light were called "light effects"[17]. The term NIF effect (non-image-forming effect) was coined by Küller in 1983 to cover effects other than vision. But it is still possible to find expressions like "non-image-forming (NIF) biological effects of light" in scientific publications.

In many publications, effects mediated by melanopsin-containing or intrinsic photosensitive retinal ganglion cells in the eye are considered "non-visual". But the subject matter of Reference [7], "the eye-mediated non-image-forming effects of light", suggests that the "ability of optical radiation to stimulate each of the five photoreceptor types that can contribute to retina-mediated non-visual effects of light in humans". If only light in the definition of CIE can stimulate the photoreceptors in the eye to name "optical radiation" instead is at least confusing.

The effects considered in Reference [7] are limited to circadian effects without circannual effects. The question is whether circannual effects are not eye-mediated. Are they not non-visual? Currently, there is not even an agreement on how to spell non-visual.

To avoid further confusion, the word "non-visual" is used as an alternative to "NIF" following the rationale of Reference [18]. If circadian effects in the sense of eye-mediated events are addressed, this will be indicated.



Key

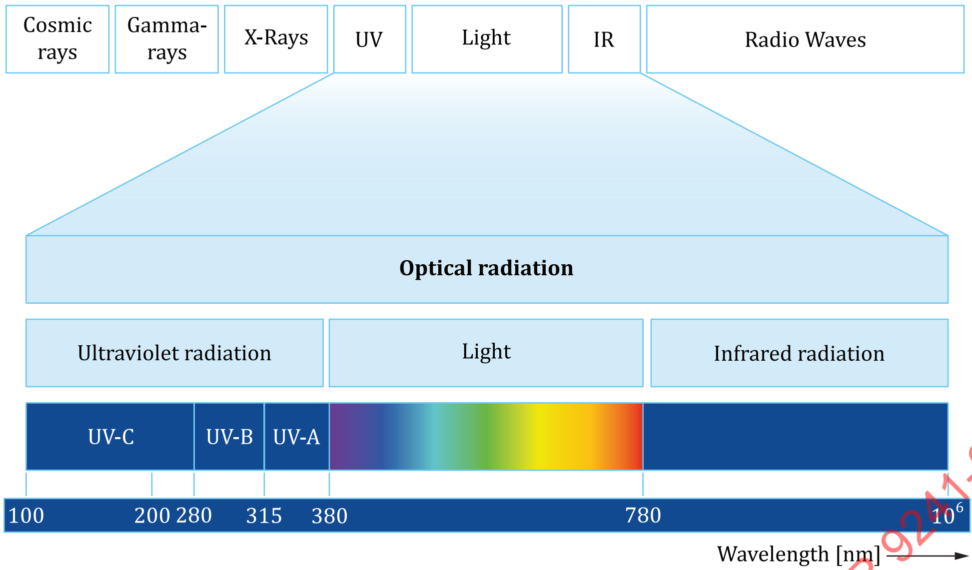
1 gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space)
2 visible light observable from Earth, with some atmospheric distortion
3 most of the infrared spectrum absorbed by atmospheric gases (best observed from space)
4 radio waves observable from Earth
5 long-wavelength radio waves blocked

NOTE The original legend of the figure uses the term transmittance instead of absorption.

SOURCE NASA[19], open source.

Figure 3 — Rough plot of Earth's atmospheric absorption (or opacity) to various wavelengths of electromagnetic radiation, including visible light

Optical radiation generally refers to all radiation that can be measured using certain techniques and equipment (mirrors, lenses, filters, diffraction gratings, prisms). Thus visible, ultraviolet (UV), and infrared (IR) radiation are collectively considered optical radiation. All parts of the optical radiation are relevant for non-visual effects, including light. (Figure 4, from Reference [8]).



SOURCE DGUV (2018). *Nicht-visuelle Wirkungen von Licht auf den Menschen.*[20] Reproduced with permission of the copyright holder.

Figure 4 — Ranges of optical radiation within the electromagnetic spectrum

Research findings have demonstrated that optical radiation has the potential not only to affect vision but also to:

— alter the secretion of hormones, with melatonin being the key hormone as a trigger for many physiologic processes;

— set and reset the “biologic” time of the individual by influencing the circadian rhythm;

— influence key parameters of the human body such as the core body temperature;

— affect thermal comfort by influencing skin temperature;

— affect brain activities beyond a level that is usual for vision;

— affect heart activities;

— modify the sense of taste;

— influence mood and arousal;

— cause or trigger long-term biological effects such as developing or inhibiting certain types of cancer or body growth of children.

Many effects have been studied, mostly under laboratory conditions. This is also true for the basic fundaments of terms and concepts applied in lighting engineering, for example the definition of light. To determine whether or not they are relevant for use environments for the users of interactive systems is not a simple task because light governs human life stronger than air or water, both known for being indispensable for living.

Many of the relevant effects have been studied and were known before the twenty-first century, but the mechanisms were not clearly known. In photobiology, the study of the interaction of biological systems with non-ionizing radiant energy in the ultraviolet (UV), visible and infrared (IR) portions of the electromagnetic spectrum, effects of solar radiation on humans and animals including such wide-ranging phenomena as damage to ocular tissues, skin effects, tumour formation and the synchronization of biological rhythms were well-known. A variety of diseases have been treated with visible light or UV radiation. And a solarium was a sanatorium before our calendar began.

In the year 2002, a sensor in the human retina was detected that is held responsible for effects related to biological rhythms. The cells are called ipRGCs and are sensitive in the wavelengths of visible radiation, i.e. light. The ipRGCs are rendered photosensitive through the expression of melanopsin, an opsin-based photopigment that is most sensitive to light at around 480 nm[21][22].

From many biological rhythms in the human body, the most relevant are daily and yearly rhythms. These do not fully follow the solar rhythm of days or years without the impact of solar radiation and are therefore called “circa”, circadian and circannual. The exposition to solar radiation triggers those rhythms to exactly follow, for example, the solar day. Light does not induce the rhythms; its role is entraining.

Since the study of circadian rhythms is easier than that of circannual rhythms, most references that can be found in the literature are related to circadian effects. And most studies are performed by measuring melatonin, the “sleep” hormone, just because of the ease of the measurement. This is only partly useful, although melatonin is a key hormone whereas the mechanisms leading to circannual rhythms are widely unknown. The same is true for the relationships between circadian and circannual rhythms.

The lighting of use environments for interactive systems is believed to affect humans beyond the intended effect of vision. To study them is rather difficult because of the nature of potential effects that can become effective with some time lag between exposure to radiation and the response. In addition, a given impact is not only related to the physical characteristics of the source but also to the timing and duration. This simply means that a certain amount of light will cause different effects depending on the time of day of exposure. It also means that the same light exposure can cause positive and negative effects depending on timing.

As explained in this document, a small part of the visible spectrum is responsible for affecting melatonin secretion or suppression and, thus, for many non-visual effects. Since this part of the spectrum, blue with a peak of 480 nm, is not suitable for lighting use environments, lighting comprises also other parts of the visible spectrum. In contrast to regular lighting, this type of spectrum is called “blue-enriched”. Almost all visual displays used for interactive systems operate also with blue-enriched light. Thus, separating the contribution of lighting from that of the work equipment is extremely difficult, if ever possible. What is really different is the role of the lighting equipment the light of which is designed not to hit the eye directly, but after being reflected whereas the light of a visual display is the intended signal, and the human eye focuses on that while working.

The known or possible effects of lighting and optical radiation in humans were evaluated in 2011 to detect the need for activities in standardization or legislation[12].

4.4 A new definition of lighting

The improved knowledge about the impacts of light as described in this document made it necessary to change the definition of one of the oldest human technologies, lighting.

Lighting has been defined by the CIE since 1938 as “lighting – application of light to a scene, objects, or their surroundings so that they may be seen” (International Lighting Vocabulary Term 845-09-01, see Reference [3]).

The definition of 2011 no longer includes vision as the goal of lighting[4]. Now, it reads “E-ilv term 17-29-001 lighting – application of light to a scene, objects, or their surroundings”.

4.5 Why light is not light and daylight in interiors is different from solar light

By physical means, light is measured by intensity (e.g. illuminance) and colour (spectrum). All units to characterize the quantity (i.e. photometric quantities: illuminance, luminance, luminous intensity, luminous flux) are derived from the corresponding physical units by adjusting them using the spectral sensitivity of the human eye.[2)]

2) The sensitivity of the human eye is represented by the $V(\lambda)$-curve as defined by CIE.

Traditionally, time does not play a role in lighting, all quantity and quality criteria are independent of time. Only for special applications, for example light exposure on a film, time has to be considered. The reason is that all concepts, units or other considerations in lighting are based on the definition of light that serves vision.[3)] Not all scientific disciplines use the term light in this sense. For vision in static environments, the actual situation is relevant. The only time dependency is related to the state of adaptation.

For dealing with the eye-mediated non-visual effects of light, it needs to be considered that the effects depend on the timing and the duration of the light exposure[7].

In lighting technology, it was believed that the spectrum does not play an important role as long as the impact (luminous colour) is the same because the eye has only rods and three types of cones as sensors. The human eye would not be able to discriminate between colour sources with the same perceived colour. For this reason, the illuminance requirements of lighting standards usually do not consider the spectrum. Thus, certain levels of illuminances are required independently from the spectrum and colour appearance (luminous colour), and even the latest lighting standard valid for all European countries (EN 12464-1) does not specify the colour appearance of the lighting[23].

Colour vision is not considered part of the visual performance (see Reference [24]), and special care was given to the light spectrum when colour rendering was deemed essential. For all the rest of use environments, lighting with lamps that are only capable to render a small set of colours to a certain degree is being considered sufficient. The "Colour Rendering Index" is not a feature of the lighting but a characteristic of the lamps used.

For dealing with all non-visual effects of light, the spectrum of the radiation including UV and IR is essential. Light, IR and UV form the range of the optical radiation in the electromagnetic spectrum.

Daylight in general use of the term is radiation of solar origin regardless of the environment where it is being used. In lighting engineering, however, it is defined differently from the general notion: "part of global solar radiation capable of causing a visual sensation" (E-ilv 17-29-105)[4]. No human or plant will ever be exposed to "daylight" in the sense of this definition. Solar radiation comprises light and other parts that are believed not to contribute to vision. But they are effective in the biological sense.

Solar radiation does not only vary depending on the time of day and year in quantity but keeps changing throughout the day including its spectrum. The composition of "daylight" in the sense of solar radiation depends on various factors like latitude, time of day, time of year, geographic orientation and altitude. Therefore, it can only be considered for design purposes under certain assumptions.

In built environments, the change in quantity is obvious and calculated, for example, using the daylight factor (D) which can vary between 10 in exceptional cases and below 1 in areas that are not adequately lit by daylight (D = 1 is 1 % of the illuminance measured outside the building). What is not obvious, and therefore widely neglected, is the filtering effect of the glazing. The best available (but not necessarily usable) glass not only absorbs and reflects more than 8 % of the incident light, it also filters the spectrum that the colour rendering is affected ($R_a = 100 > R_a \leq 90$). This is valid only for a single layer of thin glass used in tropical areas. Glazing used in moderate climate zones absorbs up to 70 % of incident light and changes the spectrum such that the colour rendering can suffer considerably. Materials used in modern buildings can reduce CRI between 97 and 77 while the transmission of visible light can be reduced between 69 % and 29 %[25].

While older types of glazing can be able to transmit some UV, modern glasses filter UV almost entirely (see Reference [26]). IR is filtered out together with some of the red parts of the spectrum. Thus, "daylight" in built environments lacks UV and IR compared to solar radiation outside buildings. Given the fact daylight in the sense of its technical definition does not comprise these parts of the solar radiation the quality of it before and behind the glazing seems comparable. But this is not true in consideration of non-visual effects. Even the crucial lack of UV behind glass remains unnoticed for most lighting experts or health and safety officials.

3) See definition of light at https://cie.co.at/eilvterm/17-21-012.

It should be noted that the CIE Illuminants such as D65 which is being used as the basis of the calculations of eye-mediated non-visual effects include UV from 300 nm. Some part of the UV (usually 340 nm to 370 nm) serve vision indirectly through the excitation of optical brighteners often used to enhance the appearance of colour of fabric and paper, causing a whitening effect.

Treating "daylight" in the meaning used in lighting engineering means a misconception of the impact of light on humans. The Technical Memorandum prepared by the IES Light and Human Health Committee, therefore, uses the term optical radiation when referring to biological responses other than the visual ones[9]. The Memorandum recommends the use of the term light only if the effect under consideration is related to vision. Also the revision of this document after 10 years includes the same recommendation (see Reference [10]): "Technically, the term *optical radiation* should be used to describe the portion of the electromagnetic spectrum spanning ultraviolet, visible, and infrared radiation that stimulates all these biological responses."[4)]

4.6 The role of daylight and solar radiation

The fact that studies on non-visual effects of artificial lighting outnumber those on the effects of natural light does not mean that they were much more important. The opposite is true. Since the 1950s when chronobiology became popular, there is no doubt that the sun is the main zeitgeber. And even in the 1960s, the majority of people over the world would expose themselves to sunlight even if they worked 9 to 5 in buildings. For example, they would walk longer distances than today because the number of cars was much smaller. Computers and data networks did not influence lifestyles, and thus, the motivation to stay indoors to use electronic media or to play games did not exist. In the course of later years, artificial lighting with higher levels became affordable and was accompanied by less discomfort through glare and heat. Thus, the need to leave the enclosed spaces has diminished.

But compared to the intensity of light and radiation outside, even high levels of artificial lighting can be considered "dark". Most workplaces in industrial countries are lit with 500 lx and less, and in other parts of the world, such levels are not even feasible. Because of the usual direction of the artificial light, from ceiling to floor, the level in the eye is 200 lx or even less. For a user with a relaxed position of the head and the eyes, i.e. 35° below horizontal (see ISO 9241-5:1998, Figure 1), the illumination level can be around 100 lx. Whereas in rooms with windows daylight can be as high as many thousand lux at times with the main direction toward the eye.

This means that daylight plays a major role even after being filtered by the glazing. In addition to the much higher intensity, the change of intensity and colour is considered a circadian cue so that many technical concepts designed to achieve circadian effects mimic the rhythm of the solar day in intensity and colour.

Therefore, the recommendations for health and safety (see Reference [8]) focus on natural "light" which is optical radiation and include aspects relevant for the time of day outside the working hours.

A recent publication of the leading chronobiologists (see Reference [1]) recommends a much higher level of vertical illuminance than usually installed in industrial buildings than ever feasible with electric lighting: "Ocular light exposure has important influences on human health and well-being through modulation of circadian rhythms and sleep, as well as neuroendocrine and cognitive functions. Current patterns of light exposure do not optimally engage these actions for many individuals …". Their recommendation to achieve higher levels of illumination is: "If available, daylight should be used in the first instance to meet these levels."

5 Light and circarhythms

5.1 Basics

Biological rhythms that occur on an approximate 24-h schedule are termed circadian rhythms (from circa = about, approximate; dia = day). Circadian rhythms are of particular interest because they

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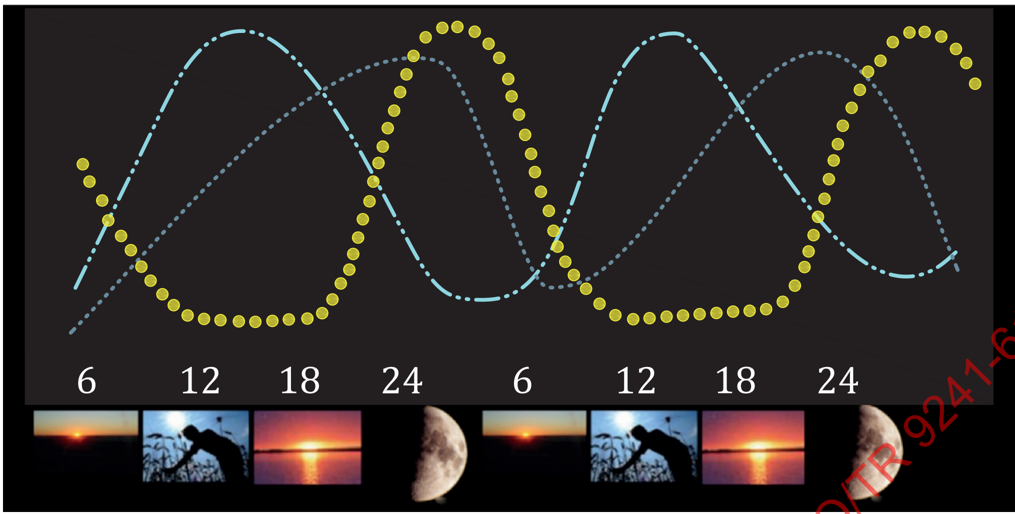
characterize the pattern of variation observed in the majority of human physiologic rhythms, including body temperature, sleep pattern, hormone secretion, and blood pressure (Figure 5). The entirety of rhythms with an approximate schedule is called circarhythms.



Key

- melatonin
- vigilance
- body core temperature

SOURCE Çakir, A. *The Rise of the Electric Sun*.[28] Reproduced with permission of the copyright holder.

Figure 5 — Illustration of the circadian rhythms of melatonin and vigilance and core body temperature

Circadian rhythms are endogenous (“built-in”, self-sustained), but are adjusted (entrained) to the local environment by external cues called zeitgebers (from German, “time giver”), which include light, temperature or social events. To synchronize the “approximate” rhythm (entraining) with the 24-h day, the human body needs certain exogenous signals. According to Aschoff, one of the founders of chronobiology, all events that can serve as signals are termed “zeitgeber”, a term coined by him. In fact, in earlier times some scientists had suggested the term “synchronizer” instead of “zeitgeber”, a German word.

NOTE A comprehensive history of the term and the scientific area is described in Reference [29].

5.2 Importance of light for the circadian rhythm

Human life has changed ever since the building of the first shelter to protect the individual from the sun or the rain. For many thousands of years, the shift toward a more artificial environment could not influence the circadian rhythms for most people since the majority of humans lived either as hunter-gatherers or farmers under natural light. Artificial light was too expensive – and also somewhat smelly – to be used to prolong the day for long hours during the night. The situation dramatically changed for workers during the industrial revolution who shifted from rural areas to overcrowded cities. During this era, people started to feel the outcome of an unnatural life. The name of rickets as the "English disease" stems from that period of human history.

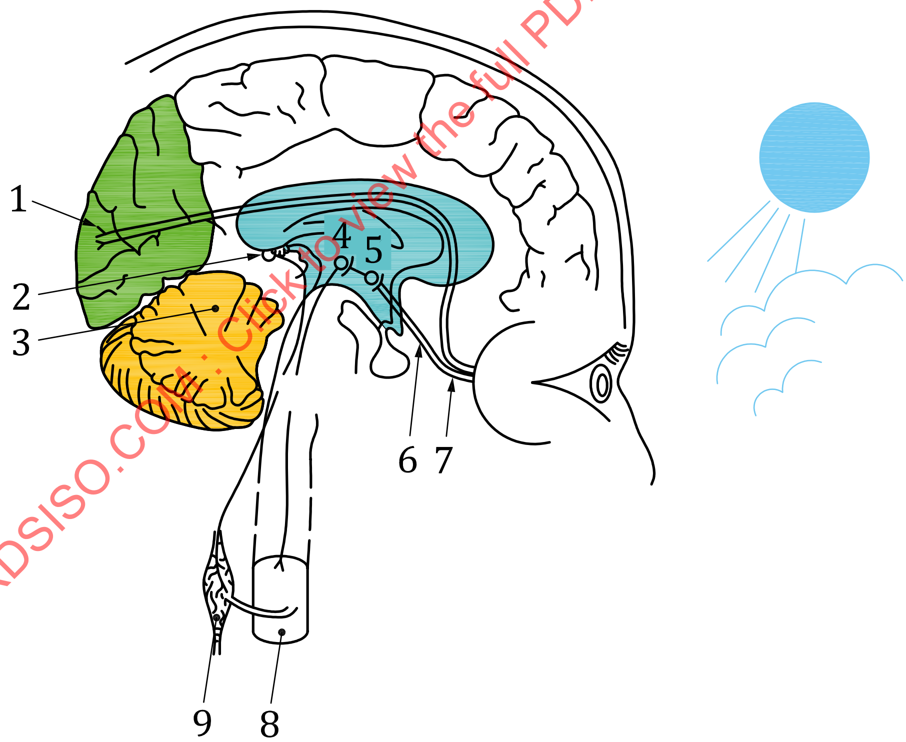
In the second half of the twentieth century, most people in industrialized countries developed a lifestyle of living up to 90 % of their time in enclosed environments such as houses, pubs and cars. Cheap artificial light allowed a working life free from the day and night rhythm. Some shift workers do not see the natural daylight for three or four consecutive weeks in winter. Workers in open-plan offices suffer from being deprived of healthy environmental influences under artificial light. No later than about 10 years after the invention of the fluorescent lamp in 1938 a worldwide interest in circadian rhythms had developed. It is not just a coincidence that the most fruitful research activities on circadian rhythms commenced in the advent of fully artificial work environments designed for 24-h operation.

During the intensive research work Aschoff performed in the 1950s, the influence of artificial light as a "zeitgeber" was not clearly demonstrated. In 1984, Lewy and colleagues[30] published a work that described that it is possible to shift the circadian rhythm using artificial light. They also explained why earlier experiments had not been able to find this effect. The claim is that a high level of illuminance is required to affect humans. Lewy et al. experimented with 2,500 lx instead of about 100 lx in earlier research.

NOTE In the current discussion, levels around 100 lx or even lower can be relevant, but only for effects during the night.

Since 1984, intensive research work has been invested to uncover the mechanism of the circadian rhythms affected by light. The main reasons for the intensity of the activities have been shift work and jet lag.[31] However, the research findings are being widely used in light therapy and even in psychiatry. There is also great interest among experts who focus on eliminating the influences of artificial environments on people. The main focus of these efforts lies in compensating the missing zeitgebers in artificial environments with static lighting and other physical conditions, for example constant temperatures.

It was demonstrated that nocturnal light pulses can directly influence the brain (SCN) similar to a gene. (see Reference [32] and Figure 6 from Reference [33]). While molecular clock genes exist elsewhere, such as the kidney, liver, pancreas and muscles, the SCN acts as the master clock.



Key

1 visual cortex
2 pineal gland
3 melatonin
4 PVN
5 SCN
6 retinohypothalamic tract
7 optic nerve
8 spinal cord
9 superior cervical ganglion

NOTE This pathway is anatomically separate from the pathway to the visual cortex, which serves the sensory capacity of vision. Highlighted areas added by the author.

SOURCE Reproduced from *The IESNA Lighting Handbook*, Ninth Edition. New York: © The Illuminating Engineering Society, 2000[33]. Reproduced with permission of the copyright holder.

Figure 6 — Simplified illustration of the pathway from the retina to the suprachiasmatic nucleus (SCN) or the hypothalamic "clock" and its projection to the pineal gland by way of the paraventricular nucleus (PVN) in the hypothalamus

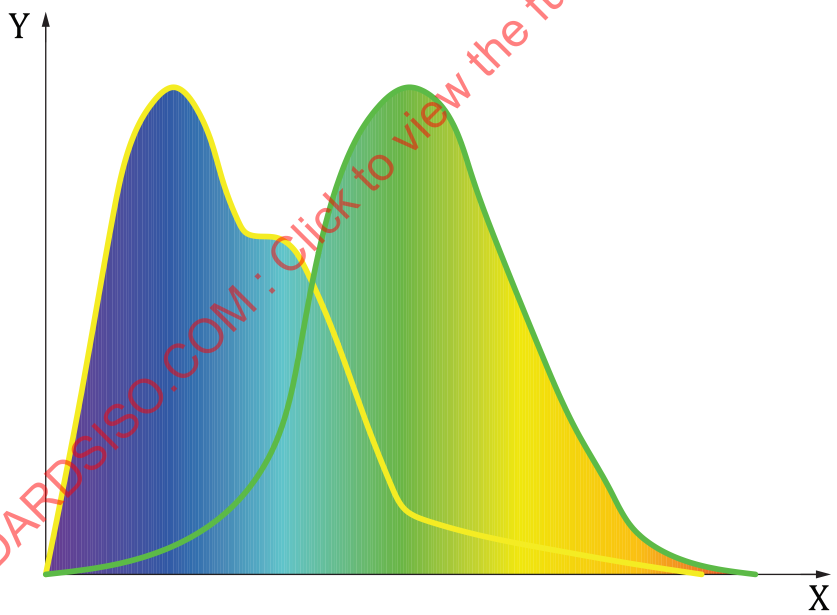
Currently, light is considered the most effective external influence factor for circadian rhythms. An extensive review and evaluation of the state of the art shortly after the discovery of the new sensor in the eye is given by Brainard and Hanifin.[34] However, to that date, Küller had reviewed a plethora of literature (1 100 entries) on non-visual effects of light in humans and published it. The oldest publication of Küller on non-visual effects was published in 1983.[18]

CIE S 026 was developed for quantifying the effect of optical radiation on circadian rhythms.

5.3 A new perspective on light

Publications related to the impact of light on circadian rhythms demonstrate more discrepancies with regard to levels of lighting required for affecting humans than usual in other areas of research. Although some discrepancies in research findings are common and not always easy to avoid, in the area of lighting and related areas there is new knowledge that helps explain why.

Probably the most important reason for the discrepancies is the definition of light that is based on vision and the visual sensitivity of the cones (2° standard photopic observer) whereas the action spectrum of the newly found receptor differs considerably from the receptors responsible for vision (see Figure 7).



Key

X wavelength

Y relative value

Source Çakir, A. *The Rise of the Electric Sun*.[35] Drawn after Reference [34]. Reproduced with permission of the copyright holder.

Figure 7 — The action spectrum for the ipRCGs (peak 490 nm) and the spectral luminous efficiency function [*V(λ)*] for photopic vision (peak 555 nm)

NOTE The original work of Brainard et al.[34] suggests a maximum melatonin suppression of 464 nm. In newer work, other wavelengths (e.g. 480 nm) can be found. The difference has been caused by the considered function (melatonin suppression vs. the sensitivity of the photopigment melanopsin). Figure 7, therefore, does not contain numbers for wavelengths. It demonstrates the difference in the sensitivity of the human eye for light and for circadian effects related to melatonin suppression ("melanopic" response to light). The standardized values for the melanopic action spectrum are given in Table 2 of Reference [7], which defines standard action spectra for all five known photoreceptors related to their ipRGC-influenced responses to light.

While the relative sensitivity of the eye for photopic vision is very low in the blue and red regions of the visible spectrum the sensor responsible for the circadian rhythm (melatonin suppression) peaks in the blue region around 480 nm. For the ipRGC (melanopic) sensitivity, a consensus that the action spectrum of human melanopsin peaks around 480 nm is accepted[7]. This document defines five action spectra for light assessments with the Lucas et al. melanopic sensitivity function[36].

CIE[7] defines spectral sensitivity functions, quantities and metrics to describe the ability of optical radiation to stimulate each of the five photoreceptor types that can contribute, via the melanopsin-containing intrinsically-photosensitive retinal ganglion cells (ipRGCs), to retina-mediated non-visual effects of light in humans. The contribution of the single receptor type to a specific non-visual effect is not defined.

The clearest indication for a new perspective on the impact of light gives the calculation of the melanopic equivalent daylight illuminance based on the spectrum of the CIE standard illuminant for daylight (D65) while its visual equivalent (illuminance) is independent of the spectrum of the light source, see Table 1.

Table 1 — Relationship between visual and melanopic quantities in dependence of the spectrum (CCT)[a]

CIE illuminant	Illuminance lx	Melanopic equivalent daylight (D65) illuminance $E_{v,mel}^{D65}$ lx	Melanopic daylight (D65) efficacy ratio $\gamma_{mel,v}^{D65}$
Fluorescent 3 000 K (CIE illuminant FL12, interpolated to 1 nm)	100	40,4	0,404
Fluorescent 4 000 K (CIE illuminant FL11, interpolated to 1 nm)	100	56,2	0,562
CIE illuminant D55 (daylight 5 500 K)	100	90,4	0,904
CIE standard illuminant D65 (daylight 6 500 K)	100	100	1,000

NOTE For the concept of melanopic equivalent daylight illuminance (M-EDI) see Reference [7].

[a] After Reference [7], Table A.2.

The melanopic quantity M-EDI is calculated for an observer of 32 years of age. For other ages, a correction factor applies which also depends on the spectrum of the light source. For people younger than 25 years of age, the differences in the transmittance function of the eye are much bigger. Therefore, the table does not specify a correction factor.

Table 2 — Correction factor for age 25 to 90 years with a reference age of 32 years[a]

CIE illuminant	Factor (25 years)	Factor (32 years)	Factor (50 years)	Factor (75 years)	Factor (90 years)
Fluorescent 3 000 K (CIE illuminant FL12, interpolated to 1 nm)	1,045	1,000	0,857	0,641	0,524
Fluorescent 4 000 K (CIE illuminant FL11, interpolated to 1 nm)	1,050	1,000	0,842	0,608	0,484
CIE illuminant D55 (daylight 5 500 K)	1,050	1,000	0,840	0,598	0,468
CIE standard illuminant D65 (daylight 6 500 K)	1,052	1,000	0,835	0,589	0,457

a After Reference [7], Table A.3.

Table 2 indicates that a (visual) illuminance of 100 lx generated by a fluorescent lamp with a CCT of 4 000 K will produce a melanopic stimulus for a person of 90 years of age 54 % below that of a 25-year-old.

NOTE For the calculation of the correction factor see Reference [7], Annex A.

Another novelty in the perspective on light is reflected by the requirement by leading chronobiologists to ensure a minimum level of melanopic stimulus during daytime and limit it to a maximum of 10 lx (EDI) in the evening, and 1 lx (EDI) during the night[1]. Given the fact that current lighting standards require or recommend the same lighting levels around the clock, it is a real new perspective.

5.4 Relation to other zeitgebers

Human endogenous biological clocks are entrained by several exogenous cues, zeitgebers. They can be photic and nonphotic. Examples of *nonphotic* zeitgebers are:

— atmospheric conditions;

— medication;

— temperature;

— social interactions;

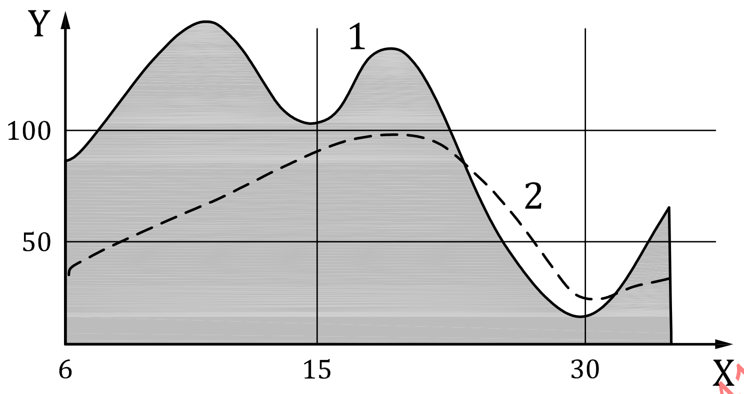
— exercise;

— eating or drinking patterns.

Aschoff's early work was performed in cave experiments where light played a major role. However, the term "social zeitgeber" has been coined as a result of those experiments, see for example References [37] and [38]. Even assuming that light really plays a major role, research cannot exclude a potential effect while determining its role as a zeitgeber. Social cues, although less powerful, can be an important form of entrainment for contemporary humans, and also serve to augment the effects of available bright light. It is important that both light and social zeitgebers are investigated for their roles in the genesis, prevention and treatment of alterations in health[39].

While the role of light has been subject to a plethora of research work and publications, social zeitgebers appear in a limited number of publications, and in addition, mostly in relation to the therapy of depressions.

Ultradian rhythms, i.e. rhythms shorter than 24 h, do appear even in much fewer publications. However, at least one relevant event in working life, the so-called "afternoon slump", characterized by a drop in alertness (or increase in error rates), is not easy to explain with circadian rhythms (Figure 8). For example the most stable physiologic rhythm (body core temperature) does not display any drop around noon time[8].



Key

X time of day

1 performance ability

2 body core temperature

Source Çakir, A. *The Rise of the Electric Sun*.[40] Reproduced with permission of the copyright holder.

Figure 8 — A daily rhythm showing an indication of an afternoon slump and the body core temperature

Other zeitgebers are known to be social zeitgebers such as personal relationships, jobs or interpersonal demands, food availability or consumption and temperature. In contrast to light, i.e. a photic zeitgeber, others (atmospheric conditions, medication, temperature, social interactions, exercise, eating/drinking patterns) are called non-photic, but they can have correlations with lighting patterns.

Focusing on a single factor (melatonin) and the major zeitgeber influencing it could prove justified after demonstrating the entire process of affecting humans by environmental factors. But currently, we are far from understanding it. The relevant documents used as a basis for this document, notably the most recent sources suggest either a research roadmap (see Reference [6]), or stress the need for more (see Reference [8]). The most recent official expertise even suggests research at a fundamental level (see Reference [11]). Thus, utilizing light to intentionally generate non-visual effects for all will remain an open question for some time.

6 Light at night (LAN)

6.1 General

The term light at night (LAN) was coined after it became clear that light exposure can cause different outcomes depending on the time of day the exposure takes place. Some research focuses on the effects of light at night outdoors ("outdoor" LAN). In general, the acronym LAN refers to the effects of light used in indoor environments.

The original intention since the 1970s was to increase the alertness of workers during late and night shifts, especially in low-risk, high-hazard areas like nuclear power plants or transportation. Since it has been demonstrated that artificial light at night decreases the blood melatonin level, the theory is that this can increase the likelihood of cancer development. Epidemiological evidence indicates an association between breast and prostate cancer risk and shift work[41].

Light at night, or better said, artificial light at night, is subject to a series of international conferences with the same name, ALAN, with a focus on circadian rhythm disruption and illness related to artificial light at night. Linking the non-visual effects of light exposure with occupational health in the light of most recent research outcomes is discussed in Reference [42]. The authors criticize the current state of the art and request better designed studies: "The impact of light exposures on the health and well-being of shift workers and indoor daytime workers has not been explored in sufficient detail. Advice to promote positive health outcomes for these groups should be based on evidence taken from or validated by, well-designed field studies into the effects of light exposure. These effects are not just driven by artificial lighting in the workplace, but may depend on exposures to daylight and the influence working hours have on 24-h exposures and workers' lifestyles."[5)]

What applies to lighting can also be valid for visual displays because most visual displays generate light with a high CCT, which is in fact higher than that of lighting installations (default CCT 9 300 K for displays versus 4 000 K or 3 000 K for lighting with fluorescent lamps)[43]. In addition, the effect can be higher because the light from a display has to meet the eyes while working whereas lighting is normally designed not to directly hit the user but the visual objects and the environment.

The contribution of visual displays is quantified by Brown et al.[1] to melanopic EDI levels of > 70 lx in the absence of any other illumination. They refer to earlier research with tablet displays as reported in References [44] and [45]. Thus, the contribution of visual displays (>70 lx) is of the same magnitude as most lighting installations and cannot be neglected.

6.2 Studies of light at night (LAN or ALAN)

The US Library of National Medicine includes a high number of studies with the subject LAN or ALAN (artificial light at night). Tens of thousands of studies, papers, review papers or meta-analyses can be found around this subject online.

All studies have to fight with the fact that the use of light for professional purposes in the night is associated with working during late hours, thus, with a disruption of circadian rhythms with or without light. Another source of bias is the so-called "healthy worker effect" which means that studies at the workplace mostly consider workers who show up. Those who could be worst affected might be ill if occupied or not present in the population under consideration by avoiding that type of work. A recent study on the impact of light in protected areas in a big number of countries partly avoids such bias, and thus, could give better insights into the issue[46]. The outcome of this study, in short, is: "Artificial light at night is significantly correlated for all forms of cancer as well as lung, breast, colorectal, and prostate cancers individually."

NOTE Correlations indicate an association between two aspects under consideration, but do not establish causal relationships.

While this study evaluates light at night from an environmental health perspective, other studies focus on shift work, resetting the circadian clock and sleep disorders through the influence of light on melatonin levels. Brainard and a growing number of researchers believe that melatonin can be the key to understanding the shift work or breast cancer risk association[47].

However, this perception is not valid for some researchers, for example the authors of a recent study state that their prospective cohort analysis of LAN did not demonstrate evidence that LAN exposure increased the risk of subsequent breast cancer, although the suggestion of a lower breast cancer risk in pre-menopausal women with a history of night waking in their twenties might warrant further investigation[48].

A study on the effects of artificial light at night on human health, a literature review for a given period, suggests that exposure to artificial bright light during the nighttime suppresses melatonin secretion, increases sleep onset latency (SOL) and increases alertness. According to this study, circadian misalignment caused by chronic ALAN exposure can have negative effects on the psychological, cardiovascular and/or metabolic functions. ALAN is also demonstrated to cause circadian phase disruption, which increases with longer duration of exposure and with exposure later in the evening. It has also been reported that shorter wavelengths of light preferentially disturb melatonin secretion and cause circadian phase shifts, even if the light is not bright[49].

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Most of the available studies suggest many impacts of lighting along the finding reported above. The CIE Technical Report describing the research roadmap for interior lighting concludes[6]:

— Light exposure at night acutely suppresses melatonin secretion.[50][51]

— Melatonin provides the signal for night-time states of immune function, digestion, wakefulness, and other biological processes.[52]

— Light at night acutely increases alertness[53] and leads to sleep loss.[54]

— Sleep loss reduces subsequent cognitive performance and diminishes immune function.[55]

— Disrupted circadian rhythms are implicated in the development of obesity, some cancers, cardiovascular disease, and depression.[56]

— Independently of sleep loss and circadian disruption, animal tests of light exposure at night have shown adverse effects on mood and cognition that some believe might explain adverse effects in humans.[57][58]

A recent literature review of KAN (Commission for Occupational Health and Safety and Standardization, Germany) on “validated OSH-related findings concerning the non-visual effect of light upon human beings” states: “In consideration of light at night there is scientific evidence that it is a probable health hazard at the workplace.”[11] 6)

7 Light history (memory effect)

Light as the most potent stimulus for synchronizing the endogenous circadian timing system has not only an immediate effect on vision but after-effects in consideration of the circadian system.

Light in the evening delays the time of the secretion of melatonin to later hours (shifting the phase, Figure 9). The opposite occurs with the incidence of bright morning light. During daytime, melatonin levels are low and start rising in the evening. Bright light causes a shift towards later hours depending on the duration of the light incidence.

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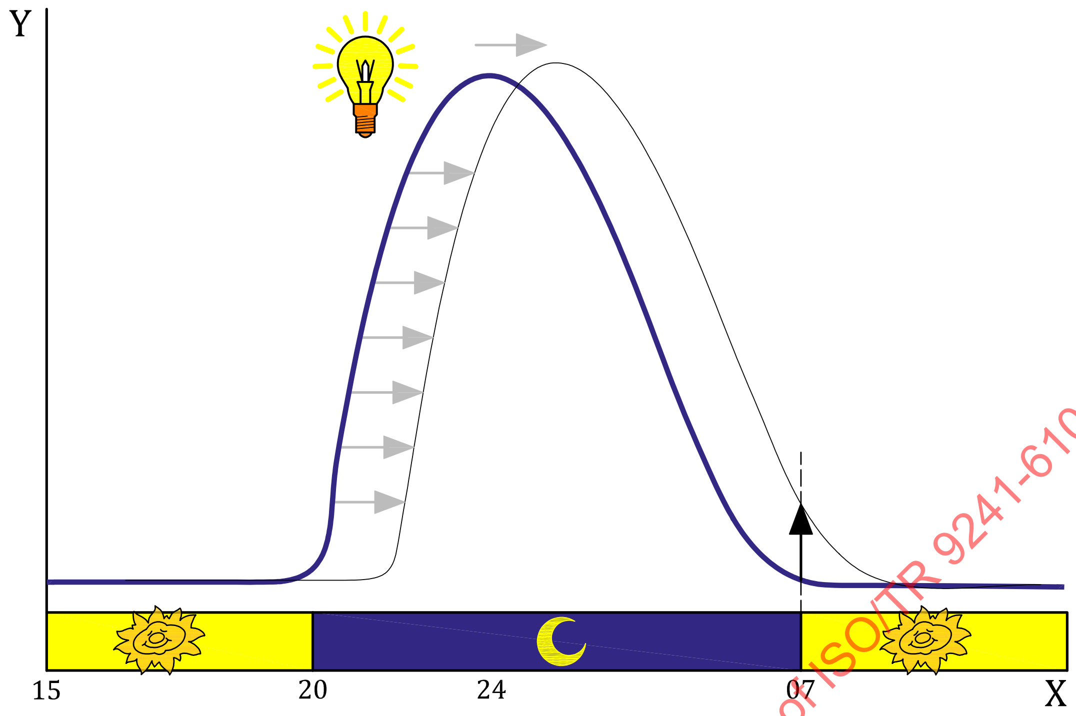


Key

X time

Y plasma melatonin

SOURCE Çakir, A. *The Rise of the Electric Sun*.[59] Reproduced with permission of the copyright holder.

Figure 9 — Schematic diagram of circadian rhythms of melatonin

The phase-shifting implies that the impact of a certain factor that could affect the circadian rhythm depends on the light history of the person under consideration. In other words, a certain event affects the body for a long time.

This means that for circadian effects, in contrast to vision, the light event does not need to be present all the time to be effective. For the circadian effects, the body has a memory reaching about 24 hours. For other non-visual effects of radiation, the "memory" is even much longer. For example, vitamin D produced through exposure to ultraviolet radiation is stored on the body's adipose tissue for a certain time much longer than a day.

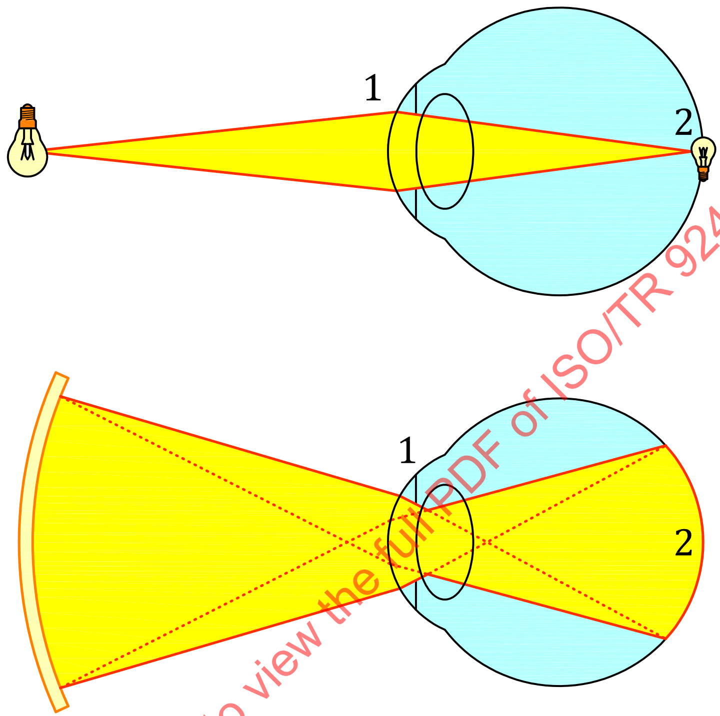
Another implication of this knowledge is that light events during working hours could affect the user in private time and vice versa. This is not uncommon, for example fatigue through an activity during work can be felt at home, and private activities can impair the abilities needed during working hours. But fatigue does not shift the biological rhythms of the body. And the major difference to fatigue is that light is being used to extend the active and productive hours without a biologically effective mechanism that reduces harmful effects.

Although not discussed in the scientific literature in detail, the memory effect can gain importance in work relations. To take any effective measures, an understanding of the conditions to which users might be exposed over the entire day and night (e.g. for workplaces, while at home and in transition as well as during working hours) is necessary. While a lighting planner or employer can consider the working environment and working hours, a bigger portion of the time of day cannot be taken into consideration while designing lighting.

8 Physical characteristics

8.1 Spatial distribution of the source

While defining photometric units like illuminance is done without considering the spatial distribution of the source (see Reference [60], Figure 10) circadian effects seem to be dependent on the size of the source given the case that the illumination on the retina is the same. The reason is that more ganglion cells are involved.[8]



Key

1 cornea

2 retina

SOURCE C. Schierz (2002). *Leben wir in der „biologischen Dunkelheit?“*.[60] Reproduced with permission of the copyright holder. Drawn after Reference [61].

Figure 10 — The light from sources of different sizes excites different areas of the retina

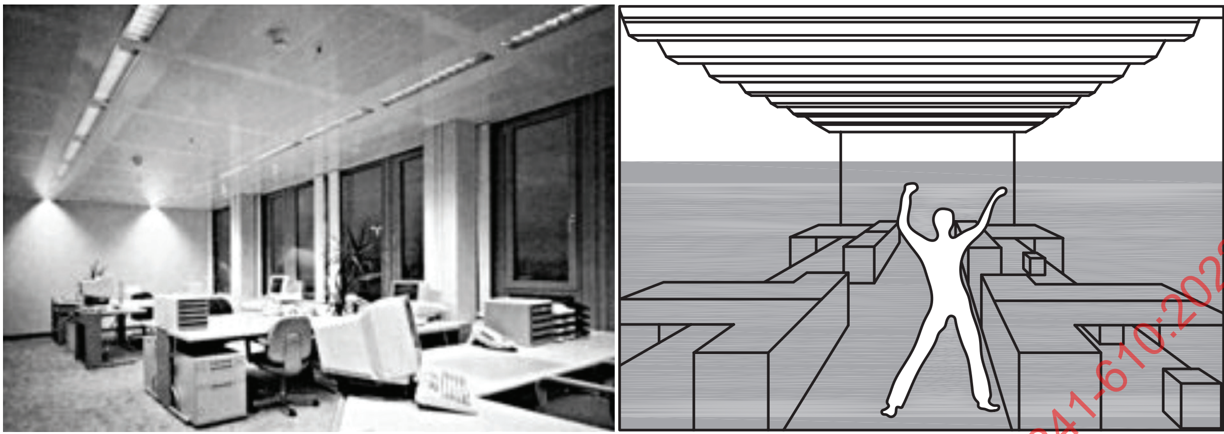
This knowledge suggests that a small light source (with a high luminance) is considered less effective than an extended source (with lower luminance). Thus, planning a lighting installation, one can select or avoid small light sources depending on the purpose of the application.

NOTE The illuminance generated by a source is proportional to its luminance and area. If the luminance is four times higher, the area needed to generate the same illuminance is only a quarter of the original source.

8.2 Location of the source

Circadian rhythms can only be influenced by light entering the eye to a different extent depending on the location of the source. The distribution of the ipRGCs in the retina suggests that light from the upper hemisphere is more efficient in suppressing melatonin, i.e. the inferior retina contributes more to the light-induced suppression of melatonin than the superior retina does at the same photon[62].

A practical application of this knowledge is shown in Figure 11. While in earlier concepts, luminaires with a downlight characteristic (high luminance and restricted light distribution) were preferred, the newer concepts would lead to light sources with a wider luminous area and, thus, to lower luminances if the level of illumination is kept equal. This would lead to a dramatic change in the concept of lighting.



SOURCES Left: Siethoff, H.D. *Beleuchtung von Arbeitsstätten*[63]. Reproduced with permission of the copyright holder. Right: licht.de. *Lichtwissen 19*.[64] Reproduced with permission of the copyright holder.

Figure 11 — Lighting concept of the late 1980s aiming for better control of reflected glare on computer screens (left) and light distribution for better non-visual effect (right)

8.3 Light spectrum and its role for vision

The spectrum of a radiating source is the distribution of the radiated energy over the wavelength or frequency. For light, the range of wavelengths between 380 nm and 780 nm are considered by definition as visible. However, young people are able to see from 310 nm (ultraviolet, UV) to about 1 100 nm (infrared, IR)[65]. The human eye does not resolve all wavelengths present in the radiation of a source, but responds through two types of photoreceptors called cones and rods, whereas cones are composed of three different photopigments that enable colour perception. Rods are highly sensitive to light but are comprised of a single photopigment, which accounts for the loss of ability to discriminate colour.

In bright environments, cones are believed to dominate the visual process, and under optimum conditions, all colours defined as such can be perceived. Any illuminated object (secondary light source) appears in colours corresponding to the reflected part of the incident light spectrum, i.e. the rest of the light after transmitting and/or absorbing some parts.

Colour rendering (R) is the ability of a light source to retrieve certain colours. In theory, one could determine it for each object, but to achieve a general understanding, the general CRI [R_a] has been defined by CIE (E-ilv 17-22-111)[4] for a set of colour samples. The CRI is no absolute value but given in comparison to two standard sources, CIE illuminant A (incandescent lamp) and daylight. Both are assigned a R_a of 100. Unfortunately, the definition is error-prone because the index can also be negative, and the upper end of 100 suggests that the index represents a percentage that is not true. The limitations of this concept are well known. Newer concepts such as an index for colour fidelity (replacement of the CRI) have been introduced and discussed.[66]–[69]

Primary light sources are perceived to display a colour depending on the spectrum they emit (luminous colour).

An important characteristic of light sources determined by the spectrum is the CCT. The basis of this calculation is the temperature of an incandescent object (blackbody radiator). The spectrum of such an object can be calculated after Planck’s law in dependence of the absolute temperature in Kelvin. Most light sources are no incandescent radiators, and therefore, their colour temperature is a fictive temperature giving the best match in the CIE 1931 chromaticity diagram. In practice, colour temperature is meaningful only for light sources that do in fact correspond somewhat closely to the radiation of some black body. It does not make sense to speak of the colour temperature of, for example, a green or purple light because no incandescent radiator will generate purple light only.

Daylight has no CCT because, at a given point and time, the colour is different in all directions and varies from the horizon to the zenith. It also keeps changing throughout the day and is among others a function of season, time of day, and geographic location. For the representation of daylight, CIE has defined several standard illuminants of the series D, for example D50 (CCT 5 003 K, "horizon light") to D75.

Standard illuminants provide a basis for comparing images or colours recorded under different lighting. The earlier representation of daylight was illuminant C with a CCT of 6 774 K. Unfortunately, it was a poor approximation of any phase of natural daylight, particularly in the short-wave visible and in the ultraviolet spectral ranges. Once more realistic simulations were achievable, illuminant C was deprecated in favour of the D series. The illuminants of the series D are also no real light sources but mathematical constructs. They are not easy to produce artificially. As indicated above, more than one representation of daylight has been defined.

To quantify the eye-mediated non-visual effects, the standard illuminant D65 ("noon light") with a CCT of 6 504 K is used. D65 corresponds roughly to the average midday light in Western or Northern Europe. D65 is intended to represent the "average" daylight spectrum. A simulation of daylight in spectrum and intensity is not feasible.

The focus of interest concerning non-visual effects on humans lies on light sources with rather high CCT (4 000 K to 17 000 K) whereas usual incandescent lamps have a CCT around 2 500 K and "soft white" fluorescent lamps around 3 000 K. Lamps used in experiments as "blue-enriched" sources have CCTs from 4 000 K upwards. Computer screens reach from 6 500 K to 9 300 K. The default value is 9 300 K because a higher CCT yields more brilliant colours. Some screens can use up to 11 000 K[43].

All illuminants of the series D include UV in their spectrum although optical radiation below 380 nm of wavelength does not contribute to vision by definition.

8.4 Light spectrum and its role for non-visual effects

Ample research findings suggest that the spectrum of light plays a prominent role in generating non-visual effects. While most researchers focus on melatonin suppression and related effects, bluish light is considered as a means to enhance alertness, too. Cognitive performance has been demonstrated to fluctuate over 24 h of the day, thus showing peaks and troughs depending on the time of day (leading to optimal and suboptimal times of day, respectively). Consequently, vigilance decrements are more pronounced along time on task when it is performed at suboptimal times of the day.

Extensive research has been performed to use light to enhance alertness (and reduce errors) at suboptimal times of day, especially in low-risk high-hazard areas such as nuclear plant operations. Initially, high levels of illuminance were tested[30]. After learning about the role of the ipRGCs and the spectrum, much lower levels are deemed effective in shifting circadian rhythms.

Whether or not this can be achieved in practical environments is one question. Another, more relevant question, is whether this kind of intervention inevitably leads to vigilance decrements at other times of day, for example on the way home after a night shift. An even more important question is whether manipulations of the circadian rhythm lead to adverse effects on the circannual rhythm. A recent decision by the official committee that develops and supervises the technical rules for workplaces (ASR) on the Workplaces Regulation (ASTA = Committee on Workplaces) for Germany states that lighting following existing standards, namely high illuminance values on the eye in association with high CCT, can cause inadvertent biological effects, including a disruption of the circadian rhythm and possible long term adverse effects on health. Thus, ASTA recommends avoiding an illumination with a CCT higher than 4 100 K at night[70]. The knowledge behind this recommendation is much older (see Reference [71]): "With regard to melatonin concentration, it shows the result of the same tendency as Morita et al. reported that the light with high colour temperature during the night-time greatly suppressed the melatonin secretion".[7)]

The latest recommendation by Brown et al. (see Reference [1]) for the evening light recommendations for residential and other indoor environments, a maximum melanopic EDI of 10 lx and white light

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depleted in short wavelengths close to the peak of the melanopic action spectrum, is a consequence of related research findings.

The range of the light spectrum considered effective by most researchers (around 480 nm) is also responsible for damaging the retina (blue light hazard, macular degeneration). While an acute exposure can only cause damage well beyond energy levels that can be reached by lighting, the mechanism of developing macular degeneration through chronic exposure is not clear. Also debatable is whether the lighting in the sense of illuminating the environments for visual purposes plays a major role given the fact that exposure to natural light with much higher levels of bluish parts has been common for the subjects under consideration who have developed macular degeneration.

8.5 Time and timing

In general, time is a physical construct measured by technical devices. Timing is the time when something happens or the spacing of events in time. While this is valid for most actions we take, timing in the sense of circadian influences means spacing the intended event in correct relation to the circadian rhythm of the individual under consideration. The effects of any light exposure also depend on the state of the individuals, including their prior light history and their internal states (e.g. groups of individuals in an airport could have differing states of jet lag or circadian disruption).

Thus, in an experiment or a real environment, there are two constructs both named time, out of which only one is a physical entity. The benefits or some pitfalls of introducing a new concept are described in 9.3.

In regulations (e.g. lighting standards) about lighting, time does not play a role because all of them have been written and issued under consideration of visual effects which are deemed to be time-independent. After officially changing the purpose of lighting from illumination (see 4.4) on the basis of new scientific evidence, time dependency is to be considered an important factor for the design and operation of lighting systems and the exposure of individuals to light in general.

A very significant change in the perspective on lighting is reflected by the CIE Position Statement on Non-Visual Effects of Light: Recommending proper light at the proper time.[72]

8.6 Intensity

In lighting engineering, a variety of concepts are used, for example luminance or luminous intensity, all based on the sensitivity of the human eye which are called photometric units. Since the spectral sensitivity function of the eye changes depending on the adaptation level, i.e. intensity of the light received in the eye, in theory, separate units would be needed for different ranges of brightness, at least three, photopic, mesopic and scotopic. Normally, photopic quantities are used based on the V(λ)-curve as defined by CIE.

The fundamental photometric quantity, luminous intensity expressed in candelas, is the equivalent of the physical power density per unit solid angle. For designing or evaluating visual environments, the intensity of the incident light is more relevant. It is luminous intensity per unit area of the relevant object, the illuminance measured in lux (lx).

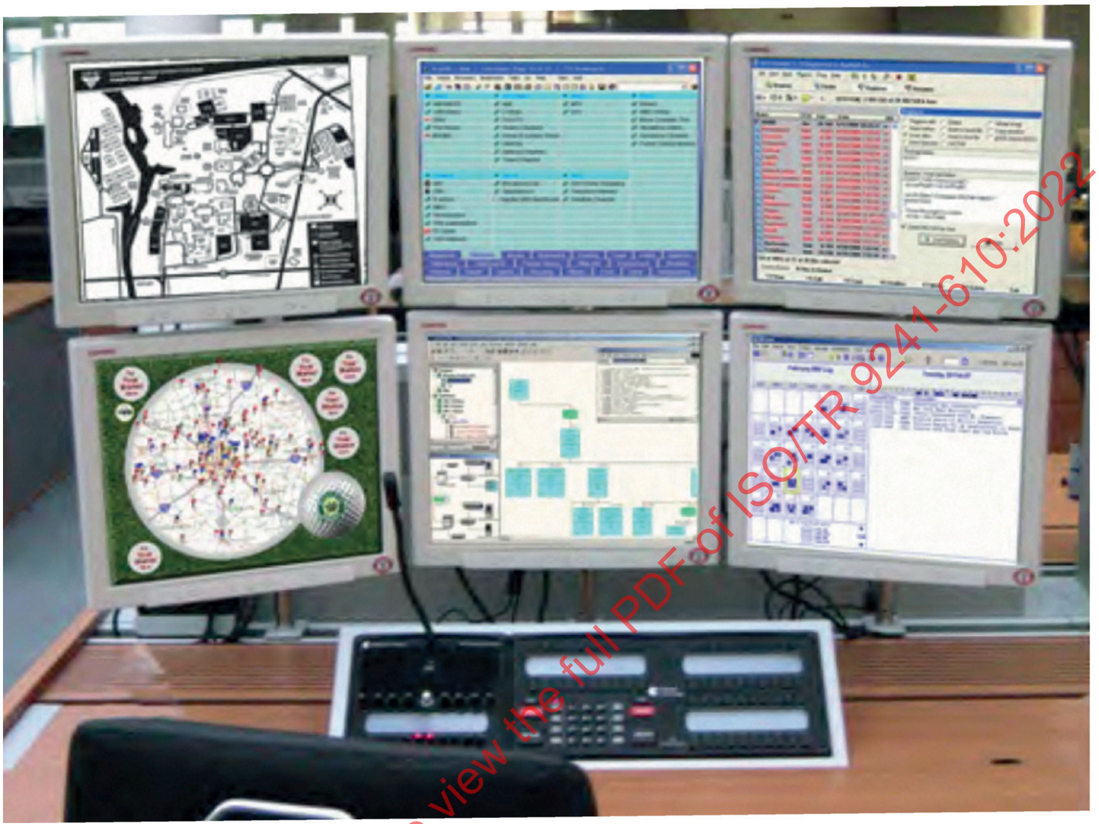
The incident light is reflected by most objects that serve as secondary illuminants. The intensity of the light reflected by the object depends on the characteristics of the object and the light source. The relevant characteristic describing the intensity is called luminance and measured in candelas per m^2. The standard definition of this photometric unit is given in term 17-21-050 of CIE[4]. Most visual effects (e.g. contrast, contrast sensitivity, recognition speed) are functions of luminance.

8.7 The role of visual displays

Computer screens are powerful light sources with luminances up to 500 cd/m^2 which are in the focus of the user for most of the day either during working hours or in private life. Newer displays can even reach up to 1,000 cd/m^2 While earlier visual display terminals were rather small (between 10″ and 15″

in diameter), today, even in office environments they can extend from 24” in diameter to combinations of 27” screens up to six units (Figure 12)[73].

NOTE The luminance values named above are maximum luminances. In practical use, the displays are used with lower luminances.



Source Çakir, A. *The Rise of the Electric Sun*.[73] Reproduced with permission of the copyright holder.

Figure 12 — Workplace with multiple screens in an office

The default CCT of such screens is 9 300 K, and thus, much higher than that of lighting equipment used for achieving an intended circadian effect (e.g. blue-enriched lamps with a CCT > 5 000 K). In addition, the apparent size of the screen combination is much bigger than that of any lighting installation.

Computer displays can be responsible for circadian effects even to a higher degree than lighting. It has been demonstrated that a single computer display can shift the circadian rhythm during normal use[74]. Certain spectral profiles of computer screens have been demonstrated to generate multiple eye-mediated non-visual effects: “Our data indicate that the spectral profile of light emitted by computer screens impacts on circadian physiology, alertness, and cognitive performance levels. The challenge will be to design a computer screen with a spectral profile that can be individually programmed to add timed, essential light information to the circadian system in humans.”[74]. Whereas some manufacturers of computer displays or computer operating systems offer means to avoid circadian effects during certain times of day.

It has been demonstrated that the light emission of a visual display can be modulated such that the activity of melanopsin can be regulated independently of colour and luminance[75].

9 Individual differences

9.1 Chronotype

The term chronotype refers to the sleep-wake patterns of humans. The circadian rhythm is independent of the number of hours of sleep a person needs, but the midpoint of the sleep period is different for groups with different sleep patterns. Some persons start the day very early and tend to feel most energetic just after they get up in the morning. Others stay up late and can feel most awake in the evening and at night. Researchers have traditionally used the terms morningness and eveningness to describe these two phenotypes.

A chronotype is the behavioural manifestation of underlying circadian rhythms of myriad physical processes. A person's chronotype is the propensity for the individual to sleep at a particular time during a 24-h period. A general classification of the overall behaviour of humans is “morning types” (larks) or “evening types” (owls). Owls are persons who work better at night while larks are those who work better in the morning. A rather small group of people can do both (hummingbirds).

A 2007 survey of over 55,000 people found that chronotypes tend to follow a normal distribution, with extreme morning and evening types on the far ends[76]. According to Roenneberg, the distribution of circadian rhythms spans from the very early to the very late chronotypes, similarly to how height varies from short to tall.

After including 300,000 persons in the sample, the conceptual question whether chronotype represents a personal trait (an attribute of a person, free of situational effects) or a current state (an attribute of a person in a situation and attribute-situation interactions, see Reference [77]) has been clarified.

The differences between persons are deemed crucial even for the careers of persons, for example morning larks fit better in industries like farming, construction, and working for public utilities. Morning larks can also work the early shift in round-the-clock industries, such as emergency services.

9.2 Age dependency

Circadian rhythms in humans are age-dependent. It is explained that, developmentally, people are generally night owls in their teens while they seem to become larks later in life. Infants also tend to be early risers[78]. There is agreement that adolescents, biologically, have an internal clock that causes their midsleep to fall later than young infants and adults. Age dependency is genetically determined.

The findings suggest that the impact of external factors such as light on the individual will be different depending on the age. Consequently, the quantification of the retina mediated non-visual effects in dependency of the age is in the scope of the relevant standard[7]. In addition, the same lighting condition can influence older and younger persons differently because of the different spectral sensitivity of the eye (a shift toward red). It has been demonstrated that aging reduces the stimulating effect of blue light on cognitive brain functions[79].

As for the eye-mediated non-visual effects, CIE (see Reference [7]) demonstrates the age-dependency of the circadian stimulus (see 5.3, Table 2) for age groups between 25 and 90 years. For individuals below 25 years of age, no advice is given.

The effects of aging on vision have been studied for many decades. For example just one factor, reduced pupil size is responsible for a reduction of 40 % of incident light on the retina[80]. But this is only a single factor whereas the age-dependent degradation of the human eye is linked with various negative consequences both for visual performance and non-visual effects (see Reference [81]):

— reduction of the eye media’s transmittance;

— yellowing of the eye lens;

— increase of light scatter in the eye media;

— decrease of the eye’s accommodative capacity (presbyopia);

— decrease of the retinal operability;

— reduction of pupil size;

— modified spare time activities due to increasing immobility.

Since it is not possible to preserve visual performance in general, the consequences of aging can only be compensated to achieve certain effects, for example increasing the illuminance on the visual objects. However, this can lead to an increased glare sensation. A measure like that named above can be needed independent of time of day, but the accompanying non-visual light effects can be detrimental – at least in theory – if the measure is applied all around the clock.

While existing regulations on the lighting of work areas such as lighting standards failed to properly address known facts about the aging effects of the visual system which are not likely to cause adverse effects for other age groups, addressing non-visual effects for an age group that can aggravate the situation of others renders even more difficult.

9.3 Internal circadian time (body time)

Time is in most countries determined by political circumstances and does normally not correspond to the solar time which is calculated in each location by the position of the sun in the sky. In earlier times, each town had its own time with the sun reaching the highest position at noon time. Circadian rhythms are triggered by the sun, thus, their time differs from the political time to a certain extent. This can be up to three hours within Europe from East to West and affect people like jetlag, hence the term “social jetlag”.[77]

External factors that lead to a shift in the circadian rhythm of a person can disrupt it. Internal circadian time is different for each individual. Any circadian influence can therefore be different for each individual depending on the internal circadian time.

The effect of light on the circadian phase depends on the timing in relation to the individual cycle. When light exposure occurs in advance of the nadir of core body temperature, it delays the rhythm, and when this exposure occurs after the temperature nadir, it advances the rhythm[82]. For day-active people, this means that light exposure in the early morning is an important trigger to start the daily activity. This knowledge supports the experience with indoor lighting situations that seem to generate too low levels of light compared to outdoors whereas lighting levels at the night are being considered too high. Light in the evening can cause phase delay (see Reference [83]), and as recent evidence shows the exposure received from electronic displays and bedroom lighting can also have the same effect[84]. Therefore, leading chronobiologists recommend minimum lighting levels (>250 lx EDI) during daytime followed by limited exposure to light in the evening hours (<10 lux EDI) (see 4.6). The impact of visual displays can provide melanopic EDI levels of > 70 lx (above the typical level of exposure required to produce half-maximal subjective alerting, melatonin suppressing and circadian phase-shifting responses in laboratory studies)[1],[85].

Chronopharmacology, the study of how the effects of drugs vary with biological timing and endogenous periodicities, takes advantage of this knowledge. The goal is to improve our understanding of periodic and thus predictable (e.g. circadian) changes in both desired effects (chronoeffectiveness) and tolerance (chronotolerance) of medications.

The practical implication of the knowledge about the internal circadian time is that lighting needs to be highly individualized if circadian effects are intended. The same is true for aging effects. The discrimination between time as a physical entity and the individual body time indicates another new concept in understanding circadian effects of light and lighting.