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Review

Standardizing Melanopic Effects of Ocular Light for Ecological Lighting Design of Nonresidential Buildings—An Overview of Current Legislation and Accompanying Scientific Studies

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Abstract: DIN SPEC 5031-100 and CIE S 026:2018 are regulatory frameworks that are intended to establish health-preserving indoor lighting in Europe. Therefore, they are crucial for the visual environment and its sustainability. The standards are largely congruent. Inconsistencies should now be harmonized with the newly published draft standard DIN/TS 5031-100, for which the objection period ended on 3 June 2020; thus, it can be expected that the standard will soon be put into operation. This publication provides the reader with a detailed technical as well as medical overview of the scope and background information on how the standard came about. Applicable laws, ordinances and standards were compiled across countries, and related studies were reviewed. It is demonstrated that the focus of this new standard, as with previous versions, is on the melanopic sensitivity of ganglion cells. The authors base this on a literature search for projects about ecological lighting design over the past 20 years. However, in practice, the publication of the standard does not yet completely counteract the health effects of inappropriate indoor lighting.

Keywords: human centric lighting; standardization; DIN/TS 5031-100; melanopic effect

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1. Introduction

When examining the sustainability of light sources, it is important nowadays to consider many different criteria across systems, not only energy efficiency, but also recyclability, raw material use and production conditions. More recently, the health effects of light sources have also been taken into account by legislators. It is essential for ecological lighting design to match the mechanism to the functions of the human body and, therefore, to consider the health-related aspects of its sustainability, not only because it supposedly makes building occupants feel better in the long term, but also from the expectation that it leads to less sick leave among employees or fewer occupational accidents due to the prevention of fatigue.

Performing a career activity generally requires people to be at work or in a home office situation indoors for many hours at a time. Employees spent 419.9 h at their workplace in the third quarter of 2019, which equates to approximately 35 h per week. [1]. Apart from occupations in agriculture industries, forestry, as well as other exceptions, people spend time in an artificial (built) environment. In particular, in industrialized countries, people spend an increasing amount of time indoors. A U.S. survey of 9386 households found that respondents spend an average of 87% of their lives indoors. Between 11 pm and 5 am, even more than 90%. The top two indoor spaces where people spent most of their time were schools (public buildings) and offices [2]. In a 2019 survey, 962 Swiss jobholders were asked what they dislike about the place where they work. Poor working conditions, such as air quality and sitting for long periods of time, were the sixth most frequently mentioned aspect [3]. Numerous health correlations with a (built) artificial environment, especially in

relation to office buildings, are grouped together under the medical term 'sick building syndrome' (SBS). The specific implications are mostly attributed to the air quality caused by poorly regulated mechanical ventilation systems, but other physical factors, such as noise and lighting, also have a substantial influence [4]. SBS is also increasingly diagnosed in jobholders who are working in buildings that comply with current regulations regarding ventilation, indoor acoustics and lighting [5]. References such as this have already been the basis for political standardization decisions in the past. Indoor lighting as one of the most important pillars of a healthy working environment has already been amended in various legal and standardization texts [cf. Section 2.2]. The technical and marketing term 'Human Centric Lighting' (HCL) summarizes the state of the art and knowledge about the interfaces of the human body with light quality, illumination levels and color. Detailed medical relationships between light and health are highlighted in Section 1.1.2.

Taking a closer look into the domain of HCL, many more medical conditions, which are linked to the quality and intensity of interior lighting can be found. Therefore, it is particularly important to take care of related diseases with the help of a well-designed ecological interior lighting environment. Since the body's melatonin balance plays such a crucial role in human health and its disruption is also associated with serious medical problems, the melanopic effect of light sources has been included in HCL evaluation criteria [cf. Section 2.1]. A review paper, specifically, on the medical field of circadian disorder, was recently published in 2020. The paper distinguishes between circadian alteration and circadian disruption, provides deeper insights into the concept and measurement of this disorder, and examines field and laboratory studies [6]. These and other health disadvantages are described in Section 1.1.2. All of this information constitutes an important criterion in the evaluation options for the sustainability of light sources. However, much more has happened in the legislation of indoor lighting within the last 20 years. Numerous laws, ordinances and standards with different focuses and varying levels of detail regulate lighting products. The publication of the standard "DIN/TS 5031-100: Optical radiation physics and illuminating engineering-Part 100: Melanopic effects of ocular light on human beings-Quantities, symbols and action spectra" is the occasion for this compilation. It is currently a draft and intended as an update for the German pre-standard DIN SPEC 5031-100 from 2015. In central elements, such as action spectra, terms and definitions, it will be harmonized with international standard CIE S 026:2018 and compliant with it. A related review article, dedicated specifically to the CIE S 026:2018 standard, was published in 2021 and examines the framework primarily from a medical perspective [7]. The deadline for objections to DIN/TS 5031-100 was 6 March 2020, which is why it can be assumed that the standard will soon be applied [8]. However, even though the medical links between workplace lighting design and occupational health have been investigated for decades, and relevant results which also allow conclusions to be drawn about serious medical conditions have long been known, those legislations evaluate lighting systems, while no legislation has yet been passed that mandates them in the workplace. In most cases, the regulations only provide specifications for measurement and planning recommendations, such as DIN SPEC 67600 [9].

1.1. Interdisciplinary Knowledge

Sustainable lighting design is an area of intersection between engineering and medical sciences, while other sciences also play a dominant role as well, such as design and architecture. Researchers in the field of medicine have been able to gain increasing clarity about the relationship between light and health in recent years, while in applied engineering research, multiple new lighting technologies have been developed. It can be observed in the technological history that light sources based on the developed technologies prevail and are used as standard in numerous buildings for several years as the state of the art, as one trend supersedes the other.

1.1.1. Engineering Contexts

The technical development of interior lighting has resulted in numerous light sources, which can be divided into temperature radiators, discharge lamps and electroluminescent lamps. Before the invention of the light bulb, fossil fuels were used to illuminate rooms, which, based on fire, provided a natural light with a warm white color spectrum of light. Short wavelengths are underrepresented in the spectrum. Therefore, despite a nominal color rendering index of 100, the perception for blue and green colors is limited with the "fire" spectrum. Before the introduction of incandescent light, petrol lamps were used for a long time. Naturally, these caused many fires in public spaces and became dangerous in daily use. The incandescent light brought mainly logistic advantages, as no gas pipes were needed anymore, but a flexible electricity medium was used. Since the light bulb converts more than 87% to 98% of the electrical energy used into heat instead of light [10], most further technical achievements were primarily aimed at increasing energy efficiency. Further milestones after the incandescent light were, therefore, far more efficient halogen lamps and energy-saving lamps. In contrast to the light bulb, which offers a rather warm white spectrum, the spectral distribution of light intensity was uneven among these light sources, which were considered to be very innovative at the time [cf. Figure 1c]. Halogen lamps are also incandescent lamps, only operated at a filament temperature of ~3000 kelvin instead of 2700 kelvin, gaining more energy efficiency due to the related shift of the light emission towards shorter wavelengths, compared to light bulbs. In EN 15193-1:2017, a correction factor for taking into account the efficiency of the lighting technology was introduced. Incandescent halogen luminaires are described here with a correction factor of 4.49, whereas the common incandescent lamp has a factor of 6.38. The correction factor for discharge and fluorescent lamps of EN 15193-1 standard lies between 1.01 and 0.90 [11]. The energy-saving lamps are fluorescent lamps, which existed before as long tubular versions and were engineered to compact versions, which were able to be used as a replacement for incandescent bulbs. They achieve the necessary illuminance by individual peaks in the spectral distribution. Figure 1 compares the intensities in individual wavelength ranges of the visible and near nonvisible spectrum of different light sources. Incandescent light bulbs (temperature radiators) emit light in the entire visible range of the spectrum with high intensity in the range of long wavelengths. Due to their poor efficiency, incandescent lamps are rarely used in lighting systems today, especially because the market for incandescent light bulbs in the European Union (EU) has been limited in order to meet climate protection targets [12]. Fluorescent lamps (discharge lamps) produce light when electrical current passes through an ionized gas or metal vapor. Discharge lamps are divided in two categories. Low-pressure discharge lamps are producing mercury emissions in a first step. The UV proportion of the emission from mercury is converted into visible light at a phosphor coating on the inside of the tube. This produces a mix of residual emission lines from mercury in the visible part and a broader emission from the phosphor. By changing the phosphor composition, the light color of fluorescent lamps can be adjusted. The second category is high-intensity discharge lamps. They are operated at high temperatures, causing vapors of metal halides in the discharge vessel. The metal atoms and ions are excited and radiate typical emission lines for these metals. In most cases, these are rare earth metals, with a multitude of spectral lines, giving the impression of a quasi-continuous light emission. They emit a light that is distributed unevenly over the visual and nonvisual spectrum and differs vastly from the daylight spectrum. Discharge lamps are the still state of the art for the illumination of industrial halls and functional buildings. Slowly but surely, fluorescent lamps are leaving the market. Sales have fallen sharply. In 2014, for example, 1.96 million energy-saving lamps were sold in Switzerland; in 2019, though, it was only 0.32 million pieces [13].

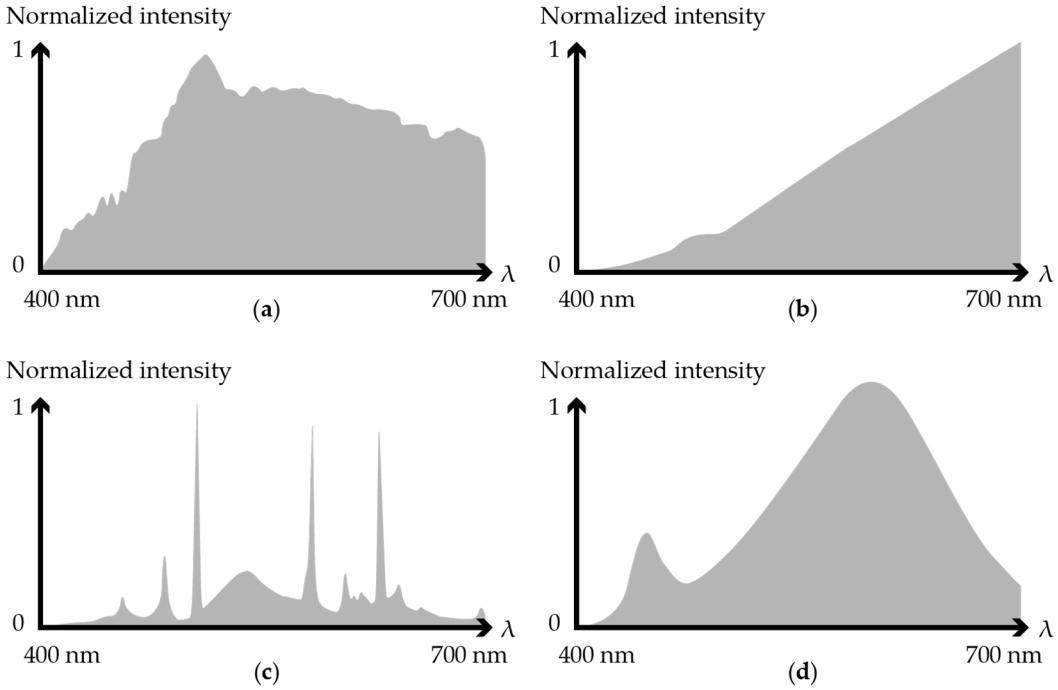


Figure 1. Spectral power distribution (SPD) of common light sources at 100 lx in the rage of 400 nm to 700 nm (normalized) in comparison; (**a**) sunlight filtered through the atmosphere; (**b**) incandescent light (e.g., light bulb); (**c**) fluorescent light (e.g., energy saving lamp); (**d**) LED.

It was not until the advent of light sources based on light emitting diode (LED) technology that experts were able to plan interior lighting specifically with a defined spectrum. Due to the further development of LED technology, different light colors could be produced. Since the first studies on the interface between lighting systems and user health were conducted at the same time, the basis of HCL technologies was built. In LEDs (electroluminescent lamps), electrical energy is converted directly into light in a semiconductor with a high degree of efficiency of about 80% to 90% [14]. The energy efficiency of LEDs for interior lighting closely follows. Therefore, the correction factor for LED lighting systems, following the EN 15193-1 standard, is 0.86 [11]. In white LEDs, the emission from the semiconductor is "blue", recently also "violet". This blue emission is partially converted to green-yellow-red light by a phosphor placed on top of the LED, which, together with the remaining "blue", is mixed with white light. Therefore, white LEDs are also somewhat "fluorescent". The focus in the introduction of the illuminant was energy performance, while another advantage over the previously mentioned light sources is their durability. LEDs lose on average 30% of their luminosity during 50,000 h of operation [15]. In the current state of the art, multichannel LED lighting systems are operated, which offer several diodes with different colored light at each 'light point' for special applications. The LEDs can be controlled via a BUS system so that a target color can be mixed. Depending on the design, the individually colored LEDs emit very warm to very cold white light colors or, for example, red, green and blue colors (RGB LED). By controlling the individual colors, almost any target color mixture can be created. Due to their high efficiency, LEDs are now predominantly used in new lighting systems. In 2014, 4.19 million LED-based lighting units were sold in Switzerland, whereas 12.29 units were purchased in 2019. This amounts to a market share of 57.78% compared to other light sources [13].

For the characterization of lighting systems—especially referring to LED electrical engineering—there are numerous measurement parameters that qualitatively and quantitatively evaluate functionality; energy efficiency; and, even in some cases, clinical efficacy. The emission of electromagnetic radiation is measured in luminance (unit: candela per

square meter) and illuminance (unit: lux) for all lamps. In France and Germany, for example, the corresponding specifications are provided by the DIN 5035-6 standard. Illuminance describes the intensity of the light falling on a target surface; luminance, on the other hand, describes the spatial and directional emission of light from a surface [16]. Today, it is known that even the standard measured quantities of lighting equipment have an impact on the health-preserving effect. For example, the illuminance in lux influences the body temperature and alertness of the exposed individual, albeit slightly. In a study from 1991, participants were exposed to a light source with 50 lx, as well as a light source with 5000 lx at night. The body temperature of the people in the bright environment varied between 36.7 °C and 37.1 °C, while the body temperatures of the subjects in the dark environment varied between 36.5 °C and 37.0 °C, for an exposure duration of 90 min [17]. Body temperature, melatonin levels and circadian phase are correlated. As light influences melatonin as well as circadian phase, today, this result seems obvious. In 1991, however, the situation was certainly different. In addition to the standard quantities, procedures for evaluating the energy efficiency of lighting installations have been introduced in European Standard EN 15193-1 and its predecessor versions. Specific electrical rating performance (watts per lumen or watts per square meter, etc.) are valid today and are particularly useful in terms of greenhouse gas reduction [11]. However, due to HCL, in recent years, far more specific metrics have started to gain prominence. Great importance was attached to color rendering (CRI). The dimensionless index indicates how accurately colors are reproduced from objects illuminated by the corresponding light source. Daylight and light from a black body radiator have by definition a CRI value of 100, while modern LED equipment achieves values over 98 [18]. The color temperature of an artificial light source in kelvin (K) likewise became an authoritative variable, since it can be easily compared with the different light colors of daylight during the course of the day. Shortly after sunrise, the daylight reaches approximately 2500 K; at midday, the value increases to between 5500 K and 8000 K, depending on the altitude of the measuring location on the Earth's surface, orientation of the measurement device, weather conditions and other influences [19]. This is the main reason for HCL-LED systems using multichannel techniques, offering adjustable light colors, such as tunable white. Luminaires emit their electromagnetic radiation at a frequency that varies depending on the illuminant. If this frequency is too low, flickering is noticed. Low frequencies are associated with physiological and psychological distress. Energy-saving lamps at 100 Hz caused headaches and eye strain, while the same lamps at a 120 Hz setting still impaired vision in concentration tests [20]. In HCL, the primary goal is to imitate the intensity, spectrum and color of light from natural daylight in order to create a healthy atmosphere for the users (employees) that corresponds to the evolutionary development of their bodies [cf. Section 1.1.2].

For future cutting-edge technological development in interior lighting technology, OLED luminaires are a candidate. A preview of this future technology is provided today by new luminaires that have already appeared as prototypes; lighthouse projects; and, in some cases, as commercially viable products. However, OLEDs have been a topic of discussion for 20 years, without significant progress to usage for indoor lighting. To date, the technology cannot compete with LED lighting systems with respect to energy efficiency, reliability and especially costs.

One example of an application in which new lighting technologies have been implemented in the past is airports. The various waiting areas of these particular buildings routinely accommodate travelers arriving from different time zones or traveling onward. Quite often, users face a situation in which they have to spend several hours indoors waiting for their connecting flight. On long-haul flights, they are in most cases outside their natural circadian rhythm. This is the reason for the interiors of airports, which are accessible to users, being environments in which circadian alterations and circadian disruptions are experienced [cf. Section 1.1.2]. In the 1980s, a study examined 186 patients with mental illness, and a relationship between the direction of flight (east to west or west to east) was established. For example, it was demonstrated that depression occurred significantly more

often in patients who regularly traveled against the Earth's rotation [21]. HCL LED systems can help adapt building users to the new environmental parameters in this use case, while even short intense exposures to artificial light can adjust the internal human clock [22]. It follows that even a short stay in transit areas, for example, can negate adaptation strategies.

1.1.2. Medical Contexts

Light is crucial for the health and well-being of people. Since the beginning of the human body's evolution, it depended on and was able to rely on a constant daylight supply. Sunlight influences physiological and psychological states, such as moods, emotions and attention, due to endogenic happiness hormone production; the circadian rhythm of other endogenous hormones [cf. Figure 2], e.g., melatonin, cortisol and adrenalin; the sleep–wake cycle; the strengthening of the immune system; and bone density by contributing to vitamin D_3 production.

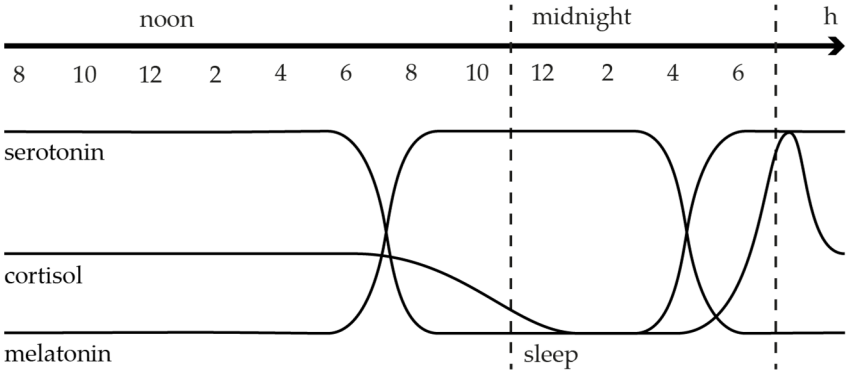


Figure 2. Circadian rhythm of the endogenous hormones serotonin, cortisol and melatonin during the course of the day (simplified and dimensionless); serotonin is mainly present in the daytime, while melatonin is present at night and during the time just before falling asleep. Cortisol has a peak shortly after awakening.

Vitamin D_3, as important as it is for the human body, plays no role in HCL. The supply of radiation, which is necessary for this vitamin´s production, is currently left exclusively to the sun. Vitamin D_3 requires UV-B radiation, which will not be available indoors or even outdoors over a wide range of geographical locations or sometimes during autumn and winter. It is difficult, and might not be advisable in the first place, to introduce vitamin D_3 production into indoor lighting. UV-B is critical for skin cancer and, therefore, has positive and negative effects that need to be balanced. This is outside the HCL discussion to date because mixing indoor lighting with vitamin D_3 might be critical. Indoor exposure to UV-B is a medical treatment and needs to be regarded as such. The required dose of UV-B for sufficient vitamin D_3 production is more or less comparable to the dose for 1 MED, which is 100 J/m^2. Administering three times per week a minimum of 50% of this dose would be required to produce more or less sufficient vitamin D_3 [23].

A small area of the hypothalamus, the suprachiasmatic nucleus (SCN), is seen as a "master clock", which has the task of controlling the circadian rhythm of the human body in interaction with the pineal gland. The pineal gland produces melatonin, but only if it is not efferentated (stimulated with sensory information) by the distribution of light. Melatonin is an endogenous hormone that the body synthesizes from serotonin. It controls the sleep/wake rhythm and, if it is present in the body in increased amounts, initiates the sleeping process. To efferentate the gland, SCN discharges its neurons and axons close to it, whenever bright light hits the eye´s retina. The system receives light information with the help of neuronal pathways from intrinsically photosensitive retinal ganglion cells (ipRGCs) in the retina of the eye via a nonvisual path. The ipRGCs react especially to blue light in the wavelength range around 484 nm [cf. Figure 3, solid line], which was shown in laboratory examinations [24]. During the same experiments, it was discovered that the ganglion cells

themselves are photosensitive without receiving signals from the typical photosensitive receptors (S-, M-, L-cones and rods due to their unique geometrical form). These receptors are responsible for the visual path of daylight vision in the retina. They have a maximum sensitivity of about 550 nm [25]. By means of external stimuli (especially light), the internal clock in the SCN is synchronized to the external 24 h cycle. When the light conditions decrease naturally, depending on the intensity of the blue light, there is a periodic reduction in the hormone serotonin, as well as the related production of the hormone melatonin, which serves to coordinate sleep [cf. Figure 2]. Strong light stimuli, e.g., bright artificial light with a high proportion of short-wave blue light, can desynchronize the internal clock; suppress the production of melatonin; and thus lead to sleep disorders and, in some cases, to more severe diseases, such as breast cancer in women [26]. Further explanations on this subject are provided later on in this chapter.

The nonvisual effect of light on the circadian rhythm depends not only on the spectral composition of the light, but also on a variety of other parameters, such as the intensity of the light, the time of exposure and the duration of exposure, as well as on the personal "light history". Individuals react differently to the same light stimuli at the same time depending on their predisposition (biological chronotypes 'night owl' or 'morning smile'), age and previous illness. In 2016, 26% to 29% of 1,063 interviewees (depending on age group) in a German study said they were a 'night owl'. In this survey, it was found that only 12% to 19% of the participants do not have sleeping problems in their daily lives. About half of them feel sleep deprived in the morning [27].

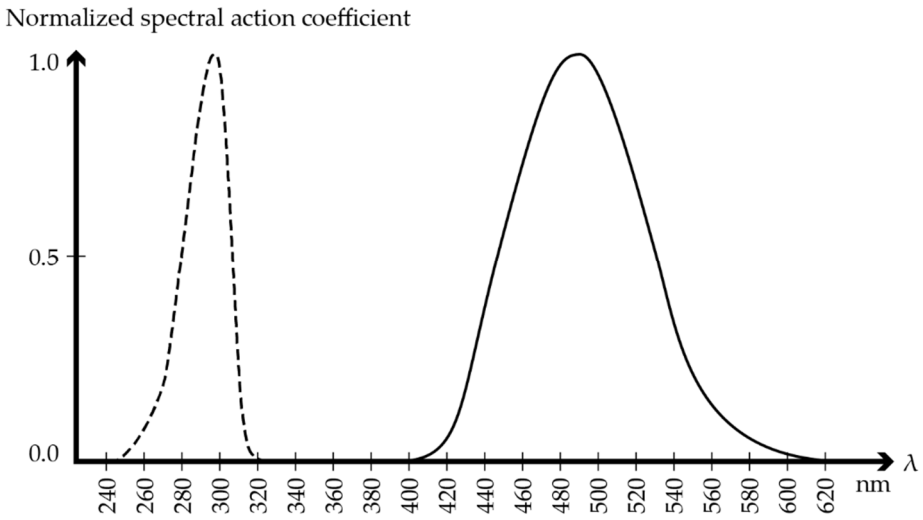


Figure 3. Human body´s reaction (dimensionless) to specific wavelengths (λ); dashed line: action spectrum of pre-vitamin D_3 [28]; solid line: maximum melanopic sensitivity for light effects (s_{mel}) according to DIN/TS 5031-100 [cf. 2.1] [8].

The eyes are not the only organs that interact with electromagnetic rays. When ultraviolet radiation hits the skin, pre-vitamin D_3 is produced in it. An action spectrum from 250 nm to 330 nm, peaking at 298 nm is documented in DIN 5031-10 [cf. Figure 3, dashed line] [28]. If exposure to UV-B radiation is prolonged, pre-vitamin D_2 is converted into trachysterol$_2$, with the highest action spectrum at 282 nm. Together with other endogenous hormones produced by the liver through the addition of nutrients, provitamin D_3 is eventually synthesized [29]

Apart from numerous disease patterns commonly associated with SBS (itchy or watery eyes, blocked or stuffy nose, dry throat, lethargy and/or tiredness and headache) [5], links to more serious diseases can also be established, if the exposure to poor indoor environmental quality (IEQ) is prolonged. The global number of cancer deaths in women is currently led by breast cancer (mammary carcinoma). In 2020, 684,996 women died from this disease [30]. The mortality rate from breast cancer is increasing in civilized

countries. E.g., African countries account for only 5.5% of global breast cancer deaths [31], although Africa is the second most populated continent in the world [32]. A clear link between the indication of breast carcinomas and building lighting systems cannot be established conclusively, since the development and spread of cancer cells in the human body depends on numerous influencing factors (nutrition, genes, immune system, etc.). However, environmental factors are mentioned as the main cause in numerous scientific publications [33–35]. Additionally, in a study in 2000, a large number of twins were statistically tested for different types of cancers in order to prove how high the risk through heredity actually is. Inherited genetic factors contributed less than initially thought to the development of most tumors [36]. The results indicate that the environment plays the main role in the development of many neoplasms, not only mammary carcinoma. As mentioned above, indoor lighting plays a substantial role in the evaluation of IEQ. In the above example in particular, the links between light as part of IEQ and health maintenance are clear, as the incidence of breast cancer has been medically linked to the disruption of the circadian rhythms of both cortisol [37] and melatonin [26]. Those endogenic hormones are both connected to the human sleep–wake pattern, which is partly controlled by sunlight. Employees who most likely take the human toll of the circadian disruption of endogenic hormones are shift workers. The International Agency for Research on Cancer (IARC) classified shift work as a probable carcinogen back in 2007 [38]. In 2008, 38 Danish women in shift work were diagnosed with mammary carcinoma. They were granted financial compensation in accordance with Danish law and the approval of breast cancer as an occupational disease in shift working is being discussed [39].

Further serious conditions associated with indoor lighting and especially with circadian rhythm disruption are long-term degenerative disorders of the central nervous system (CNS). Although cases of neurological diseases decreased by 122 in Germany, Austria and Switzerland from 2005 to 2015 and are projected to continue to decline, the number of cases of Morbus Parkinson remained constant, while the number of other degenerative diseases of the CNS, especially dementia, rose sharply [40]. This opposing trend can be traced back to lighting concepts. Fluorescent light, for example, is particularly inferior to daylight in terms of light quality [cf. Section 1.1.1]. A prolonged time indoors under the influence of this light source leads to the degradation of dopaminergic neurons in the CNS, which may be the cause of Parkinson's disease later on [41]. In addition, studies show that the endogenous hormone melatonin, whose metabolism is increasingly disturbed by poor-quality lighting, counteracts neurodegeneration, which is why melatonin supplements are preferred preventive measures against Alzheimer's disease [42].

A good summary of the medical effects of low-quality lighting can also be found in an article by Osibano et al. The team of scientists focused on residential buildings, as this is where users spend most of their time and long-term effects are highest [43]. We now examine the work that has been carried out in law making in the past and which current state of standardization prevails representatively in particular countries, in order to pose the open question of whether such a mandate would be useful. Ultimately, keeping workers healthy in the long term is a desirable objective that is established in employee protection laws in numerous countries, but HCL was disregarded for a long time, while the emphasis of interior lighting law making focused on energy efficiency.

2. Review

Review papers on the nonvisual interaction of the human body with electromagnetic radiation are already available in the current literature [44–46]. Distinct from and in addition to the existing work, the emphasis of this publication, henceforth, is on the development and specific background knowledge of current standardization, especially by more thoroughly observing underlying studies.

In order to obtain an overview of the currently applicable legislation with regard to HCL, employee protection laws, ordinances for lighting systems at workplaces, standards for workplace lighting and specific technical regulations from the origin of different coun-

tries were researched. The guidelines that apply across countries in the entire European Union were also recorded and evaluated. In order to obtain a non-European perspective in addition to the data, the generally applicable legislation for indoor lighting in the United States of America was also surveyed, as well as the rules that apply, in particular, in the state of California, since evidence has shown that the standards and regulations are somewhat more detailed in this region compared to the other U.S. states. The online platform Perinorm Application (perinorm.com) was used for the standard research. The corresponding German Chambers of Commerce Abroad were commissioned to assist in the research of French and U.S. standards. More than 10 chambers were asked to participate by providing a report, and several accepted. However, it was only possible to produce a comprehensive result for the countries documented in the publication, simply because most of the requested countries do not have structured rules concerning the subject of this review.

Since the detection of melanopsin-containing ganglion cells in humans and their spectral sensitivity in blueish radiation, it is no longer sufficient to evaluate optical radiation exclusively according to the photometric effect function described in DIN 5035-6 [16] nor its energy efficiency in lumen per watts as described in EN 15193-1 [11]. This is not to say that energy efficiency should henceforth play only a subordinate role. A review paper by Safranek et al. summarized the energy perspectives on biologically effective lighting systems. The results show that HCL systems require more electrical energy than classic LED systems and describe potential savings [47]. Further studies also show that control systems for energy-efficient lighting and, above all, the inclusion of daylight in the building simulation, not only have a positive effect on the energy balance of the building, but also on user health and satisfaction [48]. Depending on the time of exposure, narrow-band short-wave light causes the acute suppression of melatonin secretion and cortisol cycle disruption, which can lead to serious medical conditions, as already described. Additionally, while indoors, it is not possible to confirm that the body can maintain the complex chain of action for the production of vitamin D_3. Biologically positive effective light supports the human organism by health maintenance and is energetically evaluated independently according to the biological effect function. The health correlations of the measured variables with the human body (and which of its interfaces are responsible) were described in depth in Section 1.1.2.

This is the reason for the legislator having already made great efforts in the past to regulate healthy indoor lighting. However, specific laws, ordinances and standards can only be found in few countries. On 03 April 2020, the German DIN Standards Committee for Lighting Technology (FNL) published a draft standard that resolves many grey areas in current regulation.

2.1. Continued Development of DIN/TS 5031-100

Most standards are the result of consensus-based cooperation among industry, science, occupational health and safety and a range of other stakeholders. It must, therefore, be kept in mind that a standard does not always represent the best solution, but rather the lowest common denominator on which everyone involved can agree. Nevertheless, the principle that standards and laws should be based on existing knowledge and the state of the art always applies. In most cases, the working groups involved in drafting new rules draw on current published studies by research institutes. The most important research projects, which in the past were the basis for regulations and standards that in some cases are still in force today, are examined in more detail.

The core statement of the different versions of standard 5031-100 is the melanopic effect of electromagnetic radiation in the visible range [cf. Figure 3, solid line]. In the future, it will be possible to use this evaluation criterion to characterize indoor lighting with regard to its effects on the melatonin metabolism of the building occupants (employees) bodies. The regulatory framework is based on scientific evidence. As early as 1980, a study was published in the scientific journal '*Science*' in which melatonin suppression was

associated with bright artificial light sources [49]. The first studies investigating the relative spectral sensitivity of ipRGCs in detail were already conducted 20 years ago and have been updated and improved since [cf. Table 1]. The final result is based on numerous research projects, which all aimed to determine the wavelength for which the responsiveness of the photosensitive ganglion cells (ipRGCs) is the highest.

Table 1. Findings of wavelength range with maximum melanopic sensitivity (s_{mel}) that leads to ipRGCs upstream of related research projects.

Study	Year	Participants	Investigated λ	λ with Max. Melanopic Effect
Brainard et al.	2001	72	420 nm-600 nm	464 nm
Thapan et al.	2001	22	424 nm–548 nm	456 nm
Lockley et al.	2003	16	460 nm, 555 nm	460 nm
Figueiro et al.	2004	4	460 nm	N/A [1]
Figueiro et al.	2004	model *	400 nm–700 nm	480 nm
Gall	2004	model *	470 nm–510 nm	460 nm
Cajochen et al.	2005	10	460 nm, 550 nm	460 nm
Panda et al.	2005	cell culture *	410 nm–520 nm	479.8 nm
Brainard et al.	2008	26	420 nm, 460 nm	460 nm
Rea et al.	2010	Model *	420 nm–600 nm	488 nm
Bailes Lucas	2013	cell culture *	420 nm–600 nm	479 nm/490 nm [2]
Lucas et al.	2013	Model *	400 nm–700 nm	N/A [3]
DIN/TS 5031-100	2021			490 nm

* No subject trials. [1] Aim of the study was to investigate the difference between halogen and LED lighting with same λ value. [2] The second value considers age correction due to changing eye lens transmissions and color. [3] The study states that four retinal components (S-, M-, L-cones and rods) with different sensitivities trigger ipRGCs upstream.

After indications for photoreceptors other than visual ones were discovered in mouse eyes, in 1991, the implication of circadian rhythm was concluded in humans as well [50]. During subject tests, a ganzfeld dome is positioned around the participant. This sphere can be illuminated with a light source and provides homogeneous illumination. External light influences are thus reduced to a minimum. Brainard et al. in 2001 were among the first teams of scientists to undertake a dedicated experiment in participants on the wavelength sensitivity for melatonin suppression, one of the basic nonvisual circadian effects of light, which is relevant to the development of current standards. The study was conducted on 37 female and 35 male participants with a mean age span of 24.5 years. The exposure took place between 02:00 a.m. and 03:30 a.m. The duration was set to 1.5 h. The range of investigation was between 420 nm and 600 nm. Each wavelength range was tested on no fewer than 8 subjects. There was a wash-out phase of six days between each test. For each participant, ten study nights were conducted, adding up to 720 trial performances [cf. Figure 4a] [51]. In the same year, an independent, less comprehensive study with the same objective and similar study investigation scope was underway. Thapan et al. exposed 18 male and 4 female subjects with a mean age span of 27 years to the wavelengths (λ) 424 nm, 456 nm, 472 nm, 496 nm, 520 nm and 548 nm for 0.5 h each. The exposure took place between 11:30 p.m. and 02:30 am. At 1.5 h before the experiment, one drop of Mimins Tropicamide was given to each of the subjects' eyes [52]. Due to inconsistencies between the two studies in the short-wavelength range (approx. 420 nm) and new insights into the understanding of mammalian photoreceptors with the discovery of melanopsin, Brainard et al. repeated and extended their experiment in 2008. The study was divided into two parts, with 8 subjects (4 females and 4 males with mean age span of 24.5 years) exposed to only 420 nm light and 18 subjects (nine females and nine males with mean age span of 47.1 years) in which the physician tested the difference between (λ) 420 nm and (λ) 460 nm. The subsequent study confirmed the findings of Brainard et al. and Thapan et al. in 2001. Wavelength ranges around 420 nm inhibited melatonin to a much lesser extent than (λ) 460 nm [53]. Another comparable study with 8 male and 8 female young subjects (mean age

23.3 years) was conducted by Lockley et al. Only two wavelength ranges were compared in the study. (λ) The inhibition of melatonin by 65–69% was observed for 420 nm, whereas (λ) 555 nm inhibited it by 0% to 88%. Therefore, light with 420 nm wavelength shifted the circadian rhythm of melatonin significantly more, whereas the effects of (λ)555 nm were less specific [54]. Another study from Cajochen et al. was consistent with the results as well [55].

In addition to subject experiments, laboratory studies in which ipRGCs or other photosensitive cells were irradiated ex situ have been performed repeatedly in the past. In these projects, under laboratory conditions, more accurate values can be analyzed, independent of the numerous biases that 'real' subjects bring with them due to their daily lives. In a U.S. laboratory study, the maximum sensitivity of melanopsin was reported to be 479.8 nm in 2005, which differs slightly from that in the subject tests [56]. Since the target endpoint in the subject studies was melatonin, it is, therefore, reasonable to assume that the study of individual ganglion cells is not sufficient and that more complex interactions with other photosensitive cells are likely to be responsible. Figueiro et al. followed the approach of Brainard et al. and Thapan et al. with a small subject study and confirmed their results. In addition, the team of scientists calculated a mathematical model and laid a predictive curve over the measurement results of the known studies at that time [57].

Respecting the data of Brainard et al. and Thapan et al., another melanopic model was created that took into account the pre-receptoral shifting by Gall et al. in 2004 [cf. Figure 4b] [58]. A more comprehensive but competing model was presented when the Circadian Light (CL_A) Equation was established in 2008 and 2011 by Rea et al. [59,60]. The equation combines and weights stimuli not only from ipRGCs, but also from the visual photoreceptors to determine a certain circadian stimulus (CS). The model predicts that a CS > 0.3 has a strong effect on the nonvisual system, while CS < 0.1 has a neglectable effect. Applying this equation, for example, a lighting situation of 2856 K and 1000 lx results in a normalization of the CL_A value of 1000. The CL_A equation and the associated model were updated several more times to comply with current research findings and enabled an evaluation of the impact of lighting systems on human health. CL_A found application in stakeholder reports and design guidelines, such as Underwriters Laboratories (UL) DG 24480 [61]. Based on Brainard et al., Thapan et al. and the model of Gall, the DIN Standards Committee Lighting Technology (FNL) started to work on a first draft of 5031-100 during that time. In June 2009, DIN V 5031-100 was published [62]. However, the model system by Rea et al. was not pursued further in the development of the 5031-100 standard. In particular, the graph obtained by following the mathematical model displays significant differences compared to the curves of the subject tests, mainly by showing a snap-action function in the range ±500 nm [cf. Figure 4c]. These uneven areas in the diagram appear unnatural. At constant illuminance, this causes the CS value to drop by nearly half in the range from 3400 K to 3500 K, and to rise again with increasing color temperature. This leads to the inconsistency that, at the same illumination level, 3000 K and 5000 K lighting can have the same CS value.

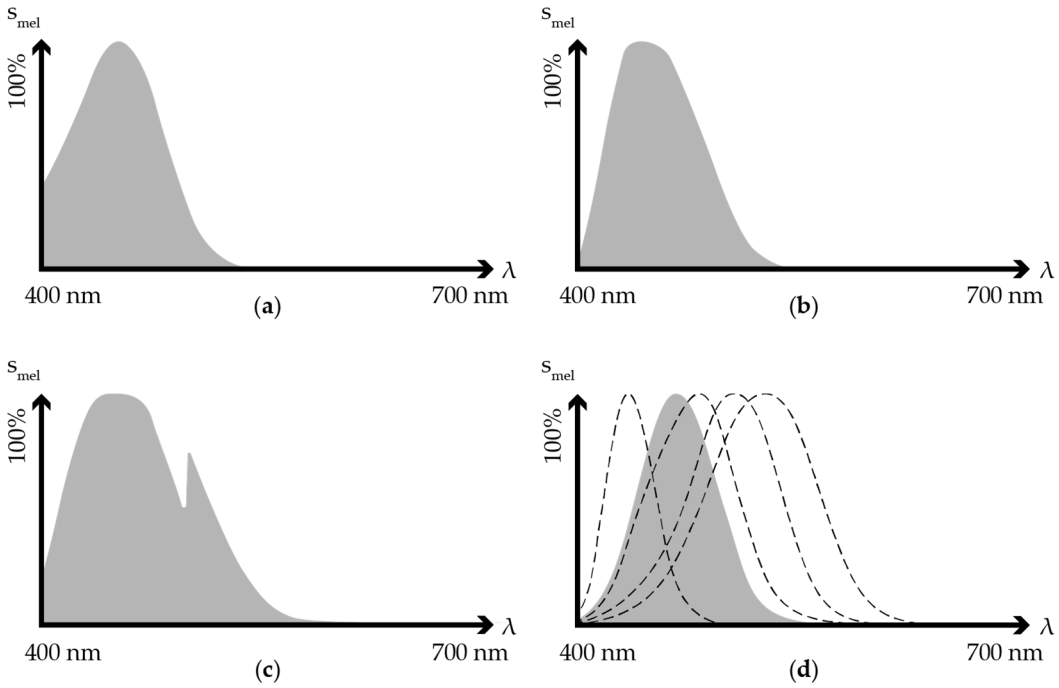


Figure 4. Optical comparison of selected research findings in the rage of 400 nm to 700 nm: (**a**) distinct curve based on numerous subject trials by Brainard et al. (simplified) [51]; (**b**) slightly asymmetric curve by von Gall, which was adopted in DIN V 5031-100 (simplified) [58,62]; (**c**) specified effect curve of Rea et al., which is based on a mathematical modelling (simplified) [59]; in the range of 500 nm, the curve shows an unusual expression (snap-action function); (**d**) curve pairs of Lucas et al. based on laboratory tests and mathematical modelling which was adopted in CIE TN 003:2015 (simplified) [54,63]; dashed lines: spectral action of the other photoreceptors.

Another milestone in understanding the sensitivity of ipRGCs was reached in 2014 when, in an opinion statement by Lucas et al., based on the so called 'Manchester Workshop', the previous approach was deemed not to be sufficiently accurate, as ipRGC firing has been shown to be triggered by intrinsic melanopsin-containing ganglion cells as well as by the additional photoreceptors also connected to ipRGCs [54]. The study proposed the concept of an integrated signal composed of the specific sensitivities of all photosensitive cells [cf. Figure 4d].

- S-cones (s_{sc}): 420 nm;
- M-cones (s_{mc}): 535 nm;
- L-cones (s_{lc}): 565 nm;
- rods (s_{rh}): 500 nm (507 nm if corrected from pre-receptoral shifting);
- melanopsin (s_{mel}): 480 nm/490 nm.

Lucas et al. hosted this International Commission on Illumination workshop in Manchester, during which the proposal was discussed, and a freely available irradiance toolbox was developed. A report on the workshop was merged with the study by Lucas et al. into the technical note CIE TN 003:2015 [63]. Lucas et al. also justified the reported maximum wavelength sensitivity with laboratory studies of ganglion cells and melanopsin ex situ. They corrected the resulting λ value by a slight red shift to a final value of 490 nm. This shift was taken into account to compensate for the age-based discoloration and change in the opacity of the human eye lens, as well as the different opening and closing behavior of the pupil. FNL of the German Institute for Standardization included the new findings from previous studies in the further development of 5031-100. In the draft DIN SPEC 5031-100, the curve for the wavelength-specific sensitivity of melanopsin from the statement by Lucas et al. and CIE TN 003:2015 can also be found. DIN SPEC 5031-100 was published on 01 August 2015. Compared to the previous version, biological light effects are summarized under the term "melanopic" light effects. The action spectrum for melanopic

light effects was redefined according to the current state of scientific knowledge. For the metrological description of light with regard to its melanopic effects, melanopic daylight-equivalent quantities were defined by referring these quantities to the corresponding photopic weighted quantities for daylight (D65), which is the standardized spectral power distribution for the visible part of the spectrum of natural daylight. Parameters for a photometric description of exposure were defined [64].

Another result of the Manchester Workshop was the introduction of the "melanopic lux" and "equivalent melanopic lux" (EML) assessment parameters, which are now mainly used in the USA, although they are not mandatorily regulated [cf. Section 2.3]. EML can be calculated by multiplying the measured lux value by a factor representing the luminaire-specific melatonin suppression. This procedure has the advantage that the melatonin inhibition can be indicated not only for the typical spectrum of the illuminant in general, but also as a snapshot depending on the adjusted classical illuminance [63]. Strictly speaking, however, the EML is thus not congruent with the generally applicable SI system of units and CIE S 026:2018. The differences, advantages and disadvantages of the various approaches have been studied by various scientists in the past [65–67]. The concept is not considered in DIN/TS 5031-100, which is why it is not addressed more in detail here.

With the upcoming publication of DIN/TS 5031-100 in 2021 or early 2022, the most important step towards the harmonization of the German standard with applicable global standards will be taken. Multiple terminologies and definitions were adapted to CIE S 026:2018, and missing terms and explanations were added. The correction function for age-dependent lens transmittance was redefined according to CIE 203:2012, and simplified approximation formulas for the evaluation of age-dependent lens transmittance in white light were amended. Furthermore, another correction function for the melanopic evaluation of the material-dependent transmission and reflection of light was introduced [8]. This standard considers and cites the previously described available evidence from research by Brainard et al. [51,53], Thapan et al. [52], Figueiro et al. [57], Gall [58], Lockley et al. [54], Cajochen et al. [55] and Lucas et al. [54]. An overview of the studies and their results is shown in Table 1.

2.2. Standardization in the European Union

The introduction of new rules follows a long causal chain, not only in the construction industry. Basically, a rule pyramid applies [cf. Figure 5]. This means that the most specific rule must always be applied if one exists. If there are no specific rules for an application, the next most nonspecific rule is chosen. The most general rule is a law. The further down the rule pyramid one follows, the more detailed the specifications in the corresponding sets of rules become. The following section examines the current situations of legislation in the European Union. There is no question that the laws in force in the majority of countries around the world protect the health of workers. However, it is advisable that, taking the example of integrative lighting systems for buildings, this protection needs more consideration in the detailing of the laws, because the dangers are slow to materialize and abstract. Biologically effective LED systems have not yet emerged as the most common choice of professional and nonprofessional customers in the lighting industry, even in 2021.

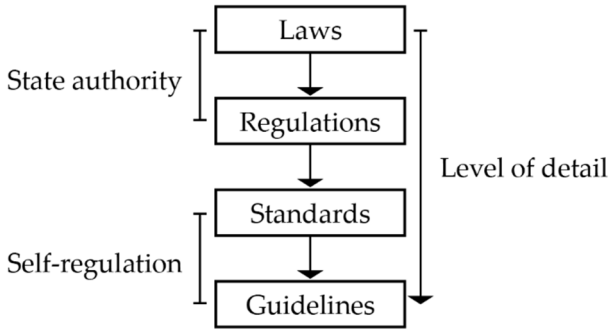


Figure 5. Hierarchy of legislations.

For the member states of the European Union, great efforts are currently being made to harmonize legislation. A number of national regulations have resulted in requirements, which are currently being processed by four authoring institutions.

- Commission internationale de l'éclairage (CIE), Division 6 "Photobiology and Photochemistry";
- European Committee for Standardization (CEN), Technical Committee "Light and Lighting" (TC 169), Sub-Committee "Non-visual effects of light on human begins" (WG 13);
- German Institute for Standardisation (DIN), Standards Committee Lighting Technology (FNL), Board "Wirkung des Lichts auf den Menschen" (27);
- International Organization for Standardization (ISO), Technical Committee (TC) "Light and Lighting" (274).

The currently existing German standard DIN SPEC 5031-100 is largely congruent with the CIE S 026:2018 of the international nonprofit organization CIE, which always aims to be as scientific as possible, without too much economic and political interference. The CIE was established for international networking on lighting issues and works closely with ISO. For Europe, there is also the technical report CEN/TR 16791, which is largely identical to CIE S 026:2018 as well. All inconsistencies between these three sets of rules have been resolved with the new version of DIN. DIN/TS 5031-100 represents a significant step forward with regard to a common standardization of healthy indoor lighting systems in the EU.

2.2.1. Standardization in France

In the current state of the legislature of France for interior lighting, numerous laws and ordinances can be found, which deal with some aspects of the subject area 'light and health'. However, since most of the articles date back to the 1980s, and at that time the HCL relationships had not yet been researched, only basic photometric parameters, such as luminance and illuminance, are considered. Naturally, therefore, the melanopic effect is not included.

The following information was collected with the help of the German Chamber of Commerce Abroad in France and is quoted and translated from their report [68].

Under French law, the employer must arrange worksites and premises in such a way that their use ensures the safety of employees. Worksites are defined as places intended to accommodate workplaces, whether or not they are located in the buildings of the establishment, as well as any other place in the area of the establishment to which the employee has access in the course of his work. These workplaces shall be maintained in a constant state of cleanliness and shall be hygienic and sanitary to ensure the health of the persons concerned. The right to a secure workplace is guaranteed to the employee by the French law article L4221-1 "Code du Travail". The conditions for the application of this article are established by the decrees of the Council of State (Conseil d'Etat) provided in article L. 4111-6 [68] (translated by the author).

Some laws that prevent health problems caused by workplace lighting are listed in article R4223-1, article R4223-2 and article R4223-3 "Code du Travail". The purpose of the regulations on the interior lighting and illumination of workplaces is to prevent eye strain and resulting eye diseases and to enable the recognition of hazards that can be identified with the eyes. These provisions apply to worksites; their adjoining spaces, such as corridors and stairways and outdoor areas where work is performed continuously; and circulation areas normally used during working hours. To the largest extent possible, workspaces shall have adequate natural light and lighting levels appropriate to the nature and accuracy of the work to be performed. Appropriate measures shall be taken to protect workers from glare and eye strain caused by surfaces with high luminance or excessive luminance ratios between adjacent surfaces [68] (translated by the author).

While occupants are present, certain illuminance levels measured at the surface of the task area at the workplace or, if not present, at the floor, must be at least equal to the minimum values established according to the type of premises. The minimum values for workspaces are documented in article R. R232-6-2 and article R. 4223-4 "Code du Travail". The French standard X 35–103 provides examples of average illuminance levels in operation, recommended by type of operation, and the adjustments of illuminance levels to the various conditions encountered. Additionally, the regulation mandates the following points in detail:

- Uneven distribution of light at the level of the work surface;
- Various factors that lead to a reduction in illuminance over time, in particular, the dusting and aging of the luminaires, the wear of the lamps and the dusting and aging of the walls of the room;
- Frequency of the maintenance to be performed.

The purpose of article R. 232-6-3 is to limit the illuminance ratios and, therefore, take into account the reflection factors and the luminance ratios, which are also referred to in article R. 232-6-5. For example, if the illuminance of the working areas of a room is 1000 lx, the general lighting of this room must not be less than 200 lx [68] (translated by the author).

The difficulty of luminance measurement has led to the fact that in the regulating article R. 232-6-5, no limiting values have been established. In general, the larger the apparent dimensions of a surface and the closer it is to the center of the employees' field of view, the lower its luminance must be. Thus, in the central field of view of an observer: The luminance of a light source shall not exceed 3000 cd/m^2. The luminance of a large luminous surface (wall, ceiling luminaire) should not exceed 600 cd/m^2. Finally, the luminance of a luminous surface should not exceed 50 times the luminance of the surfaces on which it appears, with a tolerance of 80 times for large surfaces with illuminance not exceeding 300 lx. All these precision values can be guided by the French standard X 35-103, which uses diagrams to establish more precise luminance values depending on various factors, such as [68] (translated by the author):

- Type of light source;
- The position and orientation of the sources;
- Illuminance value of the task;
- Difficulty of the task;
- Luminance;
- Illuminance ratios among working surface, ceiling and side wall;

Up to date HCL related laws, ordinances or standards cannot be found.

2.2.2. Standardization in Germany

The hierarchical chain of regulations is clearly represented in Germany and is led by the ArbSchG "Arbeitsschutzgesetz" (Act on the Implementation of Measures of Occupational Safety and Health to Encourage Improvements in the Safety and Health Protection of Workers at Work), which ensures the safety and health of employees [69]. The main statement regarding health maintenance at the workplace is that the state of the art in

science and technology must be taken into account. There are no precise instructions in this law. The detailing of the measures takes place in the ArbStättV "Verordnung über Arbeitsstätten" (workplace ordinance). The lighting of workplaces is mentioned several times, but is regulated in more detail, in particular, in the annex number 3.4 on illumination and line of sight [70].

This annex—comparable to the regulations in France, but much more comprehensive—regulates the minimum illuminance levels that must be maintained at workplaces. In addition to lux, however, this technical rule also specifies a minimum value for the color rendering index, which could not be found in the other countries investigated. For example, these different values are given in this annex for workplaces [71]:

- 100 lx and R_a = 40 for stairs, escalators, moving walks and elevators;
- 50 lx and R_a = 40 for night operation (transition area in front of the building);
- 500 lx and R_a = 80 for auditoriums;
- 500 lx and R_a = 80 for laboratories and measuring stations;
- 500 lx and R_a = 80 for writing, reading and data processing;
- 1000 lx and R_a = 80 for electrical industry—very fine measuring instruments.

Many standards regulate light exposure in Germany, such as DIN 5035-3, which regulates lighting in healthcare settings; DIN 5035-8, which regulates luminaires for individual workplace lighting in addition to ASR 3.4; and DIN 5034, which regulates daylighting in indoor spaces.

DIN/TS 5031-100 and DIN/TS 67600, both of which are expected to be implemented soon, take into account much more recent parameters of the scientific relationship between light and health. However, there is no guarantee that standards such as these will be reflected in laws and regulations. Change happens very slowly due to the many stakeholders involved. The German Statutory Accident Insurance (DGUV) is an organization that issues regulatory texts. In 2018, the DGUV published DGUV Information 215–220, an information brochure which covers the state of art regarding scientific knowledge and related recommendations for workplace lighting with respect to the nonvisual effects of light. It covers basic information and provides recommendations on how to handle this topic at workplaces [72]. The German Federal Institute for Occupational Safety and Health (BAuA) operates a workplace committee, which, together with the DGUV, considered melanopic effects in a publication for the first time very recently. This text requires that workplaces should not be illuminated at night with a colder light color than 4100 K [73]. Basically, this would mean that colder light colors are no longer permitted in workplaces at night, as the state of the art has been extended in this regard, but it is not yet stated in the relevant legal texts. It is likely that 4100 K was selected because there are numerous luminaires in use with a color temperature of 4000 K. A request to allow nighttime lighting only at below 4000 K would have triggered enormous modernization measures. Nevertheless, the publication of DIN/TS 5031-100 and other related standards represents a significant milestone for the HCL legislature, as the scientific framework is now documented in a public set of rules. In the future, laws and ordinances will be able to refer to it.

2.3. Standardisation in the USA

Through the efforts of Brainard et al. and other research teams, the U.S. became a front-runner in terms of HCL. However, in reviewing the large number of research projects examined for this publication, it is striking that the United States went into a kind of slumber for several years in terms of specific research. This picture is also reflected in the legislature. The relevant regulating body for employee health and/or interior lighting is the Occupational Safety and Health Administration (OHSA). During the screening process for laws, regulations and standards according HCL, however, it quickly became clear that despite the size of the country, its economic importance and the scientific progress, the regulation of indoor lighting lags far behind other countries. However, similar to France, minimum illuminance levels have been established for workplaces.

The following information was collected with the help of the German Chamber of Commerce Abroad in the USA and is quoted and translated from their report [74].

In summary, OSHA does not currently regulate illuminance in office spaces. Most office spaces are regulated under OSHA's general industry standards, which fall under the jurisdiction of 29 CFR 1910. However, again, no specific requirements apply with respect to specific illuminance levels (except perhaps in a general sense related to occupational safety and safety on walking surfaces, and the prevention of slips, trips, and falls there). OSHA states that it generally supports some lighting consensus standards offered by professional building and engineering organizations and others. However, it has no formal affiliation with them [74] (translated by the author).

Under the general rule of 1926.56 (a) CFR, construction areas, ramps, runways, corridors, offices, stores and storage areas must be illuminated to at least the minimum illumination levels specified in Table D-3 [of 1926.56 (a) CFR] while work is in progress. Foot-candle (fc) is a nonmetric unit of illuminance; one foot-candle equals 10.76 lx:

- 5 fc at general construction area lighting;
- 3 fc at general construction areas, concrete placement ("concrete placement"), excavation and waste areas, access roads, active storage areas, loading platforms, fueling and field maintenance areas;
- 5 fc at interiors of warehouses, corridors, hallways and exits;
- 5 fc in tunnels, shafts and general underground work areas: (exception: a minimum of 10 foot-candles required at the tunnel and shaft head during drilling, measuring and scaling;
- 10 fc at general structures and stores (e.g., mixing plants, screening plants, mechanical and electrical equipment rooms, carpentry shops, rigging lofts and active storage rooms, mess halls and indoor restrooms and workrooms);
- 30 fc in first aid stations, infirmaries and offices.

Per 1926.56 (b) CFR, for those areas and/or operations not covered above, information on recommended lighting levels can be found in the American National Standard A11.1–1965, R1970 Practice for Industrial Lighting [74] (translated by the author).

The Illuminating Engineering Society (IES) is developing standards that are more deeply implicated in connections between light and health. However, these standards are voluntary measures. To date, HCL-related mandating laws or ordinances cannot be found.

The commercial certification organization "International WELL Building Institute" introduced a "WELL Building standard" in 2015 and a revised version in 2019, which includes a lighting related category. In this lighting category, circadian aspects are assessed. They recommend at least 250 equivalent melanopic lux (cf. CIE TN 003:2015 [63]) for most workplaces over 4 h per day. Although the certification they offer to building owners does not mean that it is in any way mandatory, this fosters the inclusion of better lighting, especially in higher quality office spaces. Meanwhile, they have also expanded this certification to Europe and Germany.

3. Discussion

It is no longer sufficient to base the sustainability of lighting systems on energy efficiency. In modern times, we behave increasingly in contradiction to behavior learnt by our bodies over hundreds of thousands of years of evolution. Therefore, it becomes vital that we consider the health-related aspects of lighting design sustainability by taking precautions to counteract the specific negative health effects. Since it cannot be generally assumed that everyone knows the correlation between light and health, specific regulations are reasonable. Nevertheless, regulatory frameworks for HCL have not been established in the countries surveyed. It is important to understand that lighting can be used to trigger different processes in the body. Whether these processes are good or bad depends, for example, on their suitability to the body's chronological rhythm. High-quality light at the right time has beneficial effects, while specific colors, wavelengths or intensities of light at the "wrong" time can be harmful to the body in the long term. The nonvisual effect of light

has been deeply researched. However, sets of rules should now prescribe when to apply the intensively studied maximum sensitivity of the melanopic effect, including workers who have a shifted rhythm due to their labor. In this context, it is possible that the compliance with health maintenance is in conflict with other regulations of employee protection, for example, while on the one hand, exposure to a bright artificial light source makes working with heavy machinery safer, but on the other hand, it does not fit the worker's circadian cycle at that time. These are conflicts of interest that make it difficult for the workplace operator to comply with the relevant employee protection laws. Here, it would be useful to provide the employer with a basis for decision making with a reasonable legislation.

A wavelength sensitivity also applies to vitamin D3 production [cf. Figure 3, dashed line]. Corresponding studies can already be found in the literature for the current state of knowledge and were discussed in Section 1.1.2 as examples. However, the evaluability similar to the 5031-100 approach is in question. There is no correlation with nonvisual photoreception. Additionally, there might be no way to include UV-B radiation in a reasonable and responsible way in indoor lighting. This requires, for example, for the elderly, a medical observation. It strongly depends on individual parameters, such as skin-type and age, and other parameters, such as existing skin conditions, which make a general regulation very difficult. An approach which is not accompanied by health issues, though, is oral medication with vitamin D_3. This may be included in selected nutrition on a legal basis.

The evaluation of Table 1 clearly shows a shift in the final sensitivity results over time to the longer wavelength range, from about 460 nm to 490 nm. The main reason for this is the consideration of the stated relevant manipulative factors, such as lens opacity and discoloration. In 2014, among the more recent publications by Lucas et al. was another milestone in the research of the melanopic effect of light sources. In the scientific paper, the researchers propose an integrative approach with five sensitivity functions [cf. Figure 4d], since, according to them, the sought-after effect was not solely dependent on ganglion cells, but also on the classical photoreceptors: "[. . .] These five input signals are then combined by the retinal wiring, and within the ipRGC itself, to produce an integrated signal that is sent to nonimage-forming centers in the brain." [54]. However, the final version of 5031-100 again adopted only one of the curves, comparable to the previous approaches, from the researchers' study results. In the CIE S 026:2018, all five curves are considered, and the consideration of all photosensitive cells in the human eye is strongly recommended when performing scientific studies. The model of Rea et al. also considers four of these five curves, even with deviating sensitivities. Nevertheless, the DIN committee decided to neglect the curves that do not belong to the ganglion cells. The experts were aware of having to accept an uncertainty of an estimated 5–10%. However, this uncertainty plays a role mainly in low-illuminance environments with relatively small lux levels, which are not relevant for indoor lighting design purposes. With the common illumination of a workplace of 500 lx to 1000 lx, the melanopic effect is dependent on the pigment formation in the ganglion cells with a linear, almost exclusive dependence, which was the main reason for this decision [75] (transcribed by the author).

Lucas et al. conducted another 'Manchester Workshop' in 2020. The publication resulting from the proceedings of the workshop confirms the fact that the melanopic effect in bright environments is mainly dependent on ganglion cells. However, the publication has not yet gone through the peer reviewing process and to date has only been published as a preprint from Brown et al. [76]. However, a basic statement was that focusing on the melanopic description of light is a reliable approximation for most practically relevant situations.

"In total, the evidence from such studies supports the view that, under most practically relevant situations (extended exposures to polychromatic light in the absence of pharmacological pupil dilation), light-sensitivity of human physiological responses can be reliably approximated by the α-opic irradiance for melanopsin or the corresponding EDI (melanopic EDI)." [76]

When investigating the melanopic effect of lighting systems, the focus in scientific studies is primarily on the clear relationship between light source specification and the receptors of the human body. However, in most cases, the light emitted (e.g., by a LED) reaches the user's receptors that are hindered and manipulated by obstacles, such as airborne particles. The biological effect actually achieved in exposed humans is, therefore, the result of a long causal chain. The spectrum and intensity of the emitted light is directly modified by the geometry and materiality of the lamp body. Studies have shown that the reflectance of surfaces in the room can have a modifying effect on shortwave electromagnetic radiation, thereby altering melanopic effects to some extent [77]. It is not typical to have such a clear setup reproducing the results from DIN/TS 5031-100 in practice. Even if a person is directly at the light source and looking into it, the direct light is mixed with nondirect light that is emitted from the surrounding walls. These uncertainties can be addressed by measuring the so-called corneal illuminance. As a distinction to the classical illuminance, which is measured, for example, on the surface of a workplace, the corneal illuminance indicates the amount of light that finally hits the human cornea. Exemplary modeling procedures for determining this metric have already been proposed [78]. These numerous dependencies indicate that the luminaire specification alone is not sufficient to determine the biological effect of a lighting system. It is, therefore, conventional to use the standards analyzed in combination with planning and action instructions, such as DIN SPEC 67600:2013, "Biologically effective illumination-Design guidelines" [9], or scientific guidelines, such as "Conclusions and Possible Guidelines for Circadian Lighting Design" by Rossi [79].

4. Conclusions

With the entry into force of DIN/TS 5031-100, a regulatory framework will be introduced into legislation that harmonizes current normative and scientific standards and the ISO international standard for melanopic effects of light sources. Its entry into force will provide new evaluation and decision systems for optimized lighting with innovative luminaires that will change the human centric lighting market. This article addresses the technical and medical background, conducts legal and standard research and describes scientific studies on which the standard is based. This review paper, therefore, provides a deeper insight into the development of the new standard and informs across disciplines about the context and decisions made.

From more recent time periods, hardly any subject trails were involved. Most of the newer references are derived from mathematical models. The scientific studies with subject trials that were examined invited 4 to 72 subjects to participate in their testing. Some of the studies used are already 20 years old. The project by Brainard et al. dates back to 2001 and is stated as one of the foundations in almost all regulations. New research could adopt a 'Design of Experiment' (DoE) approach in evidence-based medicine that is standard procedure today. In DoE, threshold values are studied, and the area to be examined is narrowed down to different extents by both sides, depending on the results of the previous runs. Thus, in an optimization procedure, the ideal value is increasingly approached, instead of testing the entire area in rough resolution. By conducting further research, it would also be possible to resolve the inconsistencies between CIE S 026:2018 (in accordance with DIN/TS 5031-100) and UL DG 24480 that exist to date. For example, the CS value and the corresponding wavelength ranges could be investigated in fine resolution at the point where the snap-action function of the mathematical model of Rea et al. is located [cf. Figure 4c].

This standard will have little effect currently because laws and ordinances must first refer to the standard in their legal texts. It can be assumed that only a recommendation will initially be implemented in the laws so as not to trigger a wave of modernization. However, it would then be fairly straightforward to create a law based on these recommendations. In any case, the standard will be able to provide a sound basis for legislative decisions in the future.

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References

1. German Federal Employment Agency. Institute for Employment Research Durchschnittliche Arbeitszeit Pro Vollzeitbeschäftigten in Deutschland Vom 3. Quartal 2016 Bis Zum 3. Quartal 2020. Available online: https://de.statista.com/statistik/daten/studie/74299/umfrage/entwicklung-der-arbeitszeit-pro-vollzeitbeschaeftigten-nach-quartalen/#statisticContainer (accessed on 9 March 2021).
2. Klepeis, N.E.; Nelson, W.C.; Ott, W.R.; Robinson, J.P.; Tsang, A.M.; Switzer, P.; Behar, J.V.; Hern, S.C.; Engelmann, W.H. The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *J. Expo. Sci. Environ. Epidemiol.* **2001**, *11*, 231–252. [CrossRef] [PubMed]
3. EY Was MISSFÄLLT IHNEN an IHREM Job? Available online: https://de.statista.com/statistik/daten/studie/955539/umfrage/negative-aspekte-im-beruf-in-der-schweiz/ (accessed on 8 March 2021).
4. Redlich, C.A.; Sparer, J.; Cullen, M.R. Sick-building syndrome. *Lancet* **1997**, *349*, 1013–1016. [CrossRef]
5. Burge, P.S. Sick building syndrome. *Occup. Environ. Med.* **2004**, *61*, 185–190. [CrossRef]
6. Vetter, C. Circadian disruption: What do we actually mean? *Eur. J. Neurosci.* **2020**, *51*, 531–550. [CrossRef]
7. Schlangen, L.J.M.; Price, L.L.A. The Lighting Environment, Its Metrology, and Non-visual Responses. *Front. Neurol.* **2021**, *12*, 235. [CrossRef] [PubMed]
8. German Institute for Standardisation. *DIN/TS 5031-100:2021, Optical Radiation Physics and Illuminating Engineering—Melanopic Effects of Ocular Light on Human Beings—Quantities, Symbols and Action Spectra*; German Institute for Standardisation: Berlin, Germany, 2021.
9. German Institute for Standardisation. *DIN SPEC 67600:2013, Biologically Effective Illumination—Design Guidelines*; German Institute for Standardisation: Berlin, Germany, 2013.
10. Agrawal, D.C.; Leff, H.S.; Menon, V.J. Efficiency and efficacy of incandescent lamps. *Am. J. Phys.* **1996**, *64*, 649–654. [CrossRef]
11. German Institute for Standardisation. *EN 15193-1:2017, Energy Performance of Buildings—Energy Requirements for Lighting—Part 1: Specifications*; German Institute for Standardisation: Berlin, Germany, 2017.
12. Perino, G.; Pioch, T. Banning incandescent Light Bulbs in the Shadow of the EU Emissions Trading Scheme. *Clim. Policy* **2017**, *17*, 678–686. [CrossRef]
13. Schweizer Licht Gesellschaft Absatz von Leuchtmitteln in der Schweiz nach Technologie von 2014 bis 2019 (in Millionen Stück). Available online: https://de.statista.com/statistik/daten/studie/496573/umfrage/absatz-in-der-beleuchtungsindustrie-in-der-schweiz-nach-technologie/ (accessed on 10 March 2021).
14. Pollock, A.; Pollock, H.; Pollock, C. High Efficiency LED Power Supply. *IEEE J. Emerg. Sel. Top. Power Electron.* **2015**, *3*, 617–623. [CrossRef]
15. Gacio, D.; Cardesin, J.; Corominas, E.L.; Alonso, J.M.; Dalla-Costa, M.; Calleja, A.J. Comparison Among Power LEDs for Automotive Lighting Applications. In Proceedings of the 2008 IEEE Industry Applications Society Annual Meeting, Edmonton, AB, Canada, 5–9 October 2008; pp. 1–5.
16. German Institute for Standardisation. *DIN 5035-6:2006, Beleuchtung mit künstlichem Licht—Teil 6: Messung und Bewertung*; German Institute for Standardisation: Berlin, Germany, 2006.
17. Badia, P.; Myers, B.; Boecker, M.; Culpepper, J.; Harsh, J.R. Bright light effects on body temperature, alertness, EEG and behavior. *Physiol. Behav.* **1991**, *50*, 583–588. [CrossRef]
18. Lin, D.; Zhong, P.; He, G. Color Temperature Tunable White LED Cluster With Color Rendering Index Above 98. *IEEE Photon. Technol. Lett.* **2017**, *29*, 1050–1053. [CrossRef]
19. Judd, D.B.; MacAdam, D.L.; Wyszecki, G.; Budde, H.W.; Condit, H.R.; Henderson, S.T.; Simonds, J.L. Spectral Distribution of Typical Daylight as a Function of Correlated Color Temperature. *J. Opt. Soc. Am.* **1964**, *54*, 1031. [CrossRef]

20. Wilkins, A.; Veitch, J.; Lehman, B. LED lighting flicker and potential health concerns: IEEE standard PAR1789 update. In Proceedings of the 2010 IEEE Energy Conversion Congress and Exposition, Atlanta, GA, USA, 12–16 September 2010; pp. 171–178.
21. Jauhar, P.; Weller, M.P.I. Psychiatric Morbidity and Time Zone Changes: A Study of Patients from Heathrow Airport. *Br. J. Psychiatry* **1982**, *140*, 231–235. [CrossRef]
22. Gronfier, C.; Wright, K.P.; Kronauer, R.E.; Jewett, M.E.; Czeisler, C.A. Efficacy of a single sequence of intermittent bright light pulses for delaying circadian phase in humans. *Am. J. Physiol. Endocrinol. Metab.* **2004**, *287*, E174–E181. [CrossRef]
23. German Federal Office of Radiation Protection Synthesis of Endogenous Vitamin D. Available online: https://www.bfs.de/EN/topics/opt/uv/effect/acute/vitamin-d.html;jsessionid=9AE5CF3B73C2CC203541F46D745AC3E6.2_cid349 (accessed on 29 March 2021).
24. Berson, D.M. Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock. *Science* **2002**, *295*, 1070–1073. [CrossRef] [PubMed]
25. Lamb, T.D. Photoreceptor spectral sensitivities: Common shape in the long-wavelength region. *Vis. Res.* **1995**, *35*, 3083–3091. [CrossRef]
26. Stevens, R.G. Circadian Disruption and Breast Cancer: From Melatonin to Clock Genes. *Epidemiology* **2005**, *16*, 254–258. [CrossRef] [PubMed]
27. Statista Welchen Aussagen hinsichtlich Ihrer Schlafgewohnheiten Würden Sie Zustimmen? Available online: https://de.statista.com/statistik/daten/studie/244/umfrage/schlafgewohnheiten/ (accessed on 12 March 2021).
28. German Institute for Standardisation. *DIN 5031-10:2018, Optical Radiation Physics and Illuminating Engineering—Part 10: Photobiologically Effective Radiation, Quantities, Symbols and Action Spectra*; German Institute for Standardisation: Berlin, Germany, 2018.
29. Wacker, M.; Holick, M.F. Sunlight and Vitamin D: A global perspective for health. *Derm. Endocrinol.* **2013**, *5*, 51–108. [CrossRef]
30. International Agency for Research on Cancer Zahl der Krebstodesfälle von Frauen Weltweit nach den Häufigsten Krebsart im Jahr 2020. Available online: https://de.statista.com/statistik/daten/studie/286648/umfrage/zahl-der-krebstodesfaelle-von-frauen-weltweit-nach-krebsart/ (accessed on 9 March 2021).
31. International Agency for Research on Cancer Weltweite Verteilung von Krebstodesfällen nach Weltregionen im Jahr 2020. Available online: https://de.statista.com/statistik/daten/studie/289717/umfrage/verteilung-von-krebstodesfaellen-nach-weltregionen/ (accessed on 9 March 2021).
32. DSW Verteilung der Weltbevölkerung nach Kontinenten Mitte des Jahres 2020. Available online: https://de.statista.com/statistik/daten/studie/1738/umfrage/verteilung-der-weltbevoelkerung-nach-kontinenten/ (accessed on 9 March 2021).
33. Brody, J.G.; Rudel, R.; Maxwell, N.I.; Swedis, S.R. Mapping out a search for environmental causes of breast cancer. *Public Health Rep* **1996**, *111*, 494–507.
34. Davis, D.L.; Axelrod, D.; Osborne, M.; Telang, N.; Bradlow, H.L.; Sittner, E. Avoidable Causes of Breast Cancer: The Known, Unknown, and the Suspected. *Ann. N. Y. Acad. Sci.* **1997**, *833*, 112–128. [CrossRef]
35. Künzli, N.; Kaiser, R.; Medina, S.; Studnicka, M.; Chanel, O.; Filliger, P.; Herry, M.; Horak, F.; Puybonnieux-Texier, V.; Quénel, P.; et al. Public-health impact of outdoor and traffic-related air pollution: A European assessment. *Lancet* **2020**, *356*, 795–801. [CrossRef]
36. Lichtenstein, P.; Holm, N.V.; Verkasalo, P.K.; Iliadou, A.; Kaprio, J.; Koskenvuo, M.; Pukkala, E.; Skytthe, A.; Hemminki, K. Environmental and Heritable Factors in the Causation of Cancer—Analyses of Cohorts of Twins from Sweden, Denmark, and Finland. *N. Engl. J. Med.* **2000**, *343*, 78–85. [CrossRef] [PubMed]
37. Sephton, S.; Spiegel, D. Circadian disruption in cancer: A neuroendocrine-immune pathway from stress to disease? *Brainbehav. Immun.* **2003**, *17*, 321–328. [CrossRef]
38. Erren, T.C.; Falaturi, P.; Morfeld, P.; Knauth, P.; Reiter, R.J.; Piekarski, C. Shift Work and Cancer. *Dtsch. Aerzteblatt Online* **2010**. [CrossRef]
39. Erren, T.C.; Falaturi, P.; Morfeld, P.; Reiter, R.J. Risk, compensation, challenges. *BMJ* **2009**, *339*, b3430. [CrossRef] [PubMed]
40. Statista. *Anzahl Neurologischer Erkrankungen bei der Bevölkerung in Europa von 2005, 2015 und 2030 (je 100.000 Einwohner)*; Statista: Hamburg, Germany, 2021.
41. Fasciani, I.; Petragnano, F.; Aloisi, G.; Marampon, F.; Rossi, M.; Coppolino, M.F.; Rossi, R.; Longoni, B.; Scarselli, M.; Maggio, R. A New Threat to Dopamine Neurons: The Downside of Artificial Light. *Neuroscience* **2020**, *432*, 216–228. [CrossRef]
42. Wang, J.; Wang, Z. Role of melatonin in Alzheimer-like neurodegeneration1. *Acta Pharmacol. Sin.* **2006**, *27*, 41–49. [CrossRef]
43. Osibona, O.; Solomon, B.D.; Fecht, D. Lighting in the Home and Health: A Systematic Review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 609. [CrossRef]
44. Vetter, C.; Pattison, P.M.; Houser, K.; Herf, M.; Phillips, A.J.K.; Wright, K.P.; Skene, D.J.; Brainard, G.C.; Boivin, D.B.; Glickman, G. A Review of Human Physiological Responses to Light: Implications for the Development of Integrative Lighting Solutions. *LEUKOS* **2021**, 1–28. [CrossRef]
45. Houser, K.; Boyce, P.; Zeitzer, J.; Herf, M. Human-centric lighting: Myth, magic or metaphor? *Light. Res. Technol.* **2020**, 147715352095844. [CrossRef]
46. Tähkämö, L.; Partonen, T.; Pesonen, A.-K. Systematic review of light exposure impact on human circadian rhythm. *Chronobiol. Int.* **2019**, *36*, 151–170. [CrossRef]

47. Safranek, S.; Collier, J.M.; Wilkerson, A.; Davis, R.G. Energy impact of human health and wellness lighting recommendations for office and classroom applications. *Energy Build.* **2020**, *226*, 110365. [CrossRef]
48. Doulos, L.T.; Tsangrassoulis, A.; Madias, E.-N.; Niavis, S.; Kontadakis, A.; Kontaxis, P.A.; Kontargyri, V.T.; Skalkou, K.; Topalis, F.; Manolis, E.; et al. Examining the Impact of Daylighting and the Corresponding Lighting Controls to the Users of Office Buildings. *Energies* **2020**, *13*, 4024. [CrossRef]
49. Lewy, A.; Wehr, T.; Goodwin, F.; Newsome, D.; Markey, S. Light suppresses melatonin secretion in humans. *Science* **1980**, *210*, 1267–1269. [CrossRef] [PubMed]
50. Foster, R.G.; Provencio, I.; Hudson, D.; Fiske, S.; De Grip, W.; Menaker, M. Circadian photoreception in the retinally degenerate mouse (rd/rd). *J. Comp. Physiol. A* **1991**, *169*, 39–50. [CrossRef]
51. Brainard, G.C.; Hanifin, J.P.; Greeson, J.M.; Byrne, B.; Glickman, G.; Gerner, E.; Rollag, M.D. Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor. *J. Neurosci.* **2001**, *21*, 6405–6412. [CrossRef]
52. Thapan, K.; Arendt, J.; Skene, D.J. An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans. *J. Physiol.* **2001**, *535*, 261–267. [CrossRef] [PubMed]
53. Brainard, G.C.; Sliney, D.; Hanifin, J.P.; Glickman, G.; Byrne, B.; Greeson, J.M.; Jasser, S.; Gerner, E.; Rollag, M.D. Sensitivity of the Human Circadian System to Short-Wavelength (420-nm) Light. *J. Biol. Rhythm.* **2008**, *23*, 379–386. [CrossRef]
54. Lucas, R.J.; Peirson, S.N.; Berson, D.M.; Brown, T.M.; Cooper, H.M.; Czeisler, C.A.; Figueiro, M.G.; Gamlin, P.D.; Lockley, S.W.; O'Hagan, J.B.; et al. Measuring and using light in the melanopsin age. *Trends Neurosci.* **2014**, *37*, 1–9. [CrossRef]
55. Cajochen, C.; Münch, M.; Kobialka, S.; Kräuchi, K.; Steiner, R.; Oelhafen, P.; Orgül, S.; Wirz-Justice, A. High Sensitivity of Human Melatonin, Alertness, Thermoregulation, and Heart Rate to Short Wavelength Light. *J. Clin. Endocrinol. Metab.* **2005**, *90*, 1311–1316. [CrossRef]
56. Panda, S. Illumination of the Melanopsin Signaling Pathway. *Science* **2005**, *307*, 600–604. [CrossRef]
57. Figueiro, M.G.; Bullough, J.D.; Parsons, R.H.; Rea, M.S. Preliminary evidence for spectral opponency in the suppression of melatonin by light in humans. *NeuroReport* **2004**, *15*, 313–316. [CrossRef]
58. Gall, D. Circadiane Lichtgrößen und deren messtechnische Ermittlung. *Licht* **2002**, *54*, 1292–1297.
59. Rea, M.S.; Figueiro, M.G.; Bierman, A.; Bullough, J.D. Circadian light. *J Circadian Rhythms* **2010**, *8*, 2. [CrossRef]
60. Rea, M.; Figueiro, M.; Bierman, A.; Hamner, R. Modelling the spectral sensitivity of the human circadian system. *Light. Res. Technol.* **2012**, *44*, 386–396. [CrossRef]
61. Underwriters Laboratories. *UL DG 24480:2020. Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People*; UL Inc.: Northbrook, IL, USA, 2020.
62. German Institute for Standardisation. *DIN V 5031-100:2009, Optical Radiation Physics and Illuminating Engineering—Non-Visual Effects of Ocular Light on Human Beings—Quantities, Symbols and Action Spectra*; German Institute for Standardisation: Berlin, Germany, 2009.
63. International Commission on Illumination. *CIE TN 003:2015, Report on the First International Workshop on Circadian and Neurophysiological Photometry*; International Commission on Illumination: Vienna, Austria, 2015.
64. German Institute for Standardisation. *DIN SPEC 5031-100:2015, Optical Radiation Physics and Illuminating Engineering—Melanopic Effects of Ocular Light on Human Beings—Quantities, Symbols and Action Spectra*; German Institute for Standardisation: Berlin, Germany, 2015.
65. Bodrogi, P.; Vinh, Q.; Khanh, T. Correlations among lighting quality metrics for interior lighting. *Light. Res. Technol.* **2019**, *51*, 1192–1207. [CrossRef]
66. Durmus, D. Multi-objective optimization trade-offs for color rendition, energy efficiency, and circadian metrics. In Proceedings of the Light-Emitting Devices, Materials, and Applications XXV, Online Only, 6–12 March 2021; Strassburg, M., Kim, J.K., Krames, M.R., Eds.; SPIE: Bellingham, WA, USA, 2021; p. 52.
67. Busatto, N.; Mora, T.D.; Peron, F.; Romagnoni, P. Application of Different Circadian Lighting Metrics in a Health Residence. *J. Daylighting* **2020**, *7*, 13–24. [CrossRef]
68. German Chambers of Commerce Abroad in France Report about Human Centric Lighting Legismation in France 2021.
69. Upper house of the German Legislative. *ArbSchG:2004, Occupational Safety and Health Act of 7. August 1996 (Federal Law Gazette), as amended by the Second Data Protection Adjustment and Implementation Act EU of 20 November 2019 (Federal Law Gazette p. 1626)*; Upper house of the German Legislative: Berlin, Germany, 2004; p. 1246.
70. Upper house of the German Legislative. *ArbStättV:2004, Workplace Ordinance of 12 August 2004 (Federal Law Gazette), last amended by Article 5 (1) of the Ordinance of 18 October 2017 (Federal Law Gazette | p. 3584)*; Upper house of the German Legislative: Berlin, Germany, 2004; p. 2179.
71. Upper house of the German Legislative. *ASR A3.4:2011, Workplace Ordinance of 12 August 2004 (Federal Law Gazette), last amended by Article 5 (1) of the Ordinance of 18 October 2017 (Federal Law Gazette | p. 3584)—Annex 3.4*; Upper house of the German Legislative: Berlin, Germany, 2011; p. Annex.
72. German Statutory Accident Insurance DGUV Information 215–220. Available online: https://publikationen.dguv.de/widgets/pdf/download/article/3247 (accessed on 29 March 2021).
73. Rabstein, S. *Das Magazin für Sicherheitsbeauftragte: Arbeit & Gesundheit*; Institut für Prävention Arbeitsmedizin: Berlin, Germany, 1 January 2021; pp. 26–27.
74. German Chambers of Commerce Abroad in USA Report about Human Centric Lighting Legismation in USA 2021.

75. Lang, D.; The DIN Standards Commitee for Lighting Technology (FNL 27), Berlin, Germany. Personal communication, 2021.
76. Brown, T.; Brainard, G.; Cajochen, C.; Czeisler, C.; Hanifin, J.; Lockley, S.; Lucas, R.; Munch, M.; O'Hagan, J.; Peirson, S.; et al. Recommendations for Healthy Daytime, Evening, and Night-Time Indoor Light Exposure. *Biology* **2020**. [CrossRef]
77. Durmus, D. Impact of Surface Reflectance on Spectral Optimization for Melanopic Illuminance and Energy Efficiency. In Proceedings of the OSA Advanced Photonics Congress (AP) 2019 (IPR, Networks, NOMA, SPPCom, PVLED), Burlingame, CA, USA, 29 July–2 August 2019; Optical Society of America: Burlingame, California, 2019; p. PT2C.5.
78. Cai, W.; Yue, J.; Dai, Q.; Hao, L.; Lin, Y.; Shi, W.; Huang, Y.; Wei, M. The impact of room surface reflectance on corneal illuminance and rule-of-thumb equations for circadian lighting design. *Build. Environ.* **2018**, *141*, 288–297. [CrossRef]
79. Rossi, M. Conclusions and Possible Guidelines for Circadian Lighting Design. In *Circadian Lighting Design in the LED Era*; Research for Development; Springer International Publishing: Cham, Switzerland, 2019; pp. 257–277. ISBN 978-3-030-11086-4.