# Human Adequate Lighting in Optimal Healing Environments – Measuring Non-visual Light Effects of a LED Light Source According to German Draft Pre-standard DIN SPEC 5031-100:2012

Herbert Plischke[1,2], Christoph Schierz[3], Peyton Paulick[5], and Niko Kohls[1,2,4]

[1] Generation Research GmbH, Prof.-Max-Lange-Platz 11, 83677 Bad Toelz, Germany
[2] Generation Research Program, Human Science Center,
University of Munich, 83677 Bad Toelz, Germany
info@grp.hwz.uni-muenchen.de
[3] Ilmenau University of Technology, 98684 Ilmenau, Germany
[4] Brain, Mind and Healing Program, Samueli Institute, Washington, USA
[5] Department of Biomedical Engineering, University of California Irvine,
2227 Engineering Gateway, Irvine, CA 92697, USA
plischke@generation-research.de,
christoph.schierz@tu-ilmenau.de,
{nkohls,paulickpeyton}@gmail.com

**Abstract.** Exposing human beings to natural light has many empirically and experimentally corroborated effects on health, well-being and quality of life. One important effect is the entrainment of the human "master clock" to the 24h rhythm of the solar day. In contrast, being surrounded by darkness during the night increases blood levels of melatonin, the brain derived "sleep hormone", and thus signaling other organs aside from the brain. However, in contrast to earlier times, particularly in urban areas distinct periods of the day marked by bright and dark light conditions are scarce, as modern lifestyle has changed and artificial lighting is present in cities on a 24 hour basis. In addition to the merely "visual" effects, light also exhibits non-visual, but biologically relevant (time, spatial, quality and quantity dependent) effects, that are mediated by specialized cells in the eye. These non-visual effects, such as the suppression of melatonin during nighttime may potentially be regarded as a severe risk factor to human health. Due to the discovery of the relationship of light exposure and melatonin suppression, studies have been conducted to evaluate which properties of light are most effective in suppressing melatonin.

In 2009 a first pre-standard for determining the non-visual effects of light mediated through the eye was established by the German Institute of Standardization (DIN). In this paper we describe, according to the standard, one approach to assess melatonin suppressing potential of light sources on the basis of mathematical algorithms that can be utilized as a conceptual platform for planning visual and non-visual effective lighting for optimal healing environments.

**Keywords:** Natural light, artificial lighting, human eye, melanopsin, retinal ganglion cells, melatonin suppression, sleep, circadian rhythm, Irradiance, Luminance, melanopic sensitivity function, visual angle, DIN V 5031-100:2009.

M. Kurosu (Ed.): Human-Computer Interaction, Part II, HCII 2013, LNCS 8005, pp. 163–172, 2013.

## 1 Introduction and Motivation

Natural light plays an important role in our daily lives. Living organisms have adapted to the 24h rhythm of light and darkness, activity and rest. The individual metabolism of an organism can react and adapt to specific needs of activity- and sleep-cycles, allowing some organisms to be night-active, while others are day-active. Human beings are as a consequence of evolutionary processes specifically adapted to day-active (diurnal) live with resting periods during dark periods. The concomitant metabolic imprint is useful for survival as human beings are not well prepared to remain active in darkness. Since time immemorial human beings have reduced their activity level and hidden away during night, thereby instead using the time for resting and sleeping. Many million years of pertinent evolutionary processes have led to the development of the human organism with its useful metabolic adaptation to fulfill the demand of optimal functioning in interaction with the environment. As organisms are all exposed to night- and daytime, they have developed several types of "inner clocks" that are synchronized and entrained by a "master clock" in the brain. Light exposure, i.e. daylight period entrains this "master clock".

Some 10 years ago, two independent research groups described a new type of photoreceptor in the human eye, a ganglion cell, containing the pigment melanopsin with photosensitive properties. An action spectrum was found for this cell type with a peak of excitation in the visible blue segment (maximum at wavelength 460nm-480nm) of natural and artificial light. These ganglion cells were found to be responsible for the regulation of non-visual effects of light exposure. Specifically, the entrainment of the circadian rhythm is thereby realized by transducing the light signal to the Suprachiasmatic Nucleus (SCN), a small region above the optic chiasm where the "master clock" is situated. Mediated by the SCN over sympathic pathways Melatonin, a "sleep-inducing" hormone is secreted by the pineal gland during the night. Melatonin is proportionally suppressed by exposure to nocturnal monochromatic light [1, 2]. Moreover Melatonin also acts as a free radical scavenger, and therefore, the hormone may also be important for immune functions and cancer protection [3]. Since the industrial revolution at the end of the 19th century, artificial light has become an important factor of our economy. Shiftwork was introduced and nighttime was correspondingly no longer considered to be a resting period. As gradually more efficient light sources were developed, artificial lighting became almost similar to daylight for non-visual effects. As the entrainment function of light was no longer modulated by natural light, but also by artificial light, concomitant altering working conditions such as the introduction of shiftwork has led to chronodisruption. Chronodisruption has been conceptualized as a relevant disturbance of the circadian organization of physiology, which links light and biological rhythms. Some studies have shown that chronodisruption has been linked to the development of certain types of cancers. Particularly shiftwork has been identified as a risk factor for chronodisruption severely impeding health and wellbeing [4].

In modern economies employees spend a considerable amount of time in reduced daylight conditions in buildings, sometimes in workplaces with artificial light over 24 hours. Many of these individuals report to have sleep problems and complain about

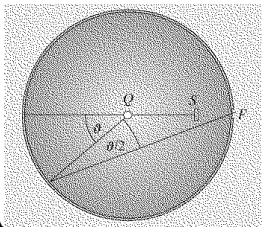
distress. While different factors may be responsible for sleep problems and distress, a protective factor for a sufficient quantity and quality of sleep during the night is maintaining adequate exposure to daytime light with suitable intensity and biological effectiveness (adequate exposure to blue spectral components), so as to entrain the inner clock. Bright artificial light can also prevent accidents as a consequence of suppressed mid-afternoon sleepiness [5]. Consequently, light leading to melatonin suppression during night time should be avoided, as melatonin is crucial for good sleep. However, the activating effects of light may be used in the evening, but exposure to high amounts of the blue spectral component may lead to delay of melatonin secretion and shifting of circadian rhythms [6]. This paper aims to describe one approach to assess the melatonin suppressing potential of light sources on the basis of mathematical algorithms that can be utilized as a conceptual platform for planning visual and non-visual effective lighting for optimal healing environments. We thereby describe the assessment of non-visual effects of artificial light using radiometric and photometric measurements in a LED-based integration sphere.

## 2 Material and Methods

The German Institute for Standardization (DIN) has established a committee for the standardization of the non-visual effects of light. In June 2009, the committee published a first pre-standard known as DIN V 5031-100 with the heading: Non-visual effects of ocular light on human beings - Quantities, symbols and action spectra". This pre-standard was intended to act as a conceptual basis for the evaluation of non-visual effects of light, as they are mediated by intrinsic photosensitive retinal ganglion cells (ipRGC) of the human eye. A prototype of a goggle allowing to assess chromatic pupillometry, the physical properties of specific LEDs were measured in an integrating sphere, and the non-visual effects are computed. In a first step, we will define the integrating sphere and the characteristics of the measured solid angle and visual angle of our prototypical measurement instrument.

### 2.1 The Integrating Sphere

A special application for Lambert's cosine law is the integrating sphere shown in figure 1. A light source (Q) is placed in the middle of a diffuse painted white sphere. Through an observation window (F), which is protected by a screen (S) from direct radiance, the intensity of the radiant can be measured. Although the light source might illuminate the sphere's surface in an inhomogeneous manner, the radiance through the observation window is almost consistent. In our measurement prototype the integrating sphere is a half bowl with red, green and blue LEDs circular placed on the outside of a commercially available safety goggles that is used to indirectly illuminate the mounted sphere. By means of this technological setup, an almost homogenous measurement of the irradiance at the eye level (with a cone shaped visual angle) can be performed.

A 

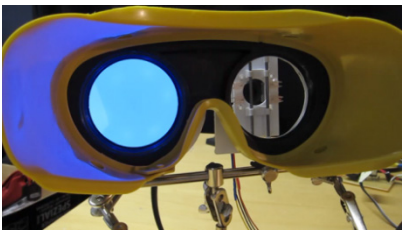
B 

**Fig. 1.** A: In principle the integrating sphere integrates the radiant intensity from a light source (Q) over the whole solid angle of a 4 $\pi$ -sphere. The observation window (F) is protected from direct radiance by a baffle (S)[1]. B: In our prototype the integrating sphere is a half bowl with red, green and blue LEDs placed outside the left part of safety goggles and three different LEDs illuminating the sphere indirectly. With this technological setup an almost homogenous radiance distribution in front of the eye (within a cone shaped visual angle) can be achieved.

### 2.2 Solid Angle and Visual Angle

If we determine the solid angle $\Omega_s$ (cone shaped visual angle) we assume that the light source has a homogenous luminance (or radiance). We can determine the solid angle from the measured illuminance E and the mean luminance $L_s$ according to (1) with $\Omega_0$ = 1 sr

$$\Omega_S = \frac{E}{L_s} \cdot \frac{2}{1+\sqrt{1-\frac{E}{L_S \cdot \pi \cdot \Omega_0}}} \tag{1}$$

The visual angle at the edge of the cone $\boldsymbol{\theta_s}$ is computed with equation (2)

$$\sin(\theta_S) = \sqrt{\frac{E}{L_S \cdot \pi \cdot \Omega_0}} \tag{2}$$

### 2.3 "Melanopic"[2] Spectral Sensitivity Function

Since the discovery of intrinsic photosensitive Retinal Ganglion Cells (ipRGC), the melanopsin mediated action spectrum associated with suppression of the endogenous melatonin hormone was described by different working groups [1, 7, 8]. However, until now the action spectrum is not exactly defined. In 2011 the term "Melanopic" spectral Efficiency Function was suggested by an European research group [9].

Some years earlier an approximation of the "action spectrum" from Thapan and Brainard was interpolated by Gall [10], and that definition was used to build the

[1] D. Meschede. Gerthsen Physik, Volume 24. Springer-Verlag, 2010.

[2] "Melanopic spectral efficiency function", English expression introduced by al Enezi et al, 2011

German pre-standard DIN V 5031-100:2009 [11]. For this paper we will use the agreement in the DIN V 5031-100:2009 with revisions in 2012 (unpublished yet).

$$X_{mel} = K_{mel} \cdot \int_{380nm}^{580nm} X_{\lambda}(\lambda) \cdot s_{mel}(\lambda) \cdot d\lambda \tag{3}$$

$X_{mel}$[3] represents a photometric quantity to estimate melatonin suppressing effects of a given spectrum. $K_{mel}$[4] (is analog to $K_m$) a maximum equivalent for melanopic effective radiation, whereas $K_m$[5] is the maximum equivalent for visual effective (photopic) radiation. $X_{\lambda}(\lambda)$ is the spectral radiometric quantity, representing the given spectrum and $s_{mel}(\lambda)$ is the relative melanopic spectral sensitivity (normalized to "1"). If we compare $X_{mel}$ with the photometric quantity for photopic vision $X_v$, shown in equation (5), the parameter $a_{mel,v}$[6] can be used as an indicator for the melanopic effectivity compared to the photopic effectivity. $X_v$ is computed accordingly (4).

$$X_v = K_m \cdot \int_{380nm}^{780nm} X_{\lambda}(\lambda) \cdot V(\lambda) \cdot d\lambda \tag{4}$$

The difference from equation (3) to equation (4) is only $K_m$ and the relative photopic spectral sensitivity for human vision $V(\lambda)$. The advantage of the melanopic factor of luminous radiation $a_{mel,v}$ is the easy computation of melanopic efficiency out of a photopic quantity.

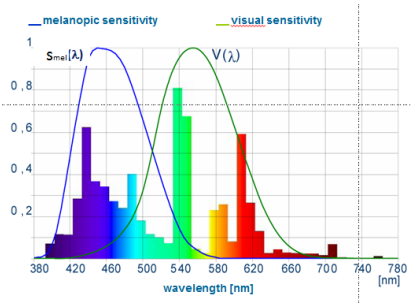



**Fig. 2.** In a spectrum of a standard fluorescence lamp the melanopic ($s_{mel}$ ($\lambda$)) and photopic ($V(\lambda)$) sensitivity functions (normalized to "1") are depicted. With the given factor $a_{mel,v}$ from the manufacturer the "melatonin suppressing effectivity" (melanopic photometric quantity e.g. in Lux) can easily be computed. (Picture adapted with kind permission of OSRAM).

$$a_{mel,v} = \frac{K_m}{K_{mel}} \frac{X_{mel}}{X_v} \tag{5}$$

[3] $X_{mel}$ = melanopic photometric quantity
[4] $K_{mel}$ = melanopic daylight equivalent = 726 lm/W for daylight illuminant D65
[5] $K_m$ = luminous efficacy of radiation = 683 lm/W
[6] $a_{mel,v}$ = melanopic factor of luminous radiation

The melanopic photometric quantity $X_{mel}$ can be computed in accordance with equation (6) without having to use a radiospectrometer, e.g with a "normal" illuminance meter, if a $a_{mel,v}$ is given from the manufacturer of a lamp or luminaire.

$$X_{mel} = \frac{K_{mel}}{K_m} \cdot a_{mel,v} \cdot X_v = 1.0627 \cdot a_{mel,v} \cdot X_v \tag{6}$$

# 3 Results

## 3.1 Visual Angle of the Light Source

With homogenous distribution of luminance in the integrating sphere with light condition "blue" (blue LEDs), $E/L_S$ had a value of 1.35 sr. With equation (1) an equivalent solid angle can be computed to 1.53 sr. With equation (2) we compute an equivalent visual angle $\theta_s$ at the edge of the cone shaped visual field with 40.9°. In Fig.3 the equivalent visual angle is marked with a filled circle. The black line represents the polar diagram of the maximum field of vision for the left eye. The upper limit of the visual field is determined by the eyelid; while the limit to the median is represented by the nose. The size of the marked visual angle is approximately the main field of vision of the left eye. Although the relevance of this area for melanopic effects is currently not exactly known, we can assume from the anatomical distribution of ipRGCs that the majority of the melatonin suppressing effects are realized in this illuminated area [12].

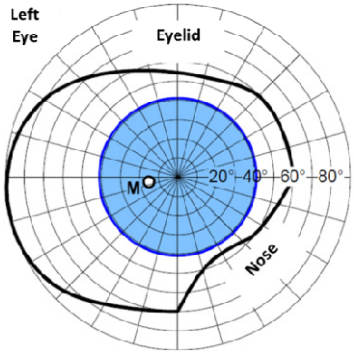



**Fig. 3.** The black line represents the polar diagram delineating the maximum field of vision for the left eye. The limit of the visual field above is the eyelid; the limit to the median is the nose. Other limitations are due to the functional borders of the retina. M represents the blind spot (passage of the optical nerve). The filled area represents the equivalent visual angle for the light stimulus. The size is approximately the usable field of vision of the left eye[7]. Although the relevance of this area for melanopic effects is currently not exactly known, we can assume from the anatomical distribution of ipRGCs that the majority of the melatonin suppressing effects is realized in this illuminated area.

[7] CIE Report 196 (2011): CIE Guide to Increasing Accessibility in Light and Lighting.

### 3.2 LED Light Source Characteristics

The measurements in this investigation were conducted with a spectroradiometer JETI specbos 1201. This instrument can be used for measurements of irradiance, radiance, illuminance and luminance. In Table 1 the electrical and optical characteristics are shown. In Fig.2 the spectral distribution is displayed for the red, green and blue stimulus.

**Table 1.** The given characteristics of the LEDs used in the measurement system with the measured characteristic parameters $\lambda_{max}$ and $E_{e,\lambda\ max}$.

| Name | Wavelength $\lambda_{max}$ (at Maximum) | Fwd. Current | Fwd. Voltage | Maximum Spectral Irradiance $E_{e,\lambda\ max}$ |
|---|---|---|---|---|
| LED-red | 655.2 nm | 20 mA | 1.8 V | 33.7 mW $m^{-2}$ $nm^{-1}$ |
| LED-green | 518.0 nm | 20 mA | 2.2 V | 79.9 mW $m^{-2}$ $nm^{-1}$ |
| LED-blue | 472.8 nm | 20 mA | 3.5 V | 46.9 mW $m^{-2}$ $nm^{-1}$ |
| | | | | |

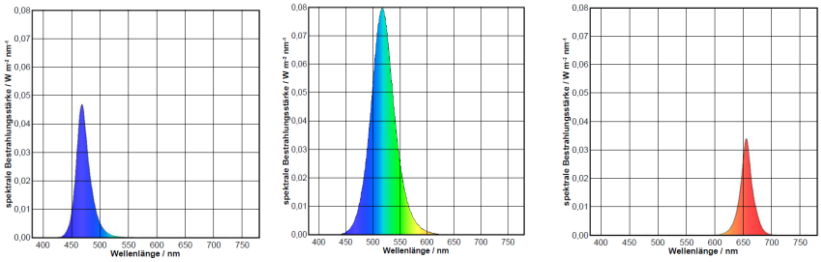



**Fig. 4.** In this figure the spectral irradiance of the three lighting conditions in the integrating sphere is shown. The maxima of the curves are described by the parameters $\lambda_{max}$ and $E_{e,\lambda\ max}$.

With the melanopic irradiance $E_{e,mel}$ (measured in W $m^{-2}$), the "melanopic daylight equivalent illuminance" $E_{mel}$ , (measuring unit lux), at the eye level can be calculated with equation (7)

$$E_{mel}=725{,}82\ \text{lm/W} \cdot E_{e,mel} \tag{7}$$

**Table 2.** Light source, wavelength, max. spectral irradiance, measured melanopic irradiance $E_{e,mel}$ (W $m^{-2}$) and "melanopic daylight equivalent illuminance"[8] $E_{mel}$ (lx) at eye level

| Light source | Wavelength $\lambda_{max}$ (at maximum) | Max Spectral Irradiance $E_{e,\lambda\ max}$ | $E_{e,mel}$ | $E_{mel}$ |
|---|---|---|---|---|
| LED-red | 655.2 nm | 33.7 mW $m^{-2}$ $nm^{-1}$ | 31.27 µW $m^{-2}$ | 0,0227 lx |
| LED-green | 518.0 nm | 79.9 mW $m^{-2}$ $nm^{-1}$ | 1.773 W $m^{-2}$ | 1286 lx |
| LED-blue | 472.8 nm | 46.9 mW $m^{-2}$ $nm^{-1}$ | 1.249 W $m^{-2}$ | 906 lx |

[8] According to draft DIN SPEC 5031-100:2012.

If we measure the „photopic“ illuminance at eye level of the three light qualities, and the factor $a_{mel,v}$ with the spectroradiometer, we can compute the melanopic daylight equivalent illuminance according equation (6) in an alternative way (see table 3).

**Table 3.** Light source, max. spectral irradiance, measured illuminance E (lx), $a_{mel,v}$ and “melanopic daylight equivalent illuminance” $E_{mel}$ (lx) at eye level

| Light source | Max. Spectral Irradiance $E_{e,\lambda\,max}$ | Illuminance at eye: E | $a_{mel,v}$ | $E_{mel}$ |
|---|---|---|---|---|
| LED-red | 33.7 mW $m^{-2}$ $nm^{-1}$ | 58 lx | 3.671 $10^{-4}$ | 0,0227 lx |
| LED-green | 79.9 mW $m^{-2}$ $nm^{-1}$ | 1866 lx | 0,649 | 1286 lx |
| LED-blue | 46.9 mW $m^{-2}$ $nm^{-1}$ | 113 lx | 7,545 | 906 lx |

**Table 4.** Light source, aligned maximum irradiance, aligned melanopic irradiance $E_{e,mel}$ (W $m^{-2}$), aligned illuminance E (lx) and “melanopic daylight equivalent illuminance”[9] $E_{mel}$ (lx) at eye level. Alignment was performed to better compare the melanopic effects of the light sources.

| Light source | Aligned max. Spectral Irradiance $E_{e,\lambda\,max}$ | $E_{e,mel}$ (aligned) | Illuminance at eye (aligned): E | $E_{mel}$ (aligned) |
|---|---|---|---|---|
| LED-red | 79,9 mW $m^{-2}$ $nm^{-1}$ | 74.1 µW $m^{-2}$ | 138 lx | 0,054 lx |
| LED-green | 79.9 mW $m^{-2}$ $nm^{-1}$ | 1,773 W $m^{-2}$ | 1866 lx | 1286 lx |
| LED-blue | 79,9 mW $m^{-2}$ $nm^{-1}$ | 2,128 W $m^{-2}$ | 193 lx | 1543 lx |

For a better comparison of $E_{mel}$ we aligned the spectral irradiances to 79.9 mW $m^{-2}$ $nm^{-1}$ (see Table 4).

## 4 Discussion

With modern luminaires and light sources, we have not only the possibility to create good visual lighting conditions, but also to execute non-visual effects on the basis of “melanopic” effective lighting. During daytime non-visual effects are important because humans are in need of light for the proper entrainment and synchronization of the inner clocks. Today, the lighting conditions for entrainment are not always sufficiently extant in work places with 24 h artificial lighting and no exposure to natural daylight (e.g. control rooms in ships or power plants). On the other hand human beings are in need of a dark environment during the night, so as to allow them to sleep and recover adequately. In many instances - be it during shift work or in urban areas - due to outside ambient light (“-pollution”) darkness is not sufficiently present. However, as light has a distinct ability to suppress melatonin, it is essential to know how much light exposure is needed for entrainment during the daytime. In a similar way, if light exposure is needed during night time, it is also pivotal to know, how much unwanted suppression of melatonin may be created as a consequence of being exposed to the respective light source. The “melanopic daylight equivalent illuminance” $E_{mel}$

[9] According to draft DIN SPEC 5031-100:2012.

provides the necessary information about the melatonin suppressing effects of a given light source. $E_{mel}$ can be easily computed, in accordance with equation (6), on the basis of a measurement with a lux meter at eye level and a given factor $a_{mel,v}$ provided by the manufacturer of the light source. If a spectroradiometer is available, $E_{mel}$ can be estimated by measuring the melanopic irradiance $E_{e,mel}$ (measured in W $m^{-2}$) and calculated with equation (7). We conducted sample measurements of light conditions with different maximum irradiances at the characteristic wavelength (see table 2 and 3). For a better comparison we aligned the spectral irradiances to 79.9 mW $m^{-2}$ $nm^{-1}$. We can observe that the red light situation has almost no melanopic effectivity. This result is in accordance with the fact that red light is far out of the relative melanopic spectral sensitivity $s_{mel}(\lambda)$ range. Of interest is the finding that a green light situation with equal irradiance produces an approximately ten times greater measured "photopic" effectivity than red or blue light, while the melanopic effectivity is comparable to the blue light situation. The described procedures in accordance with draft DIN SPEC 5031-100:2012 can be used to estimate the melanopic effects of a light source. However, this pre-standard does not consider the already established effect of a spectral opponency in melatonin suppression [8]. Additionally the melanopic spectral sensitivity function $s_{mel}(\lambda)$ is still not finally confirmed, due to unsatisfying curve fitting of the known measurement points. Nevertheless this method does not allow the exact assessment of melatonin suppression; it is an assessment of the melanopic potential of light and may be considered as an adequate estimate for practitioners.

## 5 Conclusion

In this paper, we have demonstrated how the melatonin suppressing potential of a light source can be estimated by means of calculations that are in accordance with the German Standard DIN V 5031-100. We consider this to be fundamental knowledge for biomedical engineers, light planners and architects and all individuals interested in designing lighting and luminaires for optimal healing environments. The consideration of melanopic effects of light is not only relevant to promoting and maintaining health and well-being, as it may actually help to avoid accidents, raise vigilance as well as lead to better sleep. Moreover, as individuals may gain more resilience against distress and prevent depressive episodes, human adequate lighting is certainly one pivotal aspect of optimal healing environments.

**Acknowledgements.** The authors would like to thank DIN FNL 27 for an unrestricted research grant to support this work. Niko Kohls work is made possible through the longstanding support of the Samueli Institute, USA.

## References

1. 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. 535(Pt. 1), 261–267 (2001)

2. Brainard, G.C., et al.: Influence of near-ultraviolet radiation on reproductive and immunological development in juvenile male Siberian hamsters. J. Exp. Biol. 204(Pt. 14), 2535–2541 (2001)
3. Carrillo-Vico, A., et al.: A review of the multiple actions of melatonin on the immune system. Endocrine 27(2), 189–200 (2005)
4. Erren, T.C.: Shift work and cancer research: can chronotype predict susceptibility in night-shift and rotating-shift workers? Occup. Environ. Med. (2013)
5. Hayashi, M., Masuda, A., Hori, T.: The alerting effects of caffeine, bright light and face washing after a short daytime nap. Clin. Neurophysiol. 114(12), 2268–2278 (2003)
6. Teixeira, L., et al.: Exposure to bright light during evening class hours increases alertness among working college students. Sleep Med. 14(1), 91–97 (2013)
7. Brainard, G.C., et al.: Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. J. Neurosci. 21(16), 6405–6412 (2001)
8. Figueiro, M.G., et al.: Preliminary evidence for spectral opponency in the suppression of melatonin by light in humans. Neuroreport 15(2), 313–316 (2004)
9. Enezi, J., et al.: A "melanopic" spectral efficiency function predicts the sensitivity of melanopsin photoreceptors to polychromatic lights. J. Biol. Rhythms 26(4), 314–323 (2011)
10. Gall, D., Bieske, K.: Definition and measurement of circadian radiometric quantities. In: Proceedings of the CIE Symposium 2004 on Light and Health, pp. 129–132 (2004), http://www.db-thueringen.de/servlets/DerivateServlet/Derivate-8659/CIELuH2004_GB.pdf
11. NA 058 Lighting Technology Standards Committee (FNL), http://www.fnl.din.de/projekte/DIN+SPEC+5031-100/en/134406590.html
12. Do, M.T., Yau, K.W.: Intrinsically photosensitive retinal ganglion cells. Physiol. Rev. 90(4), 1547–1581 (2010)