Chapter 15
Future Directions for Lighting Environments

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Introduction

Lighting for the built environment has traditionally centered on the places that we illuminate and the various things we do in those places. As a result, lighting typically has been designed, specified, and manufactured to meet a relatively limited number of very specific objectives. Historically, the primary requirement of lighting has been to illuminate spaces for optimization of visual performance (addressing concerns such as efficiency, productivity, and safety), to provide visual comfort to occupants, and to enhance the space's appearance for aesthetic appreciation. Over time, as indoor lighting proliferated to the point that it virtually became taken for granted by many end users, increasing energy demand and costs led to the adoption of energy conservation as an additional requirement. The lighting industry has been a key driver of technological advances to address these needs, from the development of incandescent and fluorescent sources to today's rapidly evolving solid-state lighting technologies. The most recent driver, the so-called nonvisual effects of light on the circadian system, has spurred lighting in the built environment to undergo yet another transformation in response. The lighted environment will undoubtedly continue to change as we develop a deeper understanding of how light impacts human physiology and behavior.

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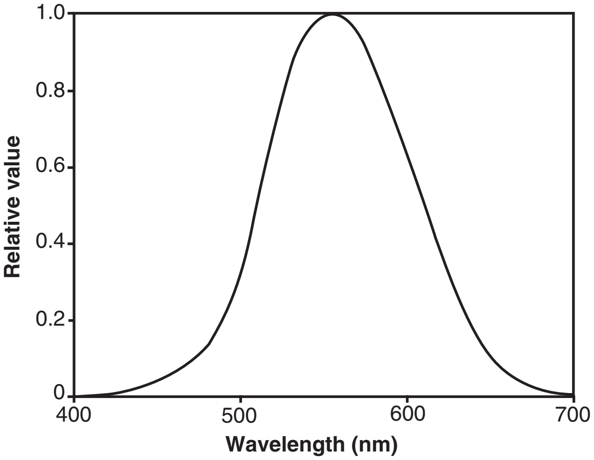
What Is Light and How Do We Characterize It?

For a more detailed definition of light, refer to Chap. 14 in this volume. Briefly though, by definition, light is optical radiation that excites photoreceptors in the human eye. The photopic luminous efficiency function, V(λ), is the primary spectral weighting function used in science and commerce to differentiate light, which is associated with a very narrow range (≈ 380–780 nanometers (nm)) of the electromagnetic spectrum (Fig. 15.1). Indeed, V(λ) underlies all quantitative descriptions of light for commercial photometry and all recommendations for lighting practice [1]. Both luminous flux (i.e., the rate of flow of light from a source, measured in lumens) and intensity (i.e., the amount of light generated by a source in a given direction, measured in candelas) are universally used by lighting manufacturers to communicate the light quantities generated by their products. For lighting applications, V(λ) is also used exclusively to weight spectral irradiance and radiance functions, so both illuminance (lumens per square meter, lm/m^2) and luminance (candelas per square meter; cd/m^2) are used for recommended practices in hospitals, schools, factories, roadways, parking lots, and homes.

Lighting standards are still set primarily in terms of illuminance and lumens per watt, both of which are based upon the implicit assumption that the value of lighting can be characterized by the lumen. However, the lumen is derived from a very narrow set of experimental conditions that are only relevant to simple visual functions and does not characterize all of the visual responses that are important to modern built environments (e.g., apparent brightness). Moreover, the lumen is only indirectly related to the provision of perceptual information about the environment (e.g., linear perspective) and is, by definition, unrelated to the nonvisual, circadian effects of lighting that help to maintain entrainment of our many biological functions to the local time on Earth. Boyce and Rea have conceptualized three domains that light can affect [2], which are shown in Fig. 15.2. Again, the lumen is relevant to only one of these three domains, which is the visual system.

Fig. 15.1 The photopic luminous efficiency function, V(λ), adopted by the CIE in 1924 [1], is generally the only luminous efficiency function incorporated into commercially available photometric instruments and the only one used internationally for lighting application standards



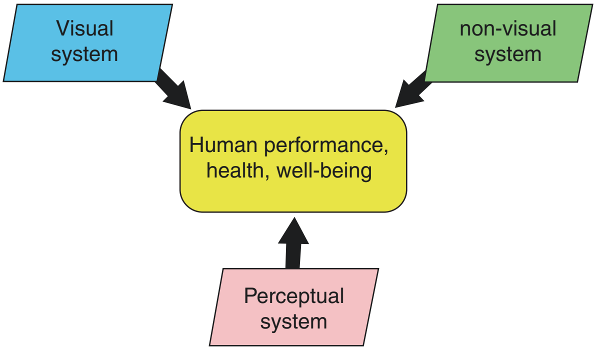


Fig. 15.2 Human performance, health, and well-being are influenced by at least three systems: visual, nonvisual, and perceptual (adapted from Boyce and Rea [2])

In addition to allowing us to see, light also impacts our nonvisual and perceptual systems. One of the most studied nonvisual responses to light is the one responsible for stimulating the circadian system. (The term *circadian* derives from Latin and is a blending of circa, or "about," and *dies*, or "day.") The 24-h light–dark patterns incident on the retina control the timing of the body's biological clock, which generates and regulates our circadian rhythms so that we are awake during the day and asleep at night. Because our circadian rhythms typically free-run on a slightly longer cycle of about 24.2 h in the absence of external cues, however, we require daily exposure to morning light to reset our biological clock and keep us synchronized (or *entrained*) with the local time on Earth. In addition to promoting entrainment, exposure to sufficient levels of light of any spectrum also exerts a direct, acute effect on people, which leads to an increase in alertness, as measured by objective (e.g., reduction in alpha power from electroencephalogram measurements) and subjective (i.e., self-reported) responses [3, 4]. Interestingly, it has been demonstrated that the spectral sensitivity of acute alertness is different than that of melatonin suppression and phase shifting of the onset of the body's secretion of melatonin in dim light (i.e., dim light melatonin onset, or DLMO) [5]. While short-wavelength ("blue") light has been shown to maximally affect the timing of the biological clock, a series of laboratory and field studies have shown that saturated red light (630 nm) at levels varying from 30 to 200 lx at the cornea exert a strong alerting effect on healthy adults [6–9]. As discussed below, when thinking about "light as a cup of coffee" and when melatonin suppression is not desired, red light may be a better choice.

Last but not least, light, especially from saturated long-wavelength "red" (≈ 630 nm) and short-wavelength "blue" (≈ 470 nm) sources, can affect human perceptual and/or psychological systems. As Elliot and Maier note in their review of research on the effects of color perception on human psychological functioning [10], comparatively little published research exists on this theme despite an extensive body of literature on related topics such as the physics of light color perception, the manner in which color stimuli are processed by the eyes and brain, and the linguistic categorization of color, among others. While the impacts of color and colored light on mood and behavior are still not well understood, these impacts should nevertheless be considered when thinking about the lighted environment.

Current Trends in Lighted Environments

Light–dark exposures experienced by humans have differed quantitatively between societies and through time. Prior to the widespread use of electric lighting, people of a century ago were exposed to very bright days and very dark nights, which is probably true today only for those who live in agrarian societies or perform some form of outdoor work. With a growing frequency that is projected to reach almost 70% of the world's population by 2050 (compared to 30% in 1950 and 55% today) [11], people are living in urban or suburban built environments and, in terms of circadian regulation, are thus becoming increasingly likely to experience extended dim days and light at night.

Data obtained using the Daysimeter (Fig. 15.3), an instrument designed to measure both conventional photopic illuminance and circadian light exposures at the eye throughout the waking day [12, 13], showed that people who work in the built environment experience much lower light levels compared to those who live in agrarian societies. The Daysimeter is a personal light meter that measures and is calibrated in terms of photopic illuminance (i.e., the density of light incident on a surface as perceived by the human eye, measured in lux (lx)), "circadian illuminance" (CL_A) [14], and the absolute sensitivity of the human circadian system (measured in circadian stimulus (CS)), based on the model of phototransduction proposed by Rea et al. [15–17]. The values of CL_A are scaled so that 1000 lx of a standard light source representing the spectral composition of an incandescent light source at 2856 K is equivalent to 1000 units of CL_A. Those values are in turn transformed into CS values corresponding to the relative suppression of nocturnal melatonin after a

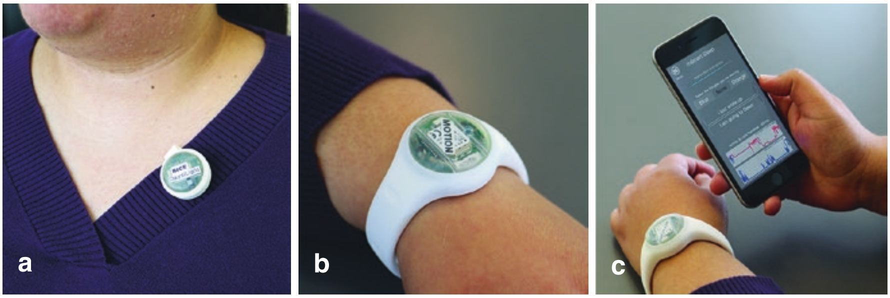


Fig. 15.3 The Daysimeter is used to measure both conventional photopic illuminance and circadian light exposures. The data presented in Table 15.1 were collected using an earlier version of the Daysimeter that was worn at eye level. For increased user compliance, newer versions of the Daysimeter are being worn as pendants or pins (**a**) to measure light exposures. The newer version of the Daysimeter also measures activity levels when worn on the wrist (**b**). A third component of the newer version of the Daysimeter uses a mobile phone app to compute light treatments (**c**)

1-h light exposure through a 2.3 mm diameter pupil during the midpoint of the body's nighttime production of that hormone [14]. Since CS is defined in terms of the circadian system's input–output relationship, from threshold (CS = 0.1) to saturation (CS ≈ 0.7), it is considered a better measure of the circadian effectiveness of light than either photopic illuminance or CL_A. The data summarized in Table 15.1 were obtained from 24 young adults aged 18–30 years [18], 22 female school teachers (mean ± standard deviation (SD) age of 36.25 ± 7.86 years) [19], 22 eighth-grade elementary school students [20], and 77 rotating- and day-shift nurses [21]. The participants in all studies wore the device for at least 5 consecutive days and were instructed to maintain their normal schedules while participating in the respective protocols.

It should be emphasized that for the rotating-shift nurses, because their morning and evening data were collected relative to bedtimes and wake times rather than actual clock time, the respective values shown in Table 15.1 could represent light exposures that occurred much earlier and/or later in the day than those of the other populations. The Daysimeter data were used to calculate mean photopic illuminance (lux), CL_A, and CS exposures. Log10 transforms of the photopic and CL_A values were also calculated because the recorded light exposures had highly skewed distributions in which brief exposures to extremely bright light (e.g., sunlight) dominated the arithmetic mean values. The log10 transforms of the photopic illuminance and CL_A values are therefore probably more representative of the light exposures' central tendency than the arithmetic means.

Several studies have postulated that exposure to electric light at night (LAN) poses health risks because it is sufficiently bright to suppress melatonin or disrupt our circadian rhythms [22–24]. However, very few data have been reported concerning actual light exposures in living and working environments during night and day. The data presented in Table 15.1 suggest that the average evening light exposures experienced by the five experimental populations were well below this level, even among the rotating-shift nurses who, research indicates, are known to be at higher risk for breast cancer [25, 26] and skin cancer [27]. The mean CS values for the five populations ranged from 0.04 to 0.07, suggesting that their evening light exposures resulted in suppression values that were below 7%.

Gooley et al. showed that an 8-h exposure to <200 lx at the cornea of a 4100 K light source resulted in significant suppression of evening melatonin in the laboratory [28]. Although no real-life light measurements were presented by the authors, and they did not utilize a photometric instrument calibrated in terms of the spectral sensitivity of the human circadian system, the group postulated that exposure to 60–180 lx at the cornea (which they referred to as the <200 lx condition) is representative of typical room lighting conditions experienced by people in their homes during the evening. Exposure to 200 lx at the cornea from a 4100 K source like the one used by Gooley et al., however, would have provided a CS value between 0.15 and 0.19, depending upon the source's specific spectral power distribution. Thus, the data in Table 15.1 underscore the fact that light in the built environment is simply too low for circadian entrainment when compared to the amount of light one would be exposed to outdoors, even on a cloudy day.

Table 15.1 Mean (±) standard error of the mean morning (4 h after rising) and evening (4 h before bed) light exposures for different populations

	Photopic illuminance (lx)		Log10 photopic illuminance (lx)		CL_A		Log10 CL_A		CS	
Population	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening	Morning	Evening
Young adults ($n = 24$)	772 ± 188	38.2 ± 4.3	2.00 ± 0.06	1.22 ± 0.06	1650 ± 438	34.3 ± 3.6	2.02 ± 0.06	1.17 ± 0.05	0.193 ± 0.015	0.046 ± 0.005
Teachers ($n = 22$)	373 ± 80	40.4 ± 9.9	1.94 ± 0.05	1.07 ± 0.06	478 ± 105	44.1 ± 14.5	1.88 ± 0.06	0.97 ± 0.07	0.172 ± 0.013	0.036 ± 0.006
Eighth-grade students ($n = 22$)	268 ± 25	63.0 ± 19.6	2.04 ± 0.04	1.19 ± 0.08	305 ± 54	78.4 ± 30.7	1.96 ± 0.03	1.13 ± 0.08	0.184 ± 0.006	0.046 ± 0.008
Day-shift nurses ($n = 33$)	296 ± 50	73.9 ± 16.9	1.49 ± 0.04	0.94 ± 0.05	408 ± 173	35.8 ± 11.1	1.30 ± 0.06	0.79 ± 0.04	0.109 ± 0.011	0.029 ± 0.004
Rotating-shift nurses ($n = 44$)	277 ± 56	104.0 ± 13.7	1.37 ± 0.04	1.09 ± 0.06	414 ± 103	135 ± 22.4	1.35 ± 0.04	1.06 ± 0.05	0.114 ± 0.009	0.066 ± 0.006

Research on the Impact of Current Lighted Environments on Health and Well-being

The lack of adequate light exposure in the built environment has been associated with negative outcomes in measures of sleep, mood, and general well-being. Boubekri et al., for example, showed that people working in offices without access to windows reported poorer sleep quality, shorter sleep duration, and more-frequent sleep disturbances as assessed by self-reports and actigraphy recordings [29]. A recent study in five office buildings, on the other hand, showed that office workers who received high circadian stimulation in the morning reported better sleep and diminished depressive symptoms compared to their colleagues who received low circadian stimulation in the morning [30]. A follow-up study involving the installation of circadian-effective lighting in four other office buildings found that the intervention reduced workers' subjective sleepiness and increased their subjective feelings of alertness, vitality, and energy [31].

While a number of studies have attempted to demonstrate the benefits of lighting that provide higher circadian stimulation in the built environment during the daytime, other studies have employed a reduction in circadian stimulation during evening hours [32, 33]. Well-recognized risks for circadian disruption have been associated with evening light exposures from sources such as kitchen lighting and bathroom vanities, especially when they are furnished with high correlated color temperature (CCT) fixtures [34]. A growing risk in this regard has accompanied the burgeoning popularity of self-luminous portable electronic devices, or PEDs (e.g., cellphones, e-readers and tablets, laptop computers), whose displays are known to disrupt sleep [35] and the melatonin rhythm [36], particularly when used in the early evening (i.e., after 2000) during the onset of melatonin secretion. While at least one laboratory study has demonstrated that watching television at this time does not affect melatonin production [37], suggesting that devices' proximity to the corneas plays a role, another laboratory study demonstrated that manufacturers' solutions to avoid melatonin suppression from self-luminous devices in the evening (e.g., Apple's "Night Shift" setting for the iPad) are not necessarily effective [17].

Researchers generally agree that lighting schemes for daytime workers should be designed to promote circadian entrainment, which in turn should result in better sleep, mood, health, and perhaps some measures of performance. These recent studies emphasize not only the importance of reducing evening light exposures to maintain a regular sleep–wake cycle, but also the benefit of providing good circadian stimulation throughout the entire workday.

Adolescents present a special case, as they can be chronically sleep deprived due to their naturally later circadian phase and related inability to fall asleep at times conducive to their fixed early wake-up times on school days. Chronic insufficient sleep within this age group has been linked to depression, behavioral problems, poor performance at school, and automobile accidents [38]. This problem can be compounded by adolescents spending most of their day indoors in dimly lit classrooms, which inhibits the synchronization of their circadian systems with the solar day. Studies by the Lighting Research Center (LRC) have pointed to the importance of controlling the entirety of adolescents' 24-h light–dark patterns while they are at school and at home to promote circadian entrainment and reduce sleep restriction [39, 40], especially in view of the popular use of self-luminous electronic devices before sleep, which can delay circadian phase [41].

Most of the other published laboratory and field research to date has examined lighting for older adults living with Alzheimer's disease and related dementias (ADRD) [42–44] as well as patients in hospital rooms [45, 46]. Field research focused on older adults with ADRD has shown that a lighting intervention that provides high circadian stimulation during the day and low stimulation at night can reduce depressive symptoms among those living at home [33]. In nursing homes, where light exposures are more easily controlled, the same intervention resulted in improvements to sleep, depression, and agitation [44]. In another LRC study conducted in a nursing home, a lighting intervention with very high circadian stimulation was delivered to residents using a specially designed light-emitting diode (LED) "light table" [47]. Residents who sat around the table, as residents conventionally do in nursing home common areas, showed significantly increased sleep duration and reduced agitation and depression scores. In another non-LRC study, cancer patients who underwent myeloma transplant and received high circadian-effective light between 0700 and 1000 were less depressed than those who received a dim, control light [48]. Although more field studies are needed to confirm these initial findings, it has been postulated that lighting can improve patients' mood and health outcomes [49] and may shorten the length of hospital stays [50].

The Need for Proposing a 24-h Lighting Scheme in our Lighted Environments

The data shown in Table 15.1 clearly indicate that people working indoors are exposed to dim, extended, and aperiodic circadian-effective light, whereas those working outdoors are likely to be exposed to a robust light–dark cycle that is ideal for regulating the circadian system. These differences are probably even more pronounced during the winter, when the duration of daylight becomes shorter and those working indoors are exposed to even lesser amounts of circadian-effective light during the day. The resulting disruption of the circadian cycle that is probably now experienced by most people in modern societies may very well have a direct influence on associated health problems such as metabolic diseases, cancer, and mood disorders, among various other conditions [23, 51, 52]. Future trends in the lighted environment should therefore include 24-h lighting solutions that promote circadian entrainment.

Initial studies of light's therapeutic application focused on treating the symptoms of seasonal affective disorder (SAD) [53, 54]. While the mechanisms associated with light's beneficial effects on SAD are not yet well established, light therapy is nonetheless recognized by physicians and recommended as a sole or adjunct treatment [55]. However, conventionally prescribed light therapy boxes, which are not an integral part of the built environment and can be very bright and glaring if not equipped with a dimming control, can reduce patients' compliance with the treatment and thereby reduce its efficacy. Fortunately, newly developed, more-effective technologies such as solid-state lighting have fostered better targeted, less glaring solutions for relieving SAD symptoms. (For more information on how to measure and specify light therapy, please refer to Chap. 14 in this volume.)

A growing body of evidence indicates that any successful field application of light therapy to correct circadian sleep disorders must control the total light exposures over the course of the 24-h light–dark cycle. Using the modified model of the human circadian oscillator [56] that permits quantitative predictions of circadian phase changes resulting from light exposure, Rea et al. [57] showed that light exposures during total waking hours must be monitored and controlled in order to predict circadian phase changes resulting from a given light treatment. Several other models for predicting phase changes have been proposed, but they have met with mixed success due to their inability to account for differential light exposures from week to week. The model by Kronauer et al. [56], for example, consists of a light-stimulus phototransduction process (L) driving an oscillator-based pacemaker process (P). In the phototransduction model proposed by Rea et al. [15, 16], unlike the Kronauer et al. model, CS is used as an input to process L instead of photopic illuminance (lux). Parameters of the process P were revised based upon data from field studies where light exposures and circadian phase changes were measured. More specifically, two parameters in the process P were adjusted (k and q), and a time-dependent sensitivity modulation factor was removed. Overall, the model proposed by Rea et al. [15, 16] improves upon Kronauer's model by incorporating new knowledge of human circadian phototransduction; thus the Rea et al. model can provide more accurate quantitative predictions of circadian phase changes resulting from differential light exposures.

To illustrate the application of this model, predictions of circadian phase changes based upon continuously measured 24-h light exposures were compared to measured phase changes (DLMO) from three field studies [18, 58, 59]. Figure 15.4a shows the correlation between DLMO and the measured phase changes calculated from the Daysimeter [12, 13] data and predicted phase change using the modified Kronauer model [56, 57], which were statistically significant ($R^2 = 0.70$, $p < 0.0001$) with a prediction uncertainty of 1.75 h (95% confidence). Interestingly, and as shown in Fig. 15.4b, when only the treatment light exposures—and not the total light exposures measured over the entire waking period—are included in the model, predictions of circadian phase change are not as good, as shown by the large deviation of the best fit from the ideal fit.

Controlling light exposures for the entire 24-h day therefore requires tracking and recording—in terms of spectrum, level, timing, and history—throughout all waking and sleeping hours. It is also necessary to understand how those light exposures have interacted with a person's biological systems and to then make the necessary lighting adjustments, effectively creating a personalized light prescription that follows them everywhere they go, including while they are at work and at home.

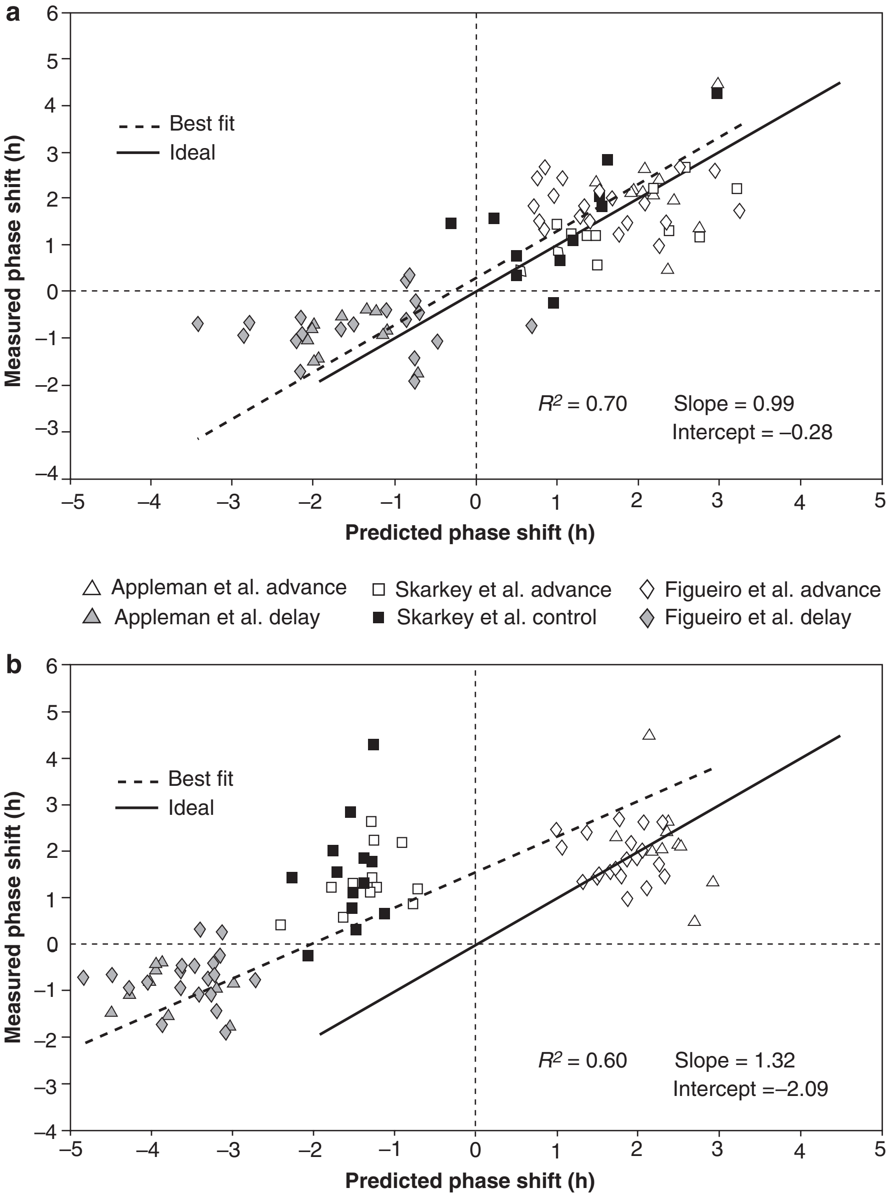


Fig. 15.4 Correlation between DLMO and the predicted phase changes calculated from the Daysimeter data and the modified Kronauer model: (**a**) measured changes in dim light melatonin onset (DLMO) from baseline to post-intervention are plotted on the ordinate, and circadian stimulus (CS)-oscillator model predictions based on actual measured light exposures during the intervention are plotted on the abscissa; (**b**) measured changes in DLMO from baseline to post-intervention are plotted on the ordinate, and CS-oscillator model predictions based solely on the treatment light exposures (i.e., not using light exposures measured throughout the day by the Daysimeter) are plotted on the abscissa. The ideal fit for both graphs was calculated using the least squares method, where the difference between the measured DLMO and the predicted DLMO was calculated

Future Trends in Lighted Environments

Since CS is defined in terms of the circadian system's input–output relationship (see section "Current Trends in Lighted Environments") and various field studies have shown that it is associated with better sleep, mood, and well-being, the future trends discussed in this section will use CS as the principal metric, with corresponding lux levels provided. In general, when occupied by day-active/night-resting people, the lighted environments should deliver a $CS \geq 0.3$ at eye level and a $CS < 0.1$ starting 2 h prior to their desired bedtimes. The LRC has developed a CS calculator (https://www.lrc.rpi.edu/cscalculator/) to help lighting professionals select light sources and targeted photopic light levels that will increase the potential for proper circadian light exposure in buildings. This tool facilitates calculations of CL_A and CS for over 180 example light source spectra as well as user-supplied light source spectra.

Workplace Lighting

To promote circadian entrainment among daytime office workers, lighting systems and solutions must be tailored to meet the circadian requirements of the people who spend their workday in a particular office space while also addressing the unique characteristics of that space. Factors to be taken into account include (1) the workers' ages; (2) the type of work performed; (3) the presence and number of windows, as well as the amount of light they contribute to the space; (4) the direction in which the windows face, (5) the space's ceiling height; (6) the presence of obstructing features such as cabinets and partitions; (7) the reflectance values of the office furniture and fixtures; and (8) the amount of CS that the space's occupants receive at eye level and the times of day when they experience it throughout the entire workday.

As with any environment, morning lighting at work should provide plenty of CS to help synchronize the biological clock and promote circadian entrainment. In the simplest terms, this can be achieved by increasing the amount of light reaching the eye by sitting next to a window for 30 min, opening window shades, and/or increasing the office's ambient light level. Field research shows that relatively simple lighting strategies can achieve sufficiently high levels of CS (i.e., $CS \geq 0.3$) using commonly available lighting systems [30, 60], such as the 2 × 4 troffer lighting fixture employed for the lighting schedule shown in Fig. 15.5. Ideally, to better promote entrainment, the lighting system's CS levels should be lowered toward the end of the day, especially if the office space is to be occupied through the early evening.

Healthcare Facility Lighting

Healthcare represents another sector that stands to benefit from circadian-effective lighting systems. The modern hospital is in effect a city in microcosm, which poses a formidable challenge to lighting design because the "city" is all under one roof.

The hospital functions around the clock and year-round, its patients can range in age from premature infants to the elderly, and the people in any given space can be very ill patients or workers and visitors who are in good health. Furthermore, many healthcare personnel work long hours that can include night shifts and rotating shifts and are exposed to different lighting characteristics at different circadian times.

For patients and their visitors, lighting schemes should more or less follow those outlined for daytime office workers in Fig. 15.5, since all patients must remain entrained to the hospital's daytime caregiving schedule and most visitors are usually present only before patients' bedtimes. The same may also be said for caregivers

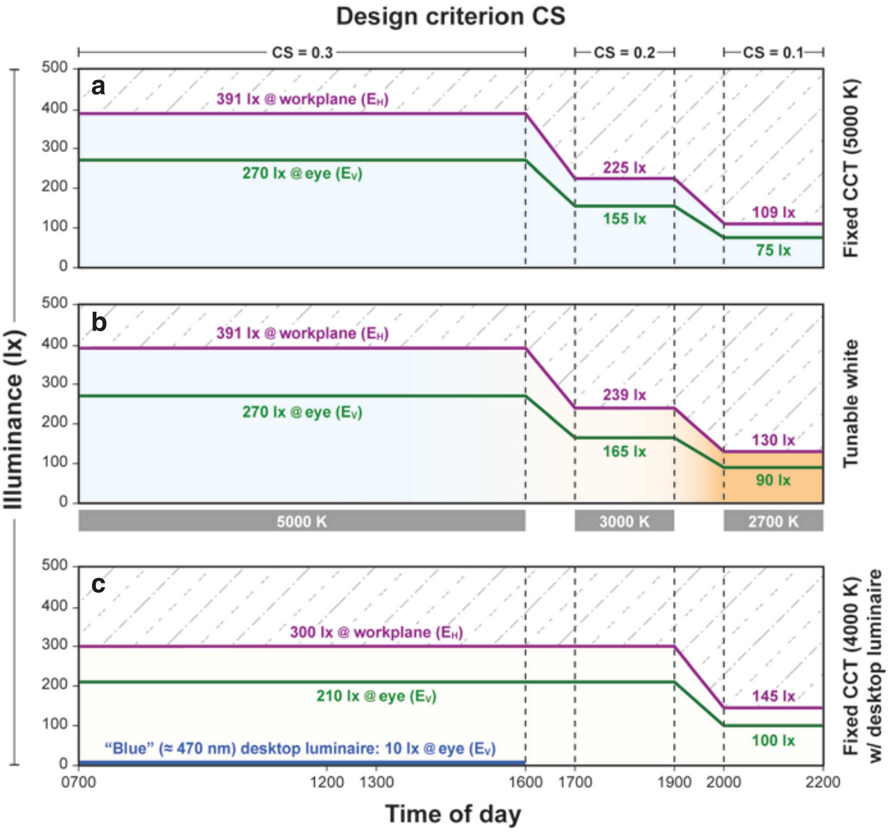


Fig. 15.5 Three lighting schemes that can be used to provide the minimum CS for promoting circadian entrainment (CS = 0.3) using typical 2 × 4 troffers in an open office environment: (**a**) fixed CCT (5000 K), (**b**) tunable white (5000–2700 K), and (**c**) fixed CCT (4000 K) supplemented by a personal desktop luminaire delivering 30 lx of saturated short-wavelength "blue" (≈ 470 nm) light at eye level. It is most desirable to specify lighting systems that vary in output and spectrum (if possible) throughout the day according to the circadian needs of the space's occupants. Though not shown here, during the night shift, systems can also be designed to deliver saturated long-wavelength "red" (≈ 630 nm) light to promote alertness without elevated CS levels and disruption to nighttime workers' melatonin rhythms [31]

Fig. 15.6 Rendering of a nurses' station during the day shift (left) and night shift (right). High CS to promote circadian entrainment and alertness is provided using higher photopic illuminance levels and saturated blue light from the desktop luminaires during the daytime. Illuminance and CS levels are lower at night, and alertness is promoted by saturated red light that does not affect the circadian system. The same desktop devices, in this case LED light therapy panels, can be configured to deliver both types of light shown here

who work exclusively during the day. Caregivers have dramatically different lighting needs during the night shift, however (Fig. 15.6), and circadian disruption (and its consequent health problems) has been demonstrated among those who work rotating shifts and, especially, among those who work throughout the night [61, 62]. Lighting tips for night-shift caregivers are provided in the sidebar.

Lighting Tips for Night-Shift Caregiver Entrainment

Night-shift caregivers are usually entrained to a day-shift lifestyle because they continue to follow daytime social and domestic activities, making adaptation to a nocturnal lifestyle both impractical and undesirable. For these caregivers, it would be best to:

- Minimize bright light (> 20–30 lx at the eye, CS > 0.05) during the night shift, starting at around 2300, taking care to avoid the use of self-luminous personal electronic devices.
- Receive saturated red (630 nm) light of at least 40–60 lx (CS = 0) at the eye in rest areas or workspaces (either intermittently or continuously), which will provide an alerting stimulus similar to drinking a cup of coffee throughout the night and will not affect melatonin levels.
- Use task lights to increase light levels on the workplane (i.e., horizontal surfaces such as desks, tables, workstations, etc.) and for specific critical tasks, such as insertion of an IV.
- Take public transportation to avoid falling asleep behind the wheel on the drive home.

Another alternative for nighttime caregivers is a “compromise solution” that uses light early in the night to delay feelings of sleepiness until after the shift is over, but not so late that it does not dramatically differ from their wake times on working days. In other words, the caregivers would remain entrained to a day-shift lifestyle but would become “night owls.” This adaptation permits easier transitions between night and day shifts and can be achieved by caregivers if they:

- Receive high levels of illumination until 0300–0400 (at least 200–300 lx ($CS \geq 0.3$) at the eye from a white light source) in workspaces followed by dim white light (20–30 lx at the eye, $CS < 0.05$) until the end of the shift.
- Lower levels of saturated blue light (e.g., 30 lx at the eye of a 470 nm light) could also be added as a task light, but care should be taken to avoid compromising important aspects of visual performance (e.g., color rendering) required for carrying out visual tasks.
- Receive saturated red (630 nm) light of at least 40–60 lx ($CS = 0$) at the eye in rest areas or workspaces (either intermittently or continuously), which will provide an alerting stimulus similar to drinking a cup of coffee throughout the night and will not affect melatonin levels
- Use task lights to increase light levels on the workplane and for specific critical tasks such as insertion of an IV.
- Wear dark sunglasses on the way home after work to prevent outdoor light from affecting the night owl adaptation.
- Take public transportation to avoid falling asleep behind the wheel on the drive home.

Home Lighting

The home lighting environment is crucial for circadian entrainment since it is where people typically wake up to begin their day and prepare for sleep at the day’s end. Given what we know about the circadian system, circadian-effective lighting systems must be adapted to follow humans *between* the spaces they occupy, from home to work, to retail and recreational spaces, and then back home again in the evening. Research by the LRC, in conjunction with Lund University and the Swedish Energy Agency, has made a crucial first step toward realizing an individualized lighting prescription system in the Swedish Healthy Home project. The system is built around the Daysimeter (or similar device) [13], which tracks personal light exposures and physical activity (actigraphy) throughout the 24-h day and transmits the data for storage on a smartphone or some other PED (see Fig. 15.3). Upon arrival at home at the end of the day, the data are then automatically transmitted to the home’s central lighting control system, which then

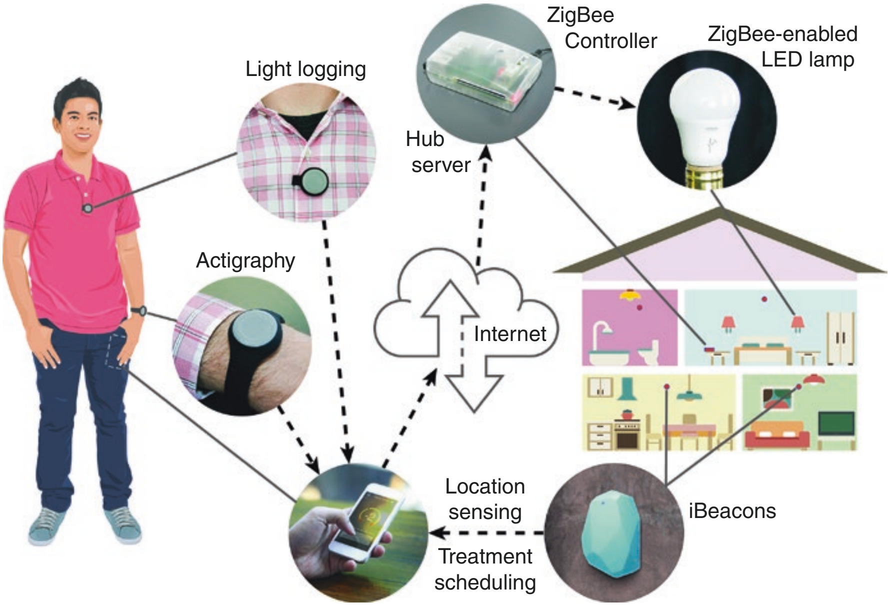


Fig. 15.7 Schematic of the Swedish Healthy Home lighting system. Light exposures and actigraphy are recorded using a Daysimeter worn as a pendant and on the wrist, and the data are transmitted via Bluetooth to a handheld electronic device such as a cellphone

makes any necessary adjustments to the lighting in any space a person happens to occupy (Fig. 15.7).

In future developments, we envision the system recognizing users' personal light exposures as they move between buildings or rooms and dynamically adjusting the ambient lighting to maintain entrainment, rather than simply making adjustments upon their arrival at home in the evening. If the automatic controls are not appropriate or practical at a given time, moreover, we also envision the system being overridden and configured to provide notifications of any lighting needs and measures that should be taken. The system could also send a notice advising users to use personal light "dosing" or filtering devices such as light goggles or spectrally filtered glasses should the system override not be appropriate for their personal needs. Because the system is dynamic and portable, it would also be easily translated to one's home, schoolroom, or workplace.

Conclusion

It is well established that a robust, regular 24-h light–dark pattern minimizes circadian disruption, which in turn minimizes negative health and performance outcomes. Circadian disruption can be observed and become an issue when people travel across multiple time zones, use self-luminous displays in the evening, spend most of their daytime hours in dim interiors, stay up late to view media, and move from building to building and space to space throughout the day. In other words, circadian disruption can occur when the 24-h light–dark pattern is no longer regular and predictable.

The challenge for lighting researchers and professionals is that they have been so closely tied to thinking about a particular building—that is, a single static place where one needs light for the performance of tasks and the perception of the space's ambience, instantaneously. Circadian hygiene is not instantaneous, but cumulative. Today, because people continually carry self-luminous displays and pursue active lives that profoundly influence their 24-h pattern of light and dark, they do not have a single lighting entity that is responsible for total 24-h light exposure patterns and therefore cannot adequately address 24-h light exposure issues.

The challenge for sleep clinicians who wish to use light as a non-pharmacological treatment for circadian sleep disorders is that they need to start "thinking outside the (light) box." Lighting technologies now exist that can incorporate precision medicine in the delivery of tailored lighting interventions to treat circadian sleep disorders. Light sources that can be tuned to maximally affect (or not) the biological clock while reducing glare can be specified and purchased. Measurement tools that can determine the real-time dose experienced by users are readily available for clinicians and researchers. As a next step, sleep clinicians should seek to collaborate with researchers to increase the number of applied research studies demonstrating the efficacy and feasibility of these new light therapy options. We have to let go of the past and take advantage of the latest lighting technology advances.

A new profession needs to emerge, such as personal light and health coaching, or new software applications need to be developed to keep track of light–dark exposures and provide recipes for maintaining entrainment or correcting circadian disruption. This can already be accomplished where users do not change their living space across the 24-h day (e.g., senior living facilities [44] and submarines [63]). Another area for real impact could be healthy lighting for schoolchildren, who have a regular daily routine, and the education of parents to better control light and thereby ensure adequate and consistent sleep. The next step would be to educate teachers and parents about the significance of a robust 24-h light–dark pattern. Office spaces pose a greater challenge, but one can begin to envision the use of a workplace "light oasis" (Fig. 15.8), where workers could receive their circadian light exposures during the daytime with the aid of an application that informs them about what they need to do and when they need to do it. The technology now exists for implementing some of these solutions and, perhaps, changing the lighted environment so that it indeed promotes circadian health.

Fig. 15.8 Light oases of varying configurations are practical solutions for providing circadian stimulus for office workers. Such oases could be used in conjunction with a personalized circadian application that informs workers about what light they might need and when they need it

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