Light - Much More Than Vision

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Abstract

A brief overview of the impact of light on the circadian system is given, which underscores the importance of developing a framework for circadian photometry. The amount of light, its spectral composition, spatial distribution, timing and duration needed for vision is so different from that needed for circadian functioning, that generalizations about "good lighting" will have to be assessed by two very different sets of criteria in the future. Although the framework provided in this paper will undoubtedly be refined as more research is undertaken, little progress will be made in delivering "healthy lighting" to society until researchers and practitioners begin to consider, measure, calculate, and control the fundamental characteristics of light for the circadian system, as well as for the visual system. It is my belief that a new system of photometry for the circadian system should be developed, and that until we do, we will be unable to lay any claim to "good lighting" with regard to human health.

Introduction

Although the topics covered in this symposium span optical radiation, I shall limit my presentation to the narrower band called light. More specifically, I shall limit my remarks to the influence of light on circadian functions because I believe we are at the threshold of a new paradigm for lighting technologies and applications as they impact human health. But, I shall argue, we can only cross that threshold when we develop a new definition of light as it impacts the circadian system.

Light is presently and formally defined as optical radiation entering the eye that provides visual sensation [1]. An international system of photometry has been developed and institutionalized to quantify, measure and communicate the properties of light as it affects human vision [2]. Robust industries of manufacturing and application engineering have evolved in concert with photometry to provide nearly every human on the planet with practical sources of light for reading printed materials, watching luminous displays, driving automobiles and other modes of transportation, and playing innumerable sports, both indoors and out [1].

Observing the past twenty-five years of research, however, I believe we have reached the inescapable conclusion that we must expand the definition of light to include optical radiation entering the eye that affects the circadian system.

Indeed, I believe *now* is the most exciting time in lighting in the last 100 years because our automatic, unconscious assumptions about "good lighting" are being challenged by this research. This is a strong statement, but consider the following recent findings:

- Light can alleviate seasonal depression [3]
- Light can increase the length and quality of sleep [4]
- Light can consolidate sleep/activity patterns in Alzheimer's Disease patients [5]
- Light can improve performance of night-shift workers [6,7]
- Light can improve weight gain in premature infants [8,9]
- Light activation of the circadian system is affected by a newly discovered photoreceptive mechanism in the eye [10,11]
- Light regulates melatonin [12], which has been shown to reduce breast cancer growth [13,14]
- Light has a direct impact on cortical brain activity [15]

These studies represent only a few of the important scientific findings that beg an answer to the question, "Are we providing healthy lighting in our offices, schools and homes?"

Some of us attending this symposium have been associated with traditional lighting for many years. We understand how light is generated, delivered, manufactured and sold. I am certain that the papers presented at this symposium will inspire us to think in new ways about light. Ideally, we will begin to translate the findings of these learned papers into practical ideas for new light sources, luminaires, and applications. To be successful in this translation, however, we must be able to think about light itself in a totally new way. Specifically, I believe we must begin to think about an entirely new form of light measurement, or photometry, because the quantity, spectrum, spatial distribution, timing and duration of light exposure for circadian impression are radically different than those that are important to vision [16]. One purpose of this talk is to provide a framework for a new system of photometry for the circadian system whereby it becomes possible to more precisely define and control light for supporting human health. Without the formality of such a system, it will be much harder to develop the best lighting technologies and applications for human health.

Background

It was known for many years that variations in light exposure was important for regulating daily and seasonal behaviors to nonhuman mammals [17,18], but it was widely assumed that humans were not particularly sensitive to cycled light. As noted above, it has become clear in the last 30 years that light/dark cycles

regulate many human behaviors as well, including seasonal depression [3], sleep/wake patterns [19], body temperature [15], brain activity [15], subjective alertness [20], and performance [6,7].

It is now well accepted that the retina is responsible for transducing photic stimulation into neural signals for the circadian system [18,21-26]. In brief, the retino-hypothalmic pathway caries that neural information from the retina to the "master biological clock" in the suprachiasmatic nucleus (SCN) of the hypothalamus. The SCN generates self-sustained, (approximately) 24-hour oscillations in neural activity. The hormone melatonin is produced by the pineal gland, a primary site for neural input from the SCN [27]. Although a full appreciation of the impact of melatonin on various systems within the body is not complete, melatonin level in blood (or saliva or urine) is the primary measure of the status of the "master biological clock" (phase information) and for circadian impression (acute suppression) by light (e.g., Lewy *et al.* [12]). Light is the primary stimulus for controlling, through the SCN, the timing and the amount of melatonin produced by the pineal gland [28] and, presumably, its effects on integrated behaviors such as subjective alertness and performance.

Although it is clear that light is the primary stimulus for the circadian system, the characteristics of light (i.e., its quantity, spectrum, distribution, timing and duration) important to the circadian system remain ambiguous because, in part, there has been no serious attempt to develop a system of photometry for the circadian system. For example, early evidence suggested that bright light was necessary to affect the circadian system, both in terms of acute melatonin suppression at night and phase information from the SCN. Typical office illuminance levels (500 lx) from fluorescent lights were shown to be ineffective on melatonin suppression [12]. More recently it has been hypothesized that very low light levels (3.5 lx) can affect the circadian system [29]. It seems very odd that such radically different generalizations can be reached about the amount of light necessary to affect the circadian system, but when one considers two simple observations about how light is being characterized, it may become clearer why ambiguities remain about a question as simple as "How much light does it take to affect the circadian system?"

First, the quantity of light expressed in these and many other studies is in terms of illuminance (lx). The use of illuminance for characterizing light for the circadian system undoubtedly reflects the wide availability of inexpensive commercial instruments for measuring illuminance. All of these meters are corrected to the photopic luminous efficiency function based upon the spectral sensitivity of the L and M cones in the human fovea. Since these two photoreceptors are essentially irrelevant to circadian phototransduction [30,31], significant confusions will occur when the amount of "light" produced by different light sources in different studies has been characterized by a spectral sensitivity

function irrelevant to the circadian system. As discussed in more detail later, for light sources commonly used in offices, schools and homes, errors in spectral characterization of light for the circadian system can be as much as 3:1. In other words, for the same measured illuminance, one light source may be 3 times more effective for the circadian system than another light source. For more exotic light sources, such as light emitting diodes (LEDs), characterization errors can exceed 1000:1!

Second, illuminance is the quantity of light falling on a surface, not how much light is made available to the retina. Depending upon the orientation of the illuminance meter, horizontal on a work plane or vertical near the plane of the retina, the same amount of light emitted by a light source can produce variations in measured illuminance of as much as 30:1. Generally, recommended and measured illuminance levels are given in terms of the amount of light, illuminance, falling on a horizontal work plane [1]. Naturally, if the illuminance meter is oriented upward, toward the light sources in the ceiling, the meter will read a higher value than if the illuminance meter is located vertically, near the line of sight. Proper orientation of the meter with respect to retinal orientation does not necessarily ensure accurate measurement of how much light enters the eye. For the same illuminance, retinal illuminance can vary substantially depending upon both environmental and individual differences. For example, the various reflectances of objects within the visual field, the optical density of pre-retinal media (e.g., the crystalline lens), and the physical structure of the brow, nose and other features of the face will produce discrepancies between actual retinal illuminance and measured illuminance [32].

These are only two of the many sources of confusion that can arise from inadequate specification of the stimulus for the circadian system and, hopefully, underscores the difficulty for lighting manufacturers and application engineers to apply the results of research for the benefit of human health. In short, all of the physical characteristics of light must be reconsidered if we are to cross that threshold in delivering healthy lighting conditions. Following is a preliminary framework, a first step, for a system of circadian photometry.

Quantity

The solid curve on the left of Figure 1 [16] comes from the model of relative visual performance (RVP) by Rea and Ouellette [33] and represents the speed and accuracy of processing high contrast, alpha-numeric text by the foveae of young adults. Even under moonlight, visual performance is well above threshold and, as shown, higher light levels results in only slight improvements. As confirmed by many studies [34-36], at typical office illuminance levels, visual performance is near maximum (for targets of high contrast and large size). Figure 1 also shows how light level affects melatonin suppression by the

circadian system. The dashed curve on the right is a dose response curve to “full spectrum” white light presented for one hour at night when melatonin levels would be normally high [37]. Several studies are consistent with this dose response curve [30,38-43] once the other photometric variables (spectrum, distribution, timing, duration) are taken into consideration.

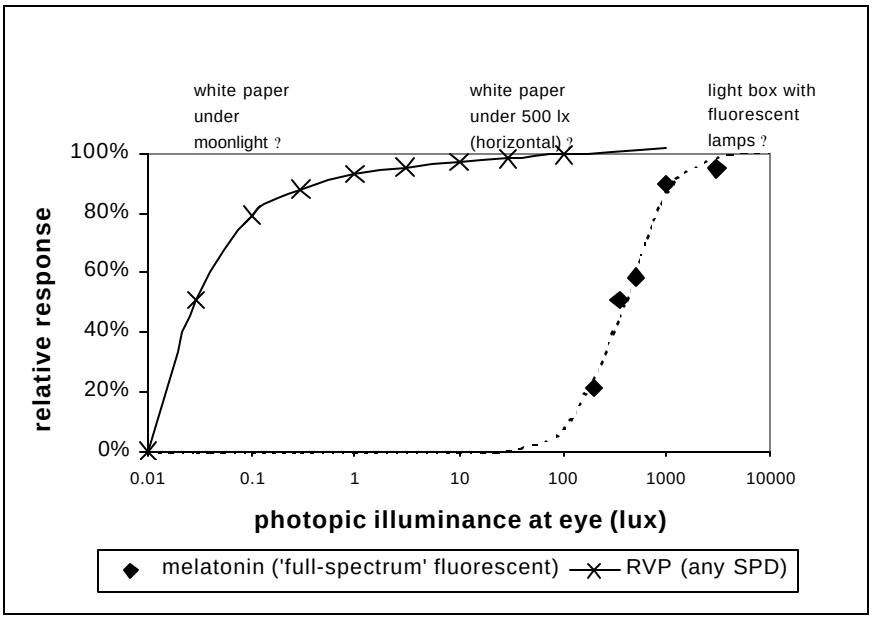

Figure 1. *Relative visual performance for high contrast reading material, and relative melatonin suppression by light as a function of illuminance at the eye [16].*

What this figure reveals is the marked disparity between the quantities necessary to achieve satisfactory visual performance and satisfactory melatonin regulation. At typical office light levels, visual performance is operating near maximum, but the circadian system is stimulated only slightly, if at all. Longer exposures to dimmer light perhaps can also suppress melatonin and shift the circadian rhythm [29], but this is probably not the best way to signal time-of-day information to the body. A prolonged weak signal may, in fact, be inadequate for synchronizing the disparate biological functions influenced, by melatonin. Significantly, modern deep-core offices with limited access to daylight [44] and typical energy-saving electric lighting levels [1] may provide inadequate stimulation to the circadian system, particularly during winter months when access to daylight is minimal. Approximately 10% of the population experiences some degree of seasonal depression in northern latitudes during the winter [45] and this may be a direct result of limited exposure to light brighter than found in modern buildings.

Spectrum

Recent research has shown that the spectral sensitivity of the circadian system is very different than the spectral sensitivity of the fovea, used to perform nearly all of our “visual work” (e.g., reading) [33,46]. Although fewer than 1% of the

photoreceptors in the retina are found in the fovea [47], nearly 80% of our visual cortex is devoted to processing information received in our central vision [47]. The fovea is dominated by L and M cones, which underlie the spectral sensitivity of the photopic luminous efficiency function used in every commercially available photometer made today [2]. Figure 2 [16] shows the marked disparity between the spectral response of photometers and the (provisional) spectral sensitivity of the human circadian system obtained by independent laboratories using monochromatic [41,42] as well as broadband sources [30,43]. This figure shows that light sources rich in short wavelengths (e.g., daylight) will be seriously under-represented by conventional photometric measurements. Table 1 [16] shows both photopic and "circadian" lumens calculated for several commercially available light sources together with the ratio of circadian lumens to photopic lumens produced by these sources. These ratios provide estimates of the relative errors that would be made in determining the effectiveness of the different light sources on the circadian system when a conventional photometer is used to measure light. For example, if the measured photopic illuminance under both incandescent light and daylight were the same, the daylight would be 2.22 (2.78/1.25) times more effective than the incandescent source for the circadian system. For conventional white light sources the errors in estimating the effectiveness of light for the circadian system from photopic measurements will rarely exceed 3:1.

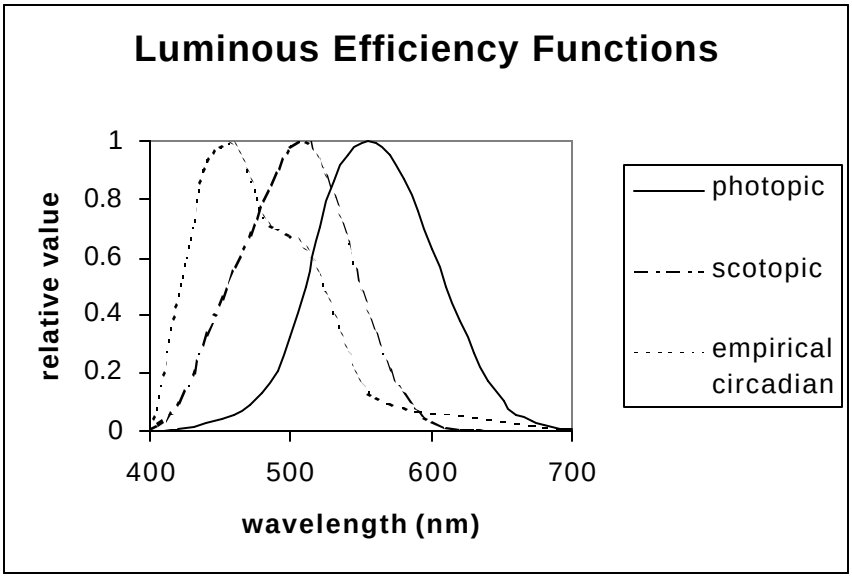

Figure 2. *Photopic and scotopic luminous efficiency functions, as well as an empirically derived action spectrum for melatonin suppression [16].*

Light source	Photopic luminous efficacy (lm/W)	'Circadian' luminous efficacy (lm/W)	Relative ratio of 'circadian' to photopic lumens
3000 K rare earth fluorescent	87 (1.00)	149 (1.00)	1.00
4100 K rare earth fluorescent	87 (1.00)	275 (1.85)	1.85
7500 K rare earth fluorescent	65 (0.75)	285 (1.91)	2.56
Sodium-scandium metal halide	108 (1.24)	300 (2.02)	1.63
High-pressure sodium	127 (1.46)	115 (0.77)	0.53
Incandescent	15 (0.17)	32 (0.21)	1.25
Red LED (630 nm)	44 (0.51)	2 (0.02)	0.03
Yellow LED (590 nm)	36 (0.41)	10 (0.07)	0.17
Green LED (520 nm)	25 (0.29)	88 (0.59)	2.06
Blue LED (460 nm)	11 (0.13)	681 (4.58)	36.2
White LED (460 nm + phosphor)	18 (0.21)	90 (0.60)	2.91
Daylight (6500 K)	—	—	2.78

Table 1. *Photopic and 'circadian' luminous efficacies (when applicable) and relative efficacies (in parentheses) normalized to 3000 K fluorescent [16]. Shown in the far right column are the ratios of the relative circadian to photopic efficacies (also normalized to 3000 K fluorescent), indicative of photometric errors in estimating the impact of spectrum on the circadian system (see text).*

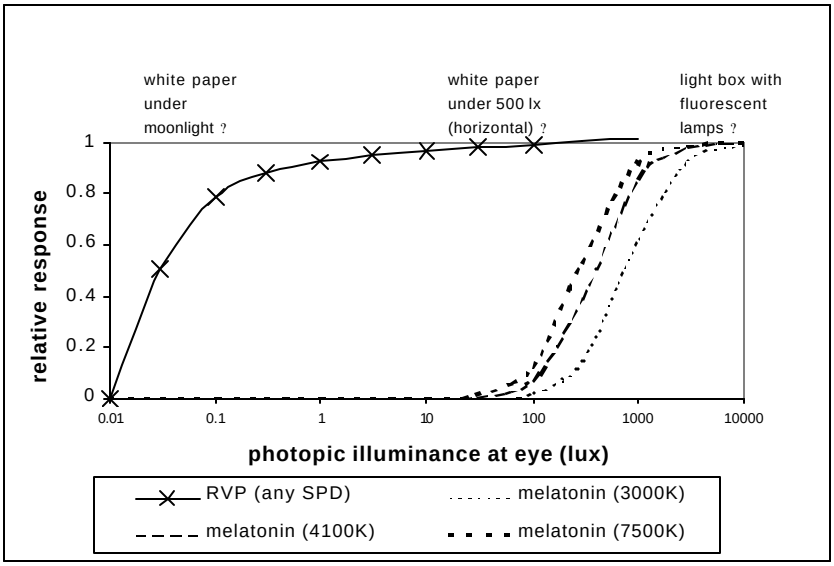

Figure 3. *Relative visual performance and relative melatonin suppression by light for several different fluorescent light sources (assuming the response shown in Figure 2), as a function of illuminance at the eye.*

Figure 3 [16] shows the impact of three different white light sources from Table 1 (fluorescent lamps with correlated color temperatures of 3000, 4100 and 7500 K) on RVP and on melatonin suppression. It will be recalled that the photopic luminous efficiency function represents the combined spectral sensitivity of L and M cones in the fovea. Since the fovea is used in visual performance, a single

curve can represent RVP [33,46] for all light source spectra when plotted as a function of the photopic illuminance. Since the L and M cones do not contribute significantly to the spectral sensitivity of the circadian system [30,31], melatonin suppression [37] must be represented by three separate curves, one for each light source, when plotted as a function of photopic illuminance. Figure 3 shows that the spectral power distributions of conventional fluorescent light sources used in architectural lighting differ only slightly in terms of their effect on melatonin suppression. This should not be surprising because the spectral power distributions of these light sources have been designed to maximize visual stimulation (brightness and color) rather than circadian impression. It is conceivable that new, colored light sources can be designed with maximum emission at short wavelengths to maximize circadian impression or with maximum emission at long wavelengths to minimize circadian impression. Consider, for example, a blue (460 nm peak) LED and a red (630 nm peak) LED that produce the same photopic illuminance. The relative effectiveness of the two sources for the circadian system will be about 1200:1! Clearly, a new system of photometry is needed to help design new light sources so that their impact on the circadian system can be properly characterized.

Spatial distribution

Through optical refraction by the cornea and lens in the eye and by neural-optical enhancements by in the retina [48], the spatial distribution of objects and textures in the environment can be processed by the visual system. Arguably accurate rendering of the spatial distribution of light in our environment by our retina is essential to our survival because subtle patterns of light and dark provide the information needed by the visual system to discriminate between friend and foe. Accurate registration of spatial information on the retina does not seem to be, however, important to the circadian system. Phototransduction of light by the circadian system seems to be performed without spatial registration, and the retina serves as a simple integrator of photon absorption. Different studies have employed diverse methods of presenting light to the retina. Some have used overhead fluorescent lamp luminaires in rooms with light-colored walls [40], some have used monochromatic light presented in a Ganzfeld [41,42], some have used light tables [30,43] and some have used light boxes positioned at different locations [37,38,49]. Despite these very different methods of presenting light, all studies show consistent results (once the timing, duration, spectrum, and quantity of light presentation are considered), which suggest that circadian activation is determined by simple integration of flux reaching the retina. It should be noted, however, that there is some evidence that the superior and inferior retinae may be populated with different densities of photoreceptors used by the circadian system. Two independent studies [50,51] reported that the inferior retina, integrating flux from above the line of sight, may be more effective for melatonin suppression than the superior retina,

although the difference was statistically significant in only one of the two studies [50]. It should also be noted that facial features affect light reaching the retina [32] and large individual differences in the amount of light transmitted through the optical media of the eye are to be expected, particularly for older subjects who have greater opacity of the crystalline lens at short wavelengths [52]. In general, however, one can assume that spectrally corrected (Figure 2) irradiance at the eye is a practical, if imperfect, measure of light available to the circadian system.

Timing

Although there are small circadian variations in visual sensitivity [53] the time of day is essentially unimportant to vision and, thus, to conventional photometry. The temporal characteristics of light are, however, particularly important to the circadian system and must be considered in any system of circadian photometry. Depending upon the time of exposure, light can phase advance, phase delay or have no impact on the timing of the circadian clock. Figure 4 [54] shows how light exposure affects the timing of the biological clock. If light is applied in the first half of the night, the biological clock is reset to a later time (phase delayed) whereas this same light applied in the second half of the night will reset the clock to an earlier time (phase advanced). The largest phase changes will occur at night when melatonin levels are high, but small effects can also occur during the day when melatonin levels are at their lowest. Indeed, it seems that melatonin suppression and phase shifting by light follow similar but not identical rules.

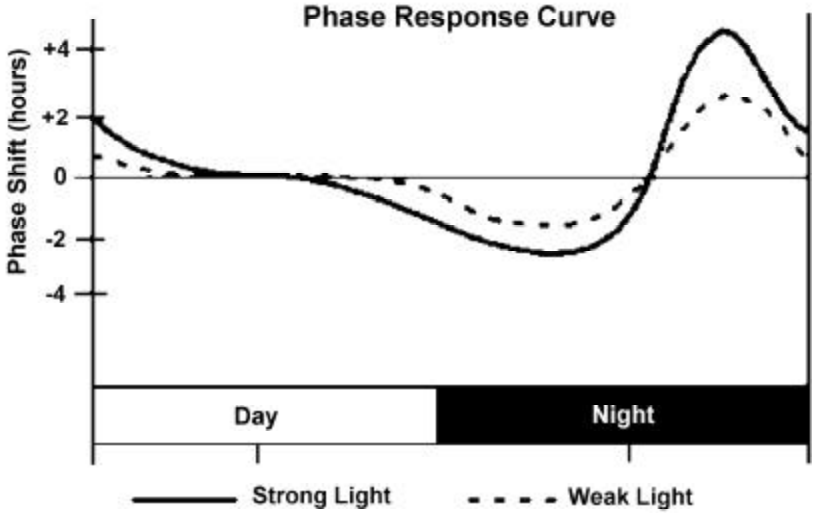

Figure 4. *The effect of the time of light application on phase shifting of the core body temperature rhythm for two different light levels [54].*

Like melatonin suppression, phase-shifting also follows a dose response function, with maximum effects occurring when the light is applied in the second half of the night. Figure 4 shows the effect of both high and low light levels on the

phase responses of the circadian system. It remains unclear, however, how light is integrated over the 24-hour period when the biological clock can be both phase advanced and phase delayed by light exposure. Some have expressed concern that bright light at night or dim light during the day may disrupt the circadian system, desynchronizing biological systems and leading to immune deficiencies or even breast cancer [55]. Continual, but aperiodic, access to light by humans throughout out the 24-hour period, is a legitimate cause for concern and systematic research.

Duration

The visual system operates very quickly. If it didn't, hazards could not be avoided and opportunities could not be seized. Almost all visual responses are mediated by neural circuitry that integrates, categorizes and transmits information about the luminous environment to the brain, which in turn initiates a behavioral response in less than a few hundred milliseconds [56]. The circadian system, however, operates at a much slower pace, mainly because it relies on infusion of the hormone melatonin into the blood stream, not upon neural circuitry, to communicate to various systems in the body.

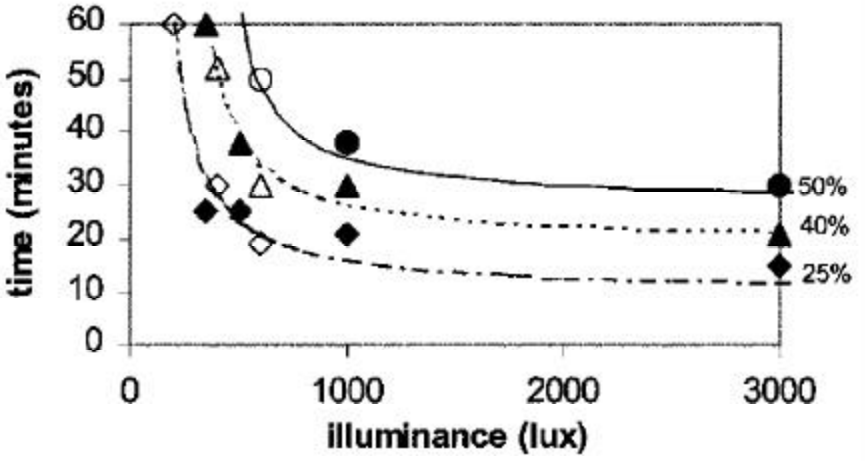

Figure 5. *The amount of time required to measure human nocturnal melatonin suppression by light, as a function of the illuminance provided at the eye [16]. Diamonds represent 25% suppression, triangles represent 40% suppression and circles 50% suppression. Filled symbols from McIntyre et al. [37]; open symbols from McIntyre et al. [38].*

Short, 5 s, pulses of bright light have been shown to have measurable effects on melatonin suppression in rodents [57], and the times to measure melatonin in the blood stream have been as short as 2 min. In humans, melatonin suppression by light has been measured within 10 min. [12] and a return to nocturnal levels of melatonin after extinguishing light will occur within at least 15 min. [37,38]. Melatonin samples have not been collected at shorter intervals, but it is likely that changes in melatonin levels in the blood stream are not immediate

even if the neural signal from the SCN to the pineal gland is very rapid because melatonin diffusion into the blood stream will take several minutes.

The results of McIntyre *et al.* [37,38] show that brighter pulses of light result in faster suppression of melatonin than dimmer pulses. Figure 5 [16] shows, for three different levels of melatonin suppression (25%, 40% and 50%) the relationship between illuminance at the eye and the time that melatonin was measured. The data come from two independent studies [37,38] but show remarkable consistency, as do other studies [12,58]. Twenty-five percent melatonin suppression could be measured in less than 20 min. as long as the sustained illuminance at the eye was greater than 1000 lx. If the illuminance at the eye decreased below 500 lx, it could take up to an hour to suppress melatonin by 25%. It also seems clear that a relatively low illuminance of 200 lx at the eye will never result in melatonin suppression greater than 25%, no matter how long it is presented. What is important to understand, but remains a mystery, is how much melatonin is needed and for how long to activate the various biological systems sensitive to by melatonin in the blood stream.

In terms of phase shifting effects, a recent study showed that a 6.5 h long pulse of bright light (9500 lx at the eye) had about the same phase-shifting effect as six 15 min. pulses of light separated by 1 h and having the same illuminance as the 6.5 h pulse [59]. These data indicate the phase shifting could occur even at diluted levels of melatonin suppression. The average melatonin level during the 6.5 h period was reduced by almost 90% for the continuous pulse of light at 9500 lx and by less than 20% for the intermittent pulses. These findings imply that it may be possible to obtain robust phase-shifting effects without having a significant impact on melatonin levels. If maintenance of melatonin rhythms is beneficial to health, then intermittent pulses of light could be of significant value in shift-work applications.

Lighting characteristics	Application Vision	Circadian—day shift work	Circadian—night shift work
Quantity	Low (300–500 lux on task: ~100 lux at eye)[1]	High (~1000 lux at eye)[37,38]	High (~1000 lux at eye)[37,38]
Spectrum	Photopic (peak sensitivity 555 nm)[2,46]	Short-wavelength (peak sensitivity 420–480 nm)[39,41-43]	Short-wavelength (peak sensitivity 420–480 nm)[39,41-43]
Spatial distribution	Distribution important (task luminance, contrast and size determine visibility)[33-36]	Independent of distribution (illuminance at eye)[48]	Independent of distribution (illuminance at eye)[48]
Timing	Any time[1]	Subjective morning[54]	Periodically throughout shift[7,58]
Duration	Very short (less than 1 s)[56]	Long (1–2 h)[40]	Short (15 min) pulses[59]

Table 2. *A framework for considering the characteristics of light to support vision and circadian functions [16].*

Conclusions

So, “Are we providing healthy light in our offices, schools and homes?” Probably the answer is, “No, we are not.” Certainly we are not providing or specifying the ideal lighting technologies and applications for circadian regulation. But how will we know what technologies and applications are ideal until we begin to measure and control the fundamental characteristics of light in completely new ways?

Hopefully this brief overview of the impact of light on the circadian system underscores the importance of developing a framework for circadian photometry. Table 2 [16] summarizes some of the important findings presented in this paper and contrasts light for the visual system and light for the circadian system. The amount of light, its spectral composition, spatial distribution, timing and duration for the two systems are so different that generalizations about “good lighting” will have to be assessed by two very different set of criteria in the future. Although this framework will undoubtedly be refined as more research is undertaken, little progress will be made in delivering “healthy lighting” to society until researchers and practitioners begin to consider, measure, calculate, and control the fundamental characteristics of light for the circadian system.

It is my belief that a new system of photometry for the circadian system should be developed, and until we do, we will be unable to lay any claim to “good lighting” with regard to human health. This symposium is a very important next step toward that goal.

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