SUSTAINABLE LIGHTING FOR HEALTHCARE FACILITIES: MORE THAN JUST LUMENS PER WATT

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INTRODUCTION

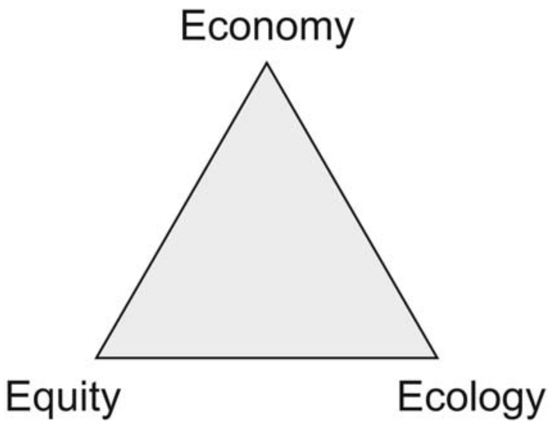
Sustainability is, as the name implies, a movement to ensure long-term, efficient utilization of resources. Sustainability does not imply that resources should be restricted nor that resource utilization should be subsidized. Bill McDonough (McDonough and Braungart 2002) has described sustainability in terms of the three E's: environment, equity, and economy. In the last quarter century the lighting industry has dramatically improved the energy efficiency (environment "E") and life-cycle cost of lighting (economy "E"). Much less attention has been given to the equity "E." Lighting standards are still set primarily in terms of illuminances (lumens per square meter) and lumens per watt, both of which are based upon the implicit assumption that the value of lighting can be characterized by the lumen. The lumen is, however, unrelated to other non-visual effects of light, such as the circadian system, and is only indirectly related to our perceptual system. In particular, our current architectural practices do not adequately support the most fragile segments of the population. And no matter how much energy is conserved or how much value engineering is applied, we are not designing or implementing sustainable lighting because we are not supporting many of the people in our built environments. In fact, the role of lighting as it affects human perceptual and circadian functions is almost completely ignored in standards. Arguably, the failure to consider these two human domain functions can be ignored in many modern applications because of the inherent flexibility and robustness of the human species. One segment of construction where the equity "E" should always be more seriously considered, however, is healthcare applications. These applications contain our most fragile humans, and lighting has been shown, for example, to demonstrably affect the lives of seniors and premature infants. But there are no standards to assist architects and engineers in supporting the well-being of these fragile people. To illustrate this assertion, this article focuses on sustainable lighting for healthcare applications where good lighting in all three human domains, visual, perceptual, and circadian, can be best documented.

BACKGROUND

Bill McDonough (McDonough and Braungart 2002) has described sustainability in terms of the three E's: environment, equity, and economy (Figure 1). The environment "E" is most often associated with the sustainability movement in lighting. Nearly every discussion of sustainable lighting is concerned, often *only* concerned, with energy efficiency. Certainly energy efficiency is essential for sustainability. But it is equally important that sustainable lighting is cost effective and it should serve the needs of building occupants.

Sustainability should support human endeavors, not waste our natural resources, and should be profitable. For "cradle to cradle" sustainability all three E's must be addressed. In the last quarter century the lighting industry has dramatically improved

FIGURE 1. The three E's: environment, equity, and economy (adapted from McDonough and Braungart 2002).



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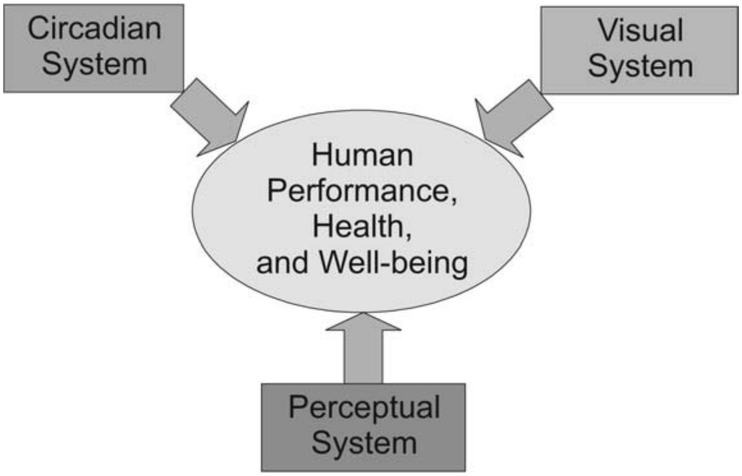


FIGURE 2. Human performance, health, and well-being is influenced by at least three systems: visual, circadian, and perceptual.

the energy efficiency and life-cycle cost of lighting. Much less attention has been given to the equity "E" of the sustainability triangle illustrated in Figure 1. Lighting standards are still set primarily in terms of illuminances (lumens per square meter) 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, but does not characterize all of the visual responses important to modern built environments (e.g., apparent brightness). Moreover, the lumen is only indirectly related to providing perceptual information about the environment (e.g., linear perspective) and it is, by definition, unrelated to the non-visual, circadian effects of lighting that help maintain entrainment of our many biological functions to local time. Boyce and Rea (2001) have conceptualized three domains that light can affect people. These are illustrated in Figure 2. Again, the lumen is relevant to only one of these three domains, which is the visual system.

LIGHT ISN'T JUST FOR VISION ANYMORE

Light is formally defined as optical radiation between 380 and 780 nm that provides visual sensation in humans (CIE 1978). The human eye has photoreceptors that convert radiant energy into neural signals for processing by the brain, a phenomenon called phototransduction. Until recently, four types of photoreceptors had been identified: rods and short, middle, and long wavelength cones (Rea 2000). Rods allow us to see at night and cones allow us to see during the day, discriminate details, and see colors. The neurophysiology and neuroanatomy of the human visual system is largely understood and all lighting technologies, standards, measurement devices and applications have been based solely on that understanding (Rea 2000). Given very recent developments in science, however, it is important to embrace the fact that *light is not just for vision anymore*. In the past few decades much work has been done to understand the non-visual effects of light on human health and well-being (Rea et al. 2002).

Light entering the human eye is transmitted to several other parts in the brain than those projecting to the visual centers. In 2002, the intrinsically photosensitive retinal ganglion cell (ipRGCs), a novel photoreceptor type in the retina, was discovered (Berson et al. 2002). The ipRGCs are central to an important "non-visual" response to light by the retina, most notably the regulation of circadian rhythms. The world rotates around its axis and, as a result, all creatures exposed to daylight on earth experience 24-hour cycles of light and dark. Biological rhythms are self-sustaining oscillations with a set of species-specific characteristics, including amplitude, phase, and period (Moore-Ede et al. 1982). Living organisms have adapted to this daily rotation of the earth by developing biological rhythms that repeat at approximately 24 hours. These are called circadian rhythms (Latin: circa, about; dies, day).

Circadian rhythms are generated endogenously (internal to the body) and are constantly aligned with the environment by zeitgebers (time givers), factors exogenous or external to the body. In mammals, circadian rhythms are regulated by an internal biological clock (pacemaker) located in the suprachiasmatic nuclei (SCN) of the hypothalamus of the brain (Moore-Ede et al. 1982). The SCN is a self-sustaining oscillator that maintains its daily activities for weeks when isolated and cultured. The SCN in humans has a natural period that is slightly greater than 24 hours and environmental cues can reset and synchronize the SCN daily, ensuring that the organism's behavioral and physiological rhythms are in synchrony with the daily rhythms in its environment. The light/dark cycle is the main synchronizer of the SCN to the solar day (Klein et al. 1991) and reaches the SCN via the retinohypothalamic tract (RHT). Although the circadian system shares receptors and neurons in the retina with the visual system, the retinal ganglion cells exiting the eye for the visual centers are different than those exiting the eye for the circadian system. Light as well as dark play an important role in regulating our circadian rhythms, and the timing of light/dark cycles are profoundly important for many of our behaviors as well as our well-being.

Light can have both an acute and a phase-shifting effect on the internal clock. Acute effects are seen shortly after light exposure. For example, it takes about five to ten minutes for light to suppress the production of nocturnal melatonin, a hormone produced at night and under condition of darkness (McIntyre et al. 1989). Acute effects also disappear soon after a light stimulus is removed; after about 30 to 45 minutes in the dark, nocturnal melatonin returns to a normal level. Phase shifting effects are seen a few hours or days after light exposure. Light applied during the early part of the night will delay the clock (for example, bed and waking times will occur later than in the previous cycle) and light applied very late at night or in the early morning will advance the clock (bed and waking times will occur earlier than in the previous cycle). If light is applied before minimum core body temperature, it will delay the clock while light applied after minimum core body temperature will advance the clock. Minimum core body temperature typically occurs about 1½ to 2 hours before one wakes up naturally (i.e., without an alarm clock) (Jewett et al. 1997).

In addition to impacting our circadian system, light reveals the many intersecting spatial planes that make up the environment (Paulus et al. 1984). Architectural features can be used to provide information about the environment and therefore improve navigation in the space (Gibson 1966). Light reveals visual information by providing a spatial reference for self-position and location of obstacles within a person's surroundings. For example, removal of visual cues by closing the eyes has been shown to result in increased body sway (Paulus et al. 1984; Turano et al. 1994). Therefore, lighting schemes that reveal or enhance architectural features should be used to aid navigation and orientation in the built environment.

LIGHTING CHARACTERISTICS AFFECTING THE VISUAL AND CIRCADIAN SYSTEMS

Light can be decomposed in five characteristic dimensions: quantity, spectrum, distribution, timing, and duration (Rea et al. 2002). These light characteristics affect the circadian system very differently than they affect the visual and perceptual systems. In brief, more light is needed to impact the circadian system than to stimulate the visual system. Young people can read a book under moonlight but no studies to date have been able to demonstrate that moonlight suppresses nocturnal melatonin production or shifts circadian phase. For reading, the daytime (photopic) visual response is maximally sensitive to light at 555 nm (yellow-green light), while the circadian system is a "blue-sky detector," maximally sensitive to wavelengths near 450 nm. The visual system has a very fast response time. The visual system can fully process light pulses as short as 80 milliseconds. The circadian system is very slow to respond requiring several minutes to fully integrate light falling on the retina. Thus the circadian system seems to be completely blind to brief but very bright lightning flashes at night. Perhaps the largest difference between the visual and circadian systems is associated with the time that light is registered on the retina. The visual system responds nearly the same any time of the day or night. However, as already mentioned, the internal clock can be reset forward (phase advance) or backward (phase delay) depending on the timing of light exposure. Finally, it should be added that the sensitivity of the circadian system to light appears to change depending on previous light exposures. For example, an office worker who stayed in a dim room all day long will suppress more melatonin when exposed to a given light at night than would a farmer, who had experienced very high outdoor light levels during the day. The circadian system seems to be more concerned with contrasting (night versus day) than absolute light levels (Herbert et al. 2002).

HOW LIGHT IMPACTS OUR HEALTH AND WELL-BEING

The effects of light on the circadian system are not trivial and should always be taken into consideration when designing lighting in a space. Upsetting the daily pattern of circadian light and dark affects performance and well-being, as well as, it seems, our basic health. The therapeutic value of circadian light (and dark) on fringe populations has been demonstrated in laboratory and field studies. Light with the appropriate characteristics can reduce symptoms of seasonal affective disorder (Levitt et al. 2002), increase sleep efficiency of older adults including those with Alzheimer's disease (van Someren et al. 1997; Figueiro et al. 2002; Figueiro and Rea 2005), improve circadian entrainment of premature infants (Rivkees et al. 2004), and increase alertness and well-being of night-shift workers (Badia et al. 1991, Cajochen et al. 2000, Figueiro et al. 2001, Cajochen et al. 2005, Figueiro et al. 2007). It has even been suggested that some forms of cancer and cardiovascular disease may be linked to the disruption of the normal circadian light/dark pattern. The impact of light on the general population is less clear. It is hypothesized that some disorders, including cancer and heart disease, may be a result of lack of entrainment, or synchronization, between the timing of one's internal clock and the day/night pattern, much like jet-lag after travel across multiple time zones.

EQUITY FOR OLDER ADULTS IN ASSISTED LIVING FACILITIES AND NURSING HOMES

After age 40, changes to the aging eye become more noticeable as visual capabilities decrease. The inability to focus on objects at close distances is noticed in particular after age 45; this is called presbyopia. As one grows older, less light reaches the back of the eyes because the pupil gets smaller and the crystalline lens inside the eye becomes thicker, absorbing more light. A 60-year-old receives about 1/3 of as much light at the retina as a 20-year-old. The lens also begins to scatter more light as one ages, adding a "luminous veil" over images on the retina, which reduces the distinctness (or contrast) of objects and the vividness of colors. After age 60 to 65 years, chances of having age-related eye diseases are greater. Common age-related problems are cataract, macular degeneration, diabetic retinopathy, and glaucoma. Cataracts are dark, cloudy, or opaque areas in parts or all of the crystalline lens. Macular degeneration refers to neural damage to central vision. Diabetic retinopathy occurs when blood vessels feeding the retina are damaged and regions of visual field are lost. Glaucoma is a result of too much fluid pressure inside the eye, which cuts off blood flow and, thus, nutrition to the retina and ultimately the optic nerve.

As one ages, changes to the circadian system are also more noticeable and may lead to sleep disturbances. Surveys indicate that 40 to 70 percent of the oldest members of the population (over 65 years old) suffer from chronic sleep disturbances (Van Someren 2000). In general, older adults tend to go to bed earlier in the evening and wake earlier in the morning than younger adults. Frequent nocturnal awakenings, difficulty falling asleep, and an increased number of naps during the day are also more common in the oldest adults. Sleep disturbances are associated with decreased physical health, including increased cardiovascular problems, disruption of endocrine functions, and decline of immune functions (Van Cauter et al. 1998).

Many physiological changes are implicated in the circadian rhythm disturbances found in older adults. Studies have shown that the SCN may become less responsive as we age. Studies have also demonstrated that changes in the amplitude and timing of melatonin and core body temperature rhythms may occur in older adults. Also, the first stage of phototransduction (when light signals are converted into neural signals) is negatively affected; older adults not only have reduced optical transmission at short wavelengths, which is maximally effective for the circadian system, but they also lead a more sedentary indoor lifestyle, with less access to bright light during the day. In fact, research has demonstrated that middle-aged adults are exposed to approximately 58 minutes of light above 1000 lux at the eye per day (Espiratu et al. 1994), while older adults in assisted living facilities were exposed to light above 1000 lux at the eye for only 35 minutes a day (Sanchez et al. 1993). Moreover, adults in nursing homes see as little as 2 minutes of light a day above 2000 lux at the eye (Ancoli-Israel et al. 1989).

Previous research demonstrated that light can be used as a non-pharmacological tool to help older adults, including those with Alzheimer's disease (AD), sleep more efficiently. Light in the evening can delay the circadian clock and help older adults sleep better at night and be more awake during the day (Murphy and Campbell 1996). Other studies have shown that exposure to bright white light improved sleep efficiency of institutionalized older adults (Satlin et al. 1992; Okawa et al. 1993; Mishima et al. 1994; Fetveit et al. 2003). One study demonstrated that evening exposure to 30 lx at the eye of blue light from light-emitting diodes (LEDs) peaking at 470 nm for two hours consolidated rest/activity rhythms and increased sleep efficiency of older adults with sleep complaints (Figueiro and Rea 2005). Exposure to bright light (at least 2500 lx and as high as 8000 lx) for at least one hour in the morning for a period of at least two weeks consolidated sleep of AD patients. Greater sleep efficiency at night decreased sleep during daytime hours and, in some cases, reduced agitation behavior (Ancoli-Israel et al. 2000; Koyama et al. 1999; Lyketsos et al. 1999; Mishima et al. 1998; Lovell et al. 1995; Mishima et al. 1994). Unattended exposure to bright white light (1136 lux average at the eye) during the entire day improved rest-activity of AD patients (van Someren et al. 1997). Evening exposure to bright white light (1500 to 2000 lx) for two hours decreased nocturnal activity and severity of evening agitation (sundowning) of AD patients (Satlin et al. 1992). Finally, evening exposure to 30 lx at the eye of blue light from LEDs peaking at 470 nm for two hours consolidated rest/activity rhythms and increased sleep efficiency of persons with AD (Figueiro et al. 2002 and Figueiro and Rea 2005). More recently, Sloane et al. showed that exposure to high intensity light all day or during morning hours only increased nighttime sleep in subjects with severe and very severe dementia. They also showed that morning light produced a mean phase advance of 29 minutes; that is, subjects went to bed earlier than prior to the lighting intervention.

The visual system also plays an important role in postural control and stability. More importantly, visual information is integrated with input from the vestibular and somatosensory systems, which are linked to balance control. Any changes that occur to any of these systems will affect the other systems' capabilities of maintaining balance (Lord et al. 1991). In fact, studies have demonstrated that removal of visual cues by closing the eyes has been shown to result in increased body sway. Recently, Figueiro and colleagues showed that nightlights that provide horizontal and vertical perceptual cues are well accepted by caregivers and, more importantly, can help increase postural stability when older adults are transitioning from sitting to a standing position (Figueiro et al. 2007).

USING LIGHTING TO PROMOTE EQUITY IN ASSISTED LIVING FACILITIES AND NURSING HOMES

Although not everything is known about the effects of light on health and well-being, it seems reasonable with the information available today to provide a 24-hour lighting scheme that maintains circadian entrainment as much as possible while promoting good visibility during waking hours and safe navigation at night. Following this logic, lighting in assisted living facilities and nursing homes should provide: high circadian light stimulation during the day and low circadian stimulation at night; good visual performance (e.g., reading) during waking hours; and low-level nightlights that enable safe movement through the space and minimize sleep disruption.

Guidelines for lighting for the aging circadian system

Proposed is a dual lighting scheme that maximizes circadian stimulation during the day and minimizes it at night, while maintaining good visibility at any time (Figueiro 2008, in press). The evidence suggests that high circadian stimulation during daytime waking hours can probably be achieved by about

400 lx at the cornea of a 6500 K (cool-white) light source. During evening waking hours, the lighting system should provide no more than 100 lx at the cornea from a white light with low energy in the short-wavelength region of the spectrum. Relatively dim ambient evening light can be provided by light sources such as a 2700 K (warm-white) compact fluorescent lamp (CFL). The dual lighting system provides older people with a day/night circadian light ratio of about 16:1.

High circadian stimulation during the day and low circadian stimulation during the evening can be achieved using a combination of daylight and electric light sources. Daylight can certainly be an effective light source for regulating the circadian system. Outdoor lighting has the ideal quantity, spectrum, distribution, timing, and duration, but it should not be assumed that daylight in buildings will always provide people with a suitable circadian light pattern. Again, a quantitative analysis of daylight in the space should be carefully made because the amount of daylight varies considerably throughout a building. Daylight levels in a room drop very quickly as the distance from the window increases; daylight levels are quite low three to four meters away from a window, even on a sunny day (Bullough et al. 1996). It should also be noted that if sunlight from the window penetrates the room, discomfort glare may cause occupants to draw blinds or shades, eliminating daylight entirely from the space. Since it cannot be assumed that daylight in buildings is always going to be a solution for circadian entrainment, electric light must always be considered.

In order to select the most efficacious light source for the circadian system, an assessment of the relative circadian effectiveness of different spectral power distributions (SPDs) emitted by common electric light sources was performed using the model of human circadian phototransduction developed by Rea and colleagues (Rea et al. 2005). This model considers the fact that the circadian system is maximally sensitive to blue light, so light sources that have more short wavelength content (i.e., look more bluish-white) are more effective in activating the circadian system for the same amount of used watts. Table 1 shows the photopic lumens per watt (lm/W) and circadian stimulus per watt (CS/W) for a selection of commercially available light sources.

TABLE 1. Photopic lumens/watt (lm/W) and circadian stimulus/watt (CS/W) for some electric light sources. Values of CS/watt were arbitrarily normalized to a black body radiator of 2856 K at 100 lux at the eye. In this way, values for both lm/W and CS/W become equal for a common incandescent light source. Adapted from Figueiro (in press).

Light source	Photopic lumens/watt	Circadian stimulus/watt
Incandescent	12	12
CFL 2700K	55	38
T8 fluorescent 3000K	100	109
T8 fluorescent 4100K	100	67
T8 fluorescent 6500K	90	184
T8 fluorescent 7500K	55	90
Metal halide	95	86
White LED	35	82
Blue LED	15	295

The relatively dim evening lighting scheme is entirely consistent with current lighting recommendations and practice and, although the light levels recommended for daytime applications are relatively high compared to current practice, they are not difficult to achieve with contemporary, high-efficacy, fluorescent lighting systems, particularly if controls are incorporated into the design. The designer should also consider using the dual lighting scheme in common areas where residents are more likely to spend their waking hours. This may vary with the application. For example, in a single room assisted living setting, the dual lighting scheme needs to be implemented in the room and in a common area, such as the dining room. In nursing homes, the dual lighting scheme can be implemented in day rooms and dining rooms. If power density requirements are still an issue, however, local supplementary lights from blue LEDs can be integrated into the design. Based on the author's previous experience, compliance by older adults to a light treatment given by a supplementary lighting system is not trivial. However, in cases where compliance is not an issue, such as when the treatment is applied to healthy older adults living at home or in assisted living, ambient light levels can be reduced to 80–100 lux at the cornea (which is about 300 lux on the horizontal surfaces) of a neutral light source (3000 K–4100 K lamp) and the use of supplemental task light delivering 30 lux at the cornea of a blue light (λ_{max} = 470 nm) from LEDs can be used for at least 2 hrs in the morning. Table 1 provides quantitative guidance on the amount of light needed to match the circadian effectiveness of many light sources, including blue LEDs.

Guidelines for lighting for the aging visual system

Of course, good visual conditions cannot be ignored in any application, but it is important particularly when designing lighting for older adults. The light levels recommended for the circadian system should be sufficient for older adults to perform daily visual tasks. In spaces where the high circadian stimulation cannot be used, ambient light levels for the aging visual system should be 300 lux on the horizontal surfaces (80–100 lux at the cornea) of a neutral light source (i.e., 3000 K–4100 K lamp). More localized light will be needed to perform tasks that require seeing fine details (e.g., sewing, reading prescription bottle labels, chopping vegetables). Architects and specifiers should still provide lighting that gives high, glare-free illumination on the task with no direct or reflected view of the light source, soft shadows throughout the space, balanced illuminance levels, and light sources that provide good color rendering.

Some other lighting principles for the aging visual system that can help architects, specifiers, builders, facility managers, and homeowners (Figueiro, 2001) light interior spaces include:

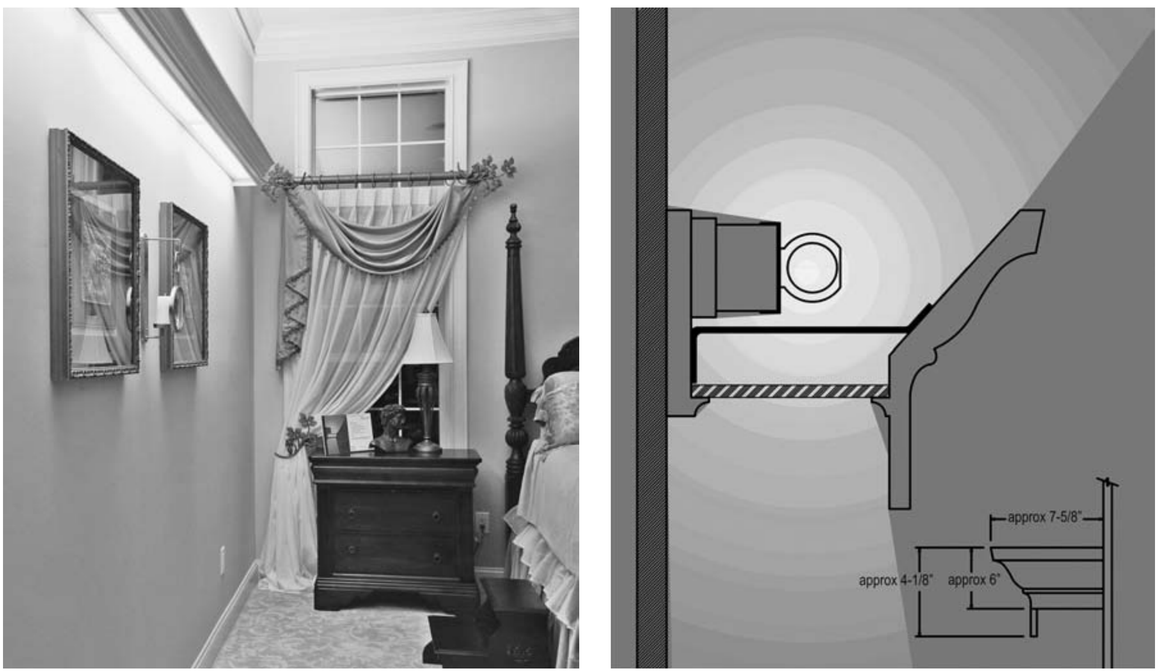
- *More light on task areas*—use concentrated light to increase illuminance levels on the task. As much as 10 times more light will be required to see fine details (e.g., reading small points) or low-contrast objects (e.g., black thread on blue cloth) than is required to see most architectural structures (e.g., doors, cabinets, furniture). Increase light level in areas where visual tasks are performed by placing adjustable light fixtures close to the task, or by selecting lamps with more lumens (look for lumen rating on the package, not wattage; be careful not to exceed the lamp fixture wattage). Fluorescent lamps are usually a good option because they provide more lumens per watt than incandescent lamps, and they last 10 times longer than common incandescent lamps; they are available with excellent color, plenty of light, no buzz or flicker; they are cooler to touch, and they can be dimmed. Increase ambient light levels by keeping surface finishes light in color. Light-colored walls, floors, and ceilings will help minimize shadows and increase overall light lev-

FIGURE 3A AND 3B. Illuminance levels should be high on working areas such as kitchen counter, sink, and stove. The light source itself should always be hidden from direct view. (Photograph by Michael Kalla.)

els in the living environment. Place light fixtures where visibility is important, such as below the kitchen countertop, over the kitchen sink, in the shower, and in closet and laundry spaces.

- *Less glare*—Although more light is required for the older eye to see, care should be taken to avoid glare. Glare is experienced when light sources or bright reflections in the field of view impair vision, or are uncomfortable. Very bright lights should not be placed against dark ceilings. The light source itself should be hidden with a shade, baffles, non-shiny louvers, or a shielding board. If a bare lamp is unavoidable (e.g., fan lights), it should be frosted to diffuse the light. In this same vein, clear glass light fixtures should also be avoided. The use of shiny floor finishes and polished surfaces should also be minimized to reduce reflection from light sources.
- *Balanced light levels*—Due to optical and perhaps neural changes to the eye, older adults cannot adapt to dim lighting conditions as well as younger people. As a result, illuminance levels in transitional spaces, such as hallways and entrance foyers, should be similar to those of the adjacent spaces. The ambient light levels in adjacent spaces should be balanced to be approximately the same. Multiple switches or dimmers to create intermediate light levels in transitional spaces that lead from bright, outdoor areas, to dim, indoor spaces should be chosen. Transitional spaces should be dimmer at night and brighter during the day.
- *Enhanced colors*—Color discrimination is poorer for older adults because of scattered light in the eye. The aged lens also absorbs relatively more short wavelength (blue) light, so it is particularly difficult to discriminate between, for example, dark purple and maroon. Use lamps with high lumens and good color rendering properties. A more extensive discussion on color properties of the light source is below.
- *Improved contrast*—Because contrast sensitivity is reduced with age, the visibility of important objects, such as stair edges, curbs, ramps, or doorways, can be greatly improved by increasing their contrast with paint or similar techniques.

FIGURE 4. Shielding boards or lenses should be used to hide a direct view of the light source. (Photograph by Michael Kalla.)



Contrasting colors to mark edges, such as doorframes, baseboards, or steps should be used.

Designing a lighting installation that meets the needs of the aging eye involves selecting the proper light source, lighting fixture, and lighting control, as well as determining the best location for the equipment in the room. The following tips help in the selection and proper installation of lighting equipment:

- For general illumination, use compact fluorescent lamps with approximately 1/3 the wattage of a common incandescent lamp to produce the same amount of light.
- To highlight certain areas (e.g., above kitchen sink) or objects (e.g., pictures on the wall), use a halogen parabolic aluminized reflector (PAR) incandescent lamp to concentrate the illumination.
- Avoid clear glass light fixtures and light bulbs; these create glare.
- Select a semi-secular or matte finish to prevent glare from the reflection of the light bulb for light fixtures with a visible reflector.
- Select a deep-recessed downright (cutoff angle between 40(and 50(from horizontal) so the light source is hidden from normal sight lines.
- Avoid placing recessed or ceiling mounted luminaires on dark ceilings; they may appear too bright and cause glare.
- Place light fixtures located above fixed working areas slightly to the side and in front of the position where a person would stand to see the task.
- Use wet location-rated light fixtures in shower/bath areas. (Figure 5).
- Select a matte countertop vanity with light colors that reflect light to the underside of the chin. To avoid harsh facial shadows, avoid using recessed downlights to light the bathroom vanity countertop (Figure 5).

Guidelines for lighting for the aging perceptual system

Just as important, nightlights that both reduce the risk of falls and help to maintain sleep should be used. Proposed nightlights with motion-sensor control are shown in Figure 6. The nightlights should

FIGURE 5. For better visibility, a light fixture should be placed in the shower or bath area. Recessed downlights to light the vanity countertop should never be used; lighting from the sides of the mirror is much better for grooming. (Photograph by Michael Kalla.)

FIGURE 6. Nightlights with motion sensor control provide dim illumination to the local environment as well as enhanced spatial perceptual information by providing horizontal and vertical cues, but only when needed by the occupant.

provide dim illumination to the local environment (1 to 5 lux at the cornea), but they also provide enhanced spatial perceptual information about the surroundings. Nightlights accent the rectilinear architectural features in the room, highlighting essential vertical and horizontal information people need to promote postural stability while navigating in an otherwise dim environment. Since the nightlights are only on when motion is detected, they do not require the occupant to grope blindly for a light switch that, when found, would then activate a bright, ambient lighting system. They are on only when a person needs to move through the space at night.

PUTTING IT ALL TOGETHER

Table 2 summarizes lighting principles for older adults that should meet the needs of their visual, circadian, and perceptual systems. Two lighting schemes are proposed, and the more appropriate solution will depend on the needs of the occupant. Although lighting scheme 1 will have higher initial and operating costs, it is the recommended solution for older adults who cannot easily or are unwilling to change their behavior. The architect and specifier should keep in mind that to save expense lighting scheme 1 can be installed in just a few highly used spaces rather than throughout the entire facility. Lighting scheme 2 should be used when compliance by older people is unlikely to occur and where ceiling renovations cannot be practically implemented.

EQUITY FOR CAREGIVERS IN HEALTHCARE FACILITIES

Healthcare facilities operate 24 hours a day, seven days a week, and, therefore, the design criteria must also take into account the needs of health care professionals, both day and night. The lighting principles for the visual system discussed above are also applicable for dayshift and nightshift workers, but their needs are not as acute. Lighting that is designed for the aging eye is good lighting for any age group! When it comes to circadian lighting, dayshift workers are more likely to have the opportunity to receive sufficient circadian light during their waking hours than more sedentary older adults. Nevertheless, this is not always the case so it is important that dayshift workers receive high circadian light stimulation during the day and low circadian light stimulation during evening hours at home to maintain circadian entrainment. Sufficient daylight from windows and skylights during working hours combined with daylight exposure outside the workplace can provide sufficient circadian light stimulation. Low circadian light during the evening and night is equally important. By strategically adopting changes in light spectrum and level at work and at home, good circadian light stimulation as well as good visual conditions can be created throughout the day and night.

Designing for the well-being of nightshift workers, however, is much more complicated. Nightshift workers are almost always required to be awake when their internal clocks are telling them to be asleep and asleep when their internal clocks are telling them to be awake. As a result, nightshift workers often feel very sleepy while at work and do not have good sleep quality during the day. Generally, nightshift workers

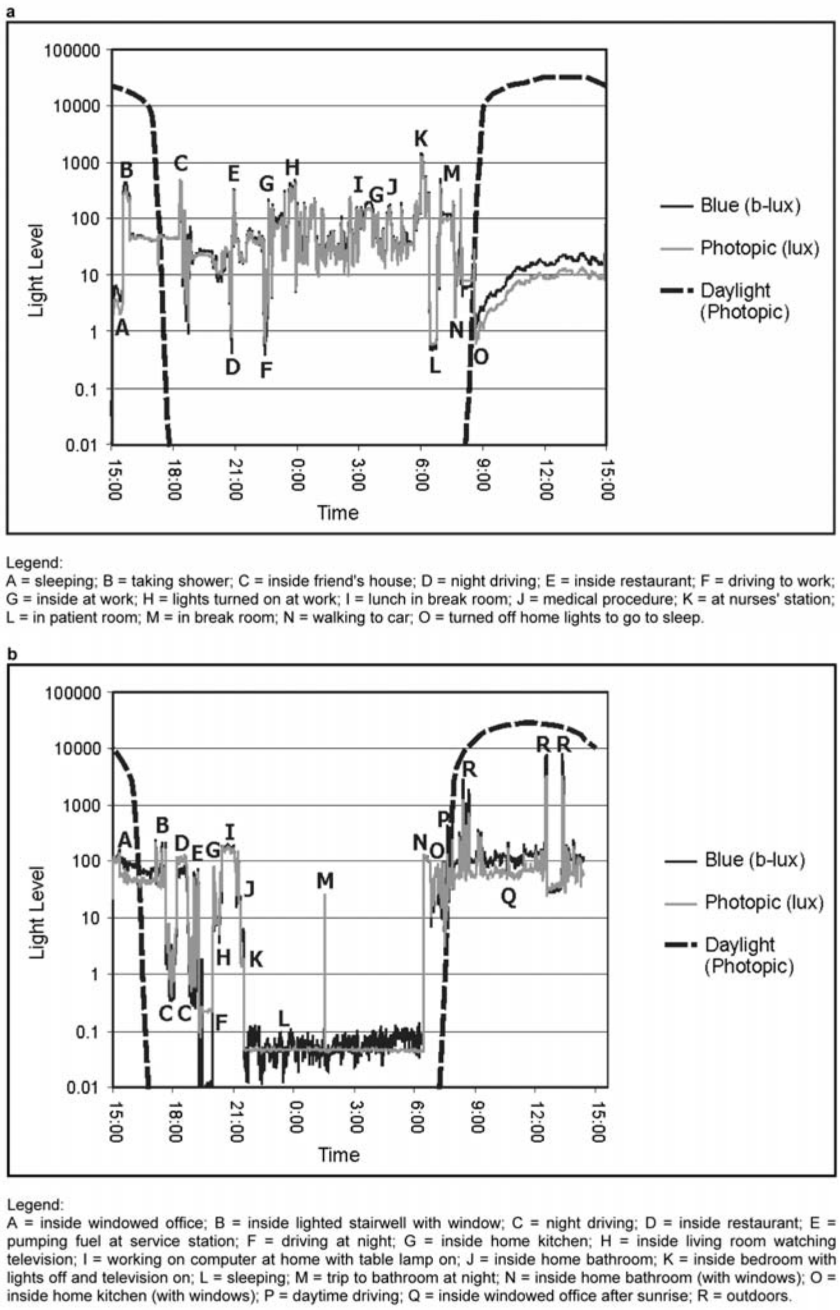
TABLE 2. Summary of two proposed lighting schemes recommended for older adults living at home, in assisted living facilities, or in nursing homes.

Lighting Scheme 1	Visual	Circadian	Perceptual
Daytime	1200 lux horizontal CCT: 6500K or higher	400 lux at the cornea CCT: 6500K or higher	N/A
Evening	<300 lux horizontal CCT: 2800K or lower	<100 lux at the cornea CCT: 2800K or lower	N/A
Nighttime	N/A	N/A	Motion sensor controlled doorframe lighting 1–5 lux of well distributed (diffuse) light at the cornea CCT: 2800K or lower
Lighting Scheme 2	**Visual**	**Circadian**	**Perceptual**
Daytime	300 lux horizontal CCT: 3000–4100K	30 lux of blue LED (470 nm) at the cornea for 2 hours in the morning	N/A
Evening	<300 lux horizontal CCT: 3000–4100K	<100 lux at the cornea CCT: 3000–4100K	N/A
Nighttime	N/A	N/A	Motion sensor controlled doorframe lighting 1–5 lux of well distributed (diffuse) light at the cornea CCT: 2800K or lower

are not entrained to the night shift because they are not presented with high circadian light stimulation during the night and low circadian light stimulation during the day. Rather, they are typically exposed to rather "flat" or aperiodic light exposures. Figure 7a illustrates one of these flat and aperiodic light exposures for one nightshift worker. Figure 7b shows a much more consolidated, light-during-the-day and dark-during-the-night pattern for a dayshift worker. This flat and aperiodic light profile is not well suitable for circadian entrainment and, due to this poor entrainment, their performance, health, and well-being can become compromised. For example, nightshift women are significantly more susceptible to breast cancer than population matched dayshift women.

The most appropriate lighting scheme for nightshift workers is still debated, mostly because of the possible negative impact of working at a time when our body is telling us to be asleep. In the late 1980s, Stevens put forward the melatonin hypothesis wherein high incidence of breast cancer in industrialized society was related to exposure to too much light at night, which, in turn, suppressed the production of nocturnal melatonin (Stevens 1987). Stevens's hypothesis stimulated various lines of research, from animal models to epidemiological studies. Blask and colleagues were among the first to use an animal model to investigate the effects of melatonin on certain types of tumor growth (Blask et al. 1999; Blask et al. 2005). Their studies clearly showed a relationship between nighttime light exposure, melatonin suppression, and growth rate of certain types of cancer. Epidemiological studies in humans suggest a high cancer risk associated with rotating shift workers (Schernhammer et al. 2001). Based on these findings, nightshift workers are exposed to light at night, which would then suppress melatonin, depriving nightshift workers from protection against cancer. It is important to note that a direct link between light at night, melatonin suppression, and cancer initiation has never been established in humans. What remains to be determined is whether the higher cancer risk is the result of light at night, or is the result of circadian disruption caused by a lack of a regular 24-hour, cyclic light exposure

FIGURES 7A AND 7B. Light profiles, in photopic illuminance (solid gray, left ordinate scale) and in circadian stimulus (solid black, right ordinate scale) units, for one night shift nurse working in South Bend, IN, USA (a) and one dayshift worker working in Troy, NY, USA (b). Measurements were made continuously starting at 15:00 on 30 January 2006 until approximately 15:00 on 31 January 2006 for the nightshift worker and starting at 15:00 on 1 December 2005 until 14:30 on 2 December 2005 for the dayshift worker. Also shown are vertical photopic illuminances (dashed black, left ordinate scale) expected from outdoor exposure to a partly cloudy sky at the same location on the same date in open country for a 45° azimuth angle from the sun. (Figueiro et al. 2006.)



pattern like that shown in Figure 7a. Because it is still unknown what the most appropriate lighting scheme for the circadian system of nightshift workers is, a lighting recommendation for nightshift workers will not be discussed here.

USING LIGHTING TO PROMOTE EQUITY FOR CAREGIVERS IN HEALTHCARE FACILITIES

The lighting principles for older adults discussed herein are applicable to dayshift workers working in healthcare facilities. It is important that lighting systems for healthcare facilities promote high circadian stimulation of workers during the day without impacting the circadian systems of nightshift workers, so the most appropriate alternative is to add a layer of blue light to the space provided by local lighting. This local lighting can be used by dayshift workers only until more is known about the most appropriate lighting for nightshift workers. When designing lighting for caregivers in healthcare environments, it is important to keep in mind that the lighting systems in these facilities are used throughout the 24-hour day/night and have to meet the needs of both dayshift and nightshift workers—therefore, flexibility is imperative.

Guidelines for lighting for dayshift workers' circadian system

Unlike older adults who tend to stay indoors most of their waking hours, dayshift workers are more likely to be exposed to high circadian stimulation from outdoor lighting during their waking hours. Nevertheless, it is still important to ensure that they are receiving sufficient circadian stimulation during the daytime hours while at work, especially in winter months when daylight periods are reduced.

Because flexibility is needed and compliance to lighting intervention may not be an issue for dayshift workers, it may be more cost effective to add a layer of blue light to the space to promote circadian entrainment of dayshift workers. For example, a local lighting system providing 30 lux of blue light (λ_{max} = 470 nm) at the cornea can be effective for the circadian system (Figures 8a and 8b). Well-designed daylight that penetrates the space without glare should always be considered in the healthcare environment to help dayshift workers' exposure to morning light.

Guidelines for lighting for dayshift (and nightshift) workers' visual systems

Studies conducted by the Lighting Research Center showed that the recommended light levels of 500 lux on the work plane can be reduced by 20% without being noticed by users. Therefore, overall ambient light levels can be reduced and task lights should be used to increase light levels in critical areas, such as reading and writing areas, examination rooms, and emergency rooms.

Light sources used in the healthcare environment should allow for good color perception. Color perception is the result of the neural characteristics of the observer's visual system, the SPD of the

FIGURES 8A AND 8B. Light boxes using blue Leeds peaking at 470 nm and delivering 30 lx at the cornea are a good solution for healthcare applications.

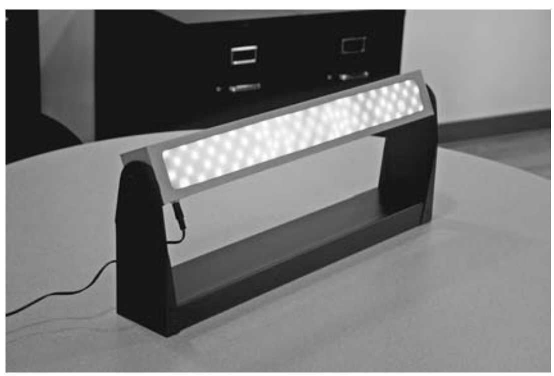


TABLE 3. CCT, CRI, FSCI, and GAI for several common light sources. (Table adapted from Figueiro et al. 2006.)

Source	CCT (K)	CRI	FSCI	GAI
Incandescent	2800	100	72	49
RE80 fluorescent	3500	81	67	68
Cool white fluorescent	4000	62	73	58
"Full-spectrum" fluorescent	5500	88	94	89
Ceramic metal halide	4100	93	93	80
High pressure sodium	2000	16	16	14

light source, and, if the light source serves as an illuminant, the spectral reflectance of the object. in order to guarantee good color perception, Rea et al. (2004) and Figueiro et al. (2006b) propose that light sources have a minimum color rendering index (CRI) value of 80, a minimum full spectrum color index (FSCI) value of 55, and a gamut area index (GAI) value between 65 and 100. While it is not within the scope of this article to present a comprehensive discussion of color perception, for more information see Rea et al. (2004). In brief, CRI is the conventional measure of light source color rendering, but has been shown in a number of studies to be inadequate as the sole measure of adequacy of a light source for providing color information. To complement CRI, FSCI and GAI were developed to help ensure good color rendering by a light source. FSCI uses an imaginary equal energy spectrum with the same radiant power across the entire visible spectrum as a reference source and scales all other light sources in terms of their ability to provide radiant power throughout the spectrum. GAI is a measure of the color separation between objects illuminated by a light source. CRI, FSCI, and GAI can all be calculated from the SPD of the light source; lamp manufacturers can provide specifiers with these three quantities. Table 3 shows CRI, FSCI, and GAI for various commercial light sources.

PUTTING IT ALL TOGETHER

Table 4 summarizes the lighting principles for dayshift workers in healthcare applications. The proposed lighting scheme should suffice the needs of daytime workers' visual, circadian, and perceptual systems. The lighting principles for the visual and perceptual systems are applicable to nightshift workers, but the lighting scheme for the nightshift circadian system is still unknown and was not discussed here.

CONCLUSIONS

As Bill McDonough stated in his book and as exemplified in this article, sustainable lighting should be designed with more than illuminance (lumens per area) and lumens per watt in mind. Public awareness about how lighting can make important contributions to the quality of life of those working and living in healthcare facilities needs to be built so that architects and specifiers can respond. Without that demand, architects and specifiers will only rely on the existing, but outdated and inadequate, lighting codes and standards. As exemplified in this article, lighting that is designed with the visual, circadian, and perceptual systems in mind *can* help the most fragile humans improve their quality of sleep, reduce

TABLE 4. Summary of proposed lighting schemes for dayshift workers in healthcare applications.

Dayshift Worker	Visual	Circadian	Perceptual
Daytime (work)	400 lux horizontal CCT: 3000–4100K	30 lux at the cornea of blue LED for at least 1 hr in the morning λ_{max} = 470 nm	N/A
Evening (home)	<200 lux horizontal CCT: 2800K or lower	<50 lux at the cornea CCT: 2800K or lower	N/A
Nighttime (home)	N/A	N/A	Motion sensor controlled doorframe lighting 1–5 lux of well distributed (diffuse) light at the cornea CCT: 2800K or lower

falls, and improve their health and well-being. It is unfortunate that these lighting design principles are not being widely practiced.

As already noted, well-intentioned energy codes are to blame because they are based upon the implicit, but erroneous, notion that sustainability deals with only the efficiency "E." Initial attempts to include design issues related to the circadian system have been made in documents such as the *Green Guide for Healthcare,* but these concepts have not been implemented in the design of healthcare environments. It is time for the public to demand that architects and specifiers pay more attention to the equity "E" by bringing research into practice. In that way lighting will meet the needs of all three human domains: visual, perceptual, and circadian. It is hoped that the concepts and tips presented in this article can help transform the basis for our lighted environments. Remember, all of us will become older and one day we too might be condemned to an unsustainable lighted environment.

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