Auto-tuning Daylight with LEDs: Sustainable Lighting for Health and Wellbeing

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ABSTRACT: While human life expectancy may be increasing due to advances in public health, technology and medicine, there are serious questions as to whether the quality of human life can keep up with this increase in longevity. Postindustrial society is experiencing a proliferation of light-related disorders and diseases specifically because our technologically-based society can operate 24 hours per day in illuminated indoor environments. Furthermore, illuminating interiors with electric lighting poses a dual dilemma: the energy efficiency of electric light versus natural daylight together with the impact of light itself on human health and wellbeing. This paper investigates sustainable design at the nexus of health, energy and technology by considering relationships between light and human health. By discussing the physiological effects of light on the body, the need for natural daylight in the human environment for improved cognitive functioning will be demonstrated. Because people spend a large portion of their time indoors, especially the elderly, unless a room is oriented to maximize light from the sun, it is necessary to illuminate the interior environment using electric light sources. However, artificially illuminating the indoors poses a sustainability issue because electric lighting is one of the largest contributors to energy consumption by buildings in the United States. Designing for older adults in health care environments, especially the elderly with age-related fragility, declining cognitive functioning and symptoms of dementia, is a particularly significant design challenge and one in which lighting can play a crucial role. To address both issues of health and sustainability, an energy-conserving diurnal daylight-matching LED luminaire is being developed to improve health outcomes for the elderly at St. Francis Country House near Philadelphia, Pennsylvania.

KEYWORDS: daylighting, health, low-energy lighting, older adults, sustainability

INTRODUCTION

The most ideal source of illumination is light from the sun, but natural daylight is not always feasible for the indoors. Illuminating interiors artificially using electricity poses a number of problems from an environmental standpoint—both for the natural environment and the indoor environment. The first dilemma has to do with lighting and sustainability; electric light uses a lot of energy, which in turn can negatively impact the environment. However, proper lighting utilization through low-energy systems that generate little heat could result in significant cooling energy savings for buildings and a smaller carbon footprint for the environment. The second dilemma is relationships between light and health; natural daylight has been shown to contribute significantly to human health and wellbeing. Natural changes in daylight synchronize and reinforce the body's circadian rhythms, which help determine sleeping and eating patterns, brain wave activity and hormone secretion to affect a cascade of responses throughout the human body. Therefore, for both improved health outcomes and energy savings, it is important to either use daylight itself in an energy-efficient manner or mimic the full spectrum of natural lighting using low-energy systems.

In this sense, sustainability becomes a broader notion than what is usually considered in architectural design, because it includes both the effects of light on human health and productivity as well as energy-efficient lighting design. The following research on this topic has been a process-based investigation that looks to nature as a way of remodeling the built environment by considering the human-building relationship as a complex, evolving ecological network (Benyus 1997). This type of approach requires a view toward indoor illumination using multiple perspectives – visual acuity, mood, chronobiology, health, energy efficiency, rapidly-changing lighting industry, etc. – in order to inform the technological development of a sustainable interior lighting system. Funded by a product innovation grant from the Green Building Alliance of Pennsylvania, an automatic diurnal daylight-matching LED luminaire is being developed for the St. Francis Country House skilled nursing facility. The goal is a daylight-matching, energy-efficient lighting system to help ameliorate symptoms of dementia in the elderly by using the non-visual aspects of light to improve cognitive functioning. To follow is a discussion of relationships between electric lighting and sustainable energy use, as well as natural daylight and its effect on health and wellbeing, to frame the rationale for auto-tuning daylight by using LEDs to develop a luminaire prototype that imitates natural light.

1.0 REVOLUTION IN LIGHTING

1.1. Light and energy use

Buildings consume 39% of the primary energy in the United States, of which approximately 18% is used by the lighting systems (DOE, 2006). Furthermore, the heat produced by a lighting system can generate up to 24% of the total building cooling load (Leslie, 2003). Proper lighting utilization through low-energy systems that generate little heat could result in significant cooling energy savings for buildings and a smaller carbon footprint. Due to studies demonstrating a connection between lighting levels and higher productivity/better performance from building occupants (Fay 2002, Leslie 2003), it is important to design a lighting system which is both sufficiently bright and energy efficient. According to the Department of Energy, solid-state lighting (SSL) technology holds the promise of reducing U.S. lighting energy usage by nearly one half by 2030, which will contribute significantly to strategies for climate change solutions. If SSL technology achieves projected price and performance attributes, then there will be even greater energy savings. It is anticipated that with advancement of the technology, light quality will improve, efficacies will increase, operating life will increase, and prices will drop (DOE 2013).

1.2. Solid-state lighting

Solid-state lighting has the potential to revolutionize the lighting market through the introduction of highly energy-efficient, longer-lasting, versatile light sources, including high-quality white light (DOE 2010). SSL refers to a type of lighting that uses semiconductor light-emitting diodes (LEDs), organic light-emitting diodes (OLED), or polymer light-emitting diodes (PLED) as sources of illumination rather than electrical filaments (used in incandescent or halogen lamps) or gas (used in arc lamps such as fluorescent lamps). The typically small mass of a solid-state electronic lighting device provides for greater resistance to shock and vibration compared to brittle glass tubes or bulbs and long, thin filament wires. SSL also eliminates filament evaporation, potentially increasing the life span of the illumination device (DOE 2013).

1.3. LED lighting

Unlike incandescent and fluorescent lamps, LEDs are not inherently white light sources. Instead, LEDs emit nearly monochromatic light, which makes them highly efficient for colored light applications such as traffic lights and exit signs, which were the first broad application of the technology. However, to be used as a general light source in building interiors, white light is needed. It is important to note that what is perceived as “white light” from the sun is actually comprised of the full spectrum of colors (Figure 1).

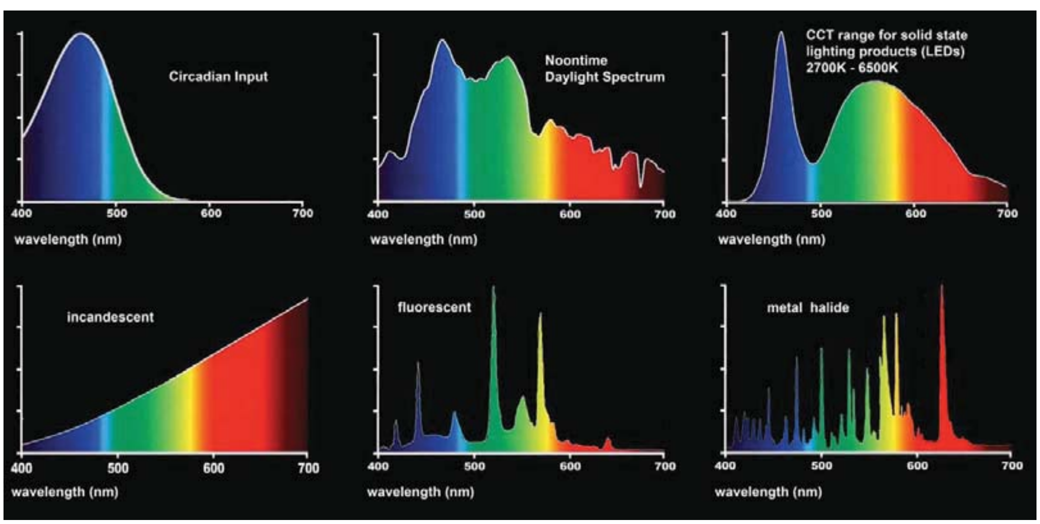

Figure 1: Comparative wavelengths for multiple light sources. Source: (adapted by author from Brainard 2010)

White light can be achieved with LEDs in three ways: 1) phosphor conversion (PC), in which a phosphor is used on or near the LED to convert the colored light to white light; 2) RGB systems, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed, resulting in white light; and 3) a hybrid method, which uses both phosphor-converted and monochromatic LEDs. Their unique characteristics include: compact size, long life and ease of maintenance, resistance to breakage and vibration, good performance in cold temperatures, lack of infrared or ultraviolet emissions, instant-on performance, and the ability to be dimmed and to provide color control. Mixed LED sources have a higher theoretical maximum efficiency, potentially longer life, and allow for dynamic control of color (DOE 2013). Compared with either electric filament or gas lamps, LEDs most closely match the full spectrum of natural daylight (Figure 1).

1.4. Color Rendition

Color temperature is an important aspect of color appearance that characterizes how “cool” (bluish) or how “warm” (yellowish) nominally white light appears. Correlated Color Temperature (CCT) is a metric that characterizes the color of the emitted light from a source and is given in Kelvin (K). However, CCT distills a complex spectral power distribution to a single number, which can create discord between numerical measurements and human perception. For example, two sources with the same CCT can look different to the naked eye, one appearing greenish and the other appearing pinkish (DOE 2012).

Color Rendering Index (CRI) is a measure of fidelity or how “true” a light source appears when compared to a familiar, or reference, source. A score of 100 indicates that the source renders colors in a manner identical to the reference. However, two light sources with the same CCT and CRI may not render colors the same way (colors may still look different). Additional factors that contribute to Color Rendition include appeal (objects appear more pleasing) and discrimination (the ability of a light source to allow for a subject to distinguish between a large variety of colors when viewed simultaneously) (DOE 2012). For example, a certain tint might make red meat more appealing or a special combination of wavelengths might enable a surgeon to more easily distinguish one part of the anatomy from another during surgery.

1.5. LED futures

LEDs are individual points of light, which make it easy to mix different colors in one light source. Solid state lighting is comprised of drivers and integrated circuits, which allow for the control of LEDs individually, in series, or in clusters. For this reason, LED technology allows for the dynamic control of both light color and illumination intensity—Color Rendition a product of both the CRI of the individual LED, as well as the combination of LEDs and their intensity levels.

While SSL technology and LED lighting hold the promise of revolutionizing the lighting industry, there are considerations to keep in mind for luminaire design. A primary cause of lumen depreciation is the heat generated at the LED junction because LEDs do not emit heat as infrared radiation like other light sources. Therefore, the heat must be removed from the device by conduction or convection (DOE 2013). Characteristically, the heat is dissipated using a heat sink that pulls the heat away from the LED; this might include vents to facilitate natural convention, or an active fan, to cool the unit. Thermal management is arguably the most important aspect of successful LED system design.

While the characteristic luminaire provides illumination through the use of lamps that need to be changed out regularly (e.g. 2,000-20,000 hours for incandescent, halogen, fluorescent, metal halide, etc.), due to an extended lifespan potential of 50,000 hours, SSL lighting offers the possibility to integrate lamp and luminaire into one inseparable unit. By using LEDs, the luminaire could take the shape of an integrated fixture where the light source and fixture housing are one. The integrated luminaire could change color and intensity; the LEDS, driver and circuitry integrated into one complete, controllable, programmable system.

2.0 NATURAL DAYLIGHT AND HUMAN HEALTH

2.1. Daylight

Recent research indicates that lighting has increasingly become a public health issue (Pauley, 2004). These studies have shown that individuals working in natural sunlight are more productive, more effective, and happier than those who work under traditional artificial light (Fay 2002, Leslie 2003, Mills et. al. 2007). Natural changes in daylight balance the body’s circadian rhythm, which determines sleeping and eating patterns, brain wave activity, heart rate, cognitive functioning, and hormone production—virtually all physiological and behavioral parameters. Circadian phase shift and transmeridian travel have been shown to contribute to jetlag, seasonal affective disorder (SAD), delayed sleep phase syndrome (DSPS), and is implicated in more various diseases and disorders, including cancer (Roberts 2001). In industrialized nations it is estimated that up to 20% of the workforce is involved in some kind of shift work (Webb, 2006), which is associated with exposure to unusual or abnormal levels and/or patterns of light and dark. Studies have associated these unusual levels and patterns with higher incidences of breast cancer and colorectal cancers, as evidenced by those people involved in shift work (Aanonsen 1959, Akestedt and Gillber 1981, Czeisler et. al. 1990, Pauley, 2004). These studies reinforce the notion that the sustainability of human productivity and wellbeing, even life itself, is directly tied to environmental lighting.

To maintain health and save energy it is important to either use or *mimic the full spectrum of natural lighting*. Ocular light, or light reaching the eye, has both visual and non-visual effects on the body: 1) vision and 2) synchronization of circadian rhythms (Roberts 2008). The synchronization of circadian rhythms is one of the most significant non-visual effects of light. Circadian rhythms are regulated by changes in visible light from the sun throughout the day (Aschoff 1965) and are normally controlled daily by the full spectrum of natural light (photopic vision) together with darkness in the environment (scotopic vision). The full spectrum of light includes UVA, UVB and visible light: at noon there is high intensity in the blue light region, in the late afternoon blue light is preferentially scattered out of (removed from) incoming sunlight so that the late afternoon sun provides red and orange light, and when the sun sets it becomes dark. Circadian rhythms are controlled primarily by daily exposure to levels of light in the blue-green spectrum, concentrated in the wavelength region 446-477nm (Brainard 2001), together with alternating darkness in the environment. Blue light triggers the production of serotonin in the body, which enhances alertness and cognitive performance, while red or amber light signals the onset of dusk; the absence of light encourages melatonin secretion (Kaplan 1995, Roberts 2001, Brainard 2001, Lubkin et. al. 2002).

In architectural design, the challenge is to either provide daylight, *or mimic daylight* using artificial light sources, and ensure that lighting levels and color temperature change throughout the day in sync with nature's rhythms—including darkness at night. The *wavelength* of light absorbed by the body together with the *timing* of that light are the two most important factors for a biological effect. Returning buildings to a more natural light environment through the use of daylighting, or mimicking the full spectrum of natural light, would be energy efficient and would promote wellbeing.

2.2. Inner vision

In addition to object recognition—visual information—light provides data on the timing and intensity of light and dark in order to synchronize the body's biological rhythms. This non-visual photonic information is transmitted from the eye to the suprachiasmatic nuclei (SCN) located in the hypothalamic region in the center of the brain, which trigger a cascade of hormonal changes in the pituitary, pineal, adrenal and thyroid glands. Neural activity within the SCN modulates the release of pituitary hormones and the release of melatonin from the pineal gland. Through this and other pathways, the SCN synchronizes the circadian rhythms that regulate and modify virtually every physiological and behavioral process in the human body (Brainard 2010). The SCN controls a variety of events in the body including temperature, reproductive cycles, appetite, and mood. Circadian rhythms are phase shifted by visible light, which also suppresses melatonin production. When this process is disrupted through environmental light changes, it can lead to damaging emotional and physiological effects such as those associated with seasonal affective disorder, jet lag, delayed sleep phase syndrome, and may exacerbate serious conditions such as cancer.

2.3. Chronobioengineering

The emerging field of chronobioengineering is providing a new paradigm for health care design. *Chronobiology* is a field of biology that examines periodic (cyclic) phenomena in living organisms and their adaptation to solar- and lunar-related rhythms; whereas, *photobiology* is the scientific study of the interactions of light on living organisms such as the effect of light on circadian rhythms. *Chronobioengineering* translates these observations and concepts into practical applications (McEachron 2012), such as the automatic diurnal daylight-matching LED luminaire being developed for the St. Francis Country House skilled nursing facility. Designing for older adults in health care environments, especially the elderly with symptoms of dementia, is a very special and significant design challenge for health care architects, and lighting can play a crucial role (Noell-Waggoner 2004, 2006, ANSI/IESNA 2007).

2.4. Design for older adults

Residents in dementia units of skilled nursing facilities have special needs beyond the characteristic assistance with activities of daily living (ADL). Because their internal circadian clocks are out of sync with nature's rhythms, residents experience "sundowner's," or agitated behavior toward the end of the day, and difficulty sleeping at night (Wu and Swabb 2005). Additionally, residents exhibit a need for mobility and wandering (Doliansky and Dagan, 2006). Many of these symptoms have been linked to the disruption of biological rhythms (Wu and Swabb 2007). These symptoms reduce the quality of life of the individual with dementia, while sleep disruptions and behavioral disturbances also contribute to the burden on family and formal (paid) caregivers. In addition to the disease itself, symptoms are exacerbated due to institutional lighting levels that not only do not provide residents with the biologically required full spectrum of changing lighting levels throughout the day, but also do not provide total darkness at night—difficult to do when caregivers need to work throughout the night monitoring patient health and safety, as well as fulfilling their administrative tasks. While many skilled nursing facilities are often designed with sunrooms for their residents, it is not always possible to bring the residents to the daylight or the daylight to building interiors. Research has shown that dementia patients tend to receive significantly less exposure to environmental light than people living in the community (Campbell 1988, Mishima 2001). Due to the aging of the eye that leads to opacification and yellowing of the vitreous and the lens, circadian photoreception is compromised (Turner and Mainster 2012), which when coupled with the indoor lifestyle of the elderly (Torrington 2007) contributes to an overall out of sync circadian rhythmicity.

Links have been made between sundowning and the circadian timing system; studies have shown that bright light therapy can have some effect in reducing agitation and improving sleep for people with dementia (Burns 2009). While some researchers disagree as to the exact level of light required (Deschenes 2009), studies have shown that it is necessary to provide dementia residents with a minimum of 1000 lux "in the gaze direction" (vertical illuminances) for a significant portion of the day (Riemersma-van der Lek 2008, van Hoof 2009); however, for older adults with aged eye tissue, the illuminance levels may need to be at least 3 times higher due to the diminished light transmittance of the eye (Van Someren 1997, Aarts 2005, Sinoo 2011). Age-related losses in retinal illumination are reasonably uniform over time, with a ten percent loss per ten years of aging. Thus, a ninety-year-old would require ten times the light of a 10-year-old for similar photoreception. Effect on circadian rhythmicity is further exacerbated with age because the shorter violet and blue wavelengths (400-500nm) are most affected by yellowing of the aging eye (Turner and Mainster 2012). Latest research indicates that high-intensity light of at least 2500 to 3000 lux with a high CCT (6500K) improves circadian rhythmicity in institutionalized older adults with dementia and can reduce or alleviate insomnia; increase sleep efficiency, total sleep time, and restorative slow-wave sleep; and improve daytime vigilance and nighttime sleepiness (van Hoof 2009, Turner 2010, Sinoo 2011). Figure 2 depicts one Lighting Schedule being tested. This schedule slowly increases lighting levels upon residents' awakening, peaks light intensity and CCT around the noontime hour, maintains relatively high lighting levels for the rest of the day for vision and visual acuity, and then the light intensity slowly "sets" to a low-level red for nighttime hours. Initially, the light will be installed in community rooms and corridors; levels and wavelength will be modified based on patient outcomes.

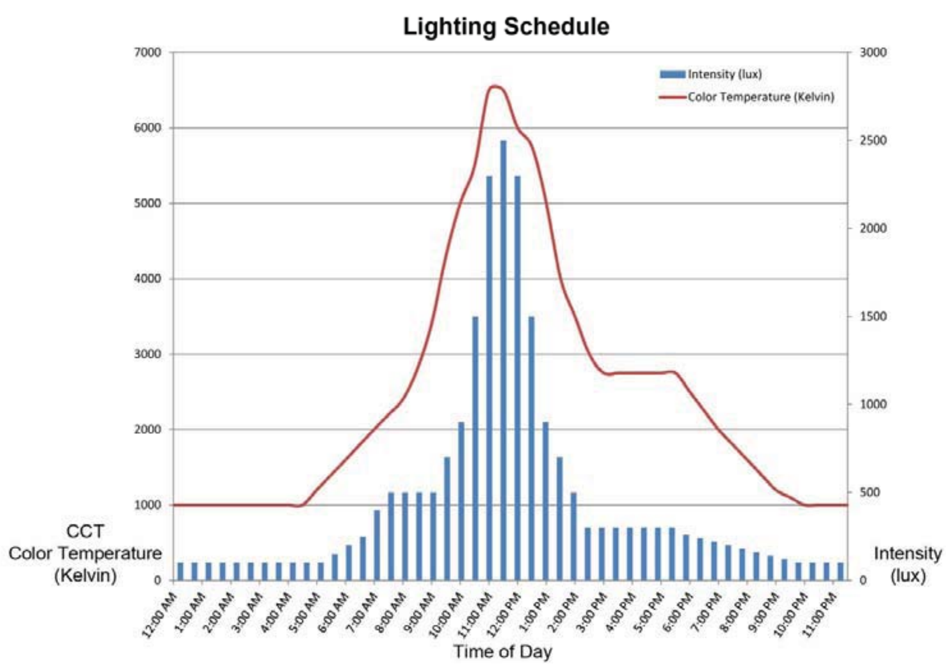

Figure 2: Lighting Schedule. Source: (authors)

3.0 AUTO-TUNING DAYLIGHT USING LED TECHNOLOGY

3.1. Introduction

Maintaining circadian rhythmicity in a postindustrial society is becoming increasingly difficult for a culture that spends a disproportionate amount of time indoors in artificially illuminated environments facing electronic screens that largely emit light in the blue spectrum. However, technological advances in the lighting industry are making it possible to create a more naturalistic indoor environment to support human biological rhythms and to improve cognitive functioning, especially for people with deteriorating systems. The technology of solid state lighting is making it possible to seamlessly imitate the lighting of the natural environment.

The hypothesis is that sleep patterns and global functioning of residents will improve. The goal is to help ameliorate symptoms of dementia in the elderly by using the non-visual aspects of light to improve cognitive functioning. Considerations include: 1) patient attention and concentration, 2) changes in vision due to the aging eye, 3) limited mobility, 4) wandering due to Alzheimer's disease and effects of "sundowning", and 5) difficulty sleeping.

3.2. Fixture design

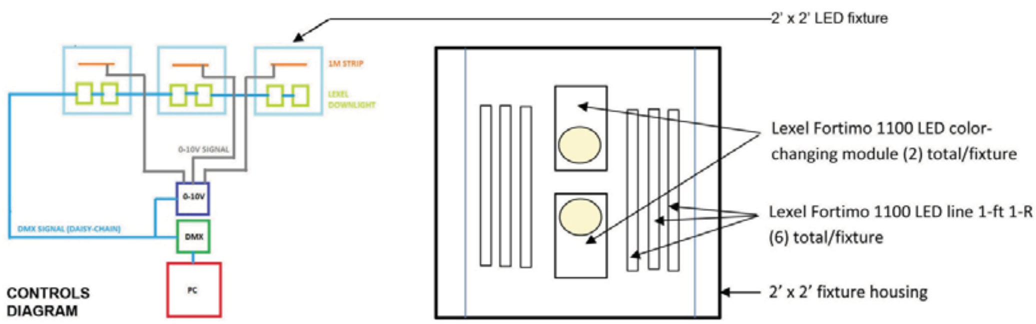

Figure 3: Fixture Design. Source: (authors)

Funded by a product innovation grant from the Green Building Alliance of Pennsylvania, researchers are developing an automatic diurnal daylight-matching LED luminaire for the St. Francis Country House skilled nursing facility. The retrofit 2'x2' LED luminaire will replace the existing traditional fluorescent artificial lighting. This LED luminaire will mimic the full spectrum of natural daylighting, including darkness at night—darkness will be achieved by using red LEDs, which are not recognized by the body as light for the circadian system. The LED luminaire is comprised of Philips Lighting components: (2) Lexel Fortimo 1100 LED color-changing DLM modules and (6) Lexel Fortimo 1100 LED lines to achieve the intense white light required at midday (Figure 3). The color-changing DLM modules are daisy-chained together using DMX cable to an interface and then to a computer to control intensity levels and emitted colors; a similar system is used by the music industry for audio controls to mix sounds (Figure 4). The white LEDs are simply dimmed.

3.3. Auto-tuning daylight

The advanced technology of solid state lighting is based on electronics and integrated circuitry controlled by drivers that can turn individual or groups of LEDs on or off, can dim them, and can connect them individually, or in series, or can daisy-chain groups of LEDs together. LED controls operate like an audio mixer in a recording studio; like mixing sound from multiple sources, LED controls have the capability to mix different colors of light. Auto-Tune is recent technology in the music industry, which is an audio processor created to measure and alter pitch in vocal and instrumental music recording and performances to correct off-key inaccuracies, allowing vocal tracks to be perfectly tuned despite originally being slightly off-key. In other words, auto-tuning synthesizes sound to match perfect pitch. Similarly, the LED luminaire being developed will auto-tune interior lighting to mimic the full spectrum of natural daylight throughout the day considering CCT, CRI and Color Rendition "tuned" for older adults. This would then provide quality illumination for visual tasks and help synchronize biological rhythms for better health, cognitive ability and performance. The theory is that by auto-tuning daylight with LEDs, a sustainable integrated LED luminaire can visualize energy efficiency and produce the non-visual lighting effects needed for human health, wellbeing and performance.

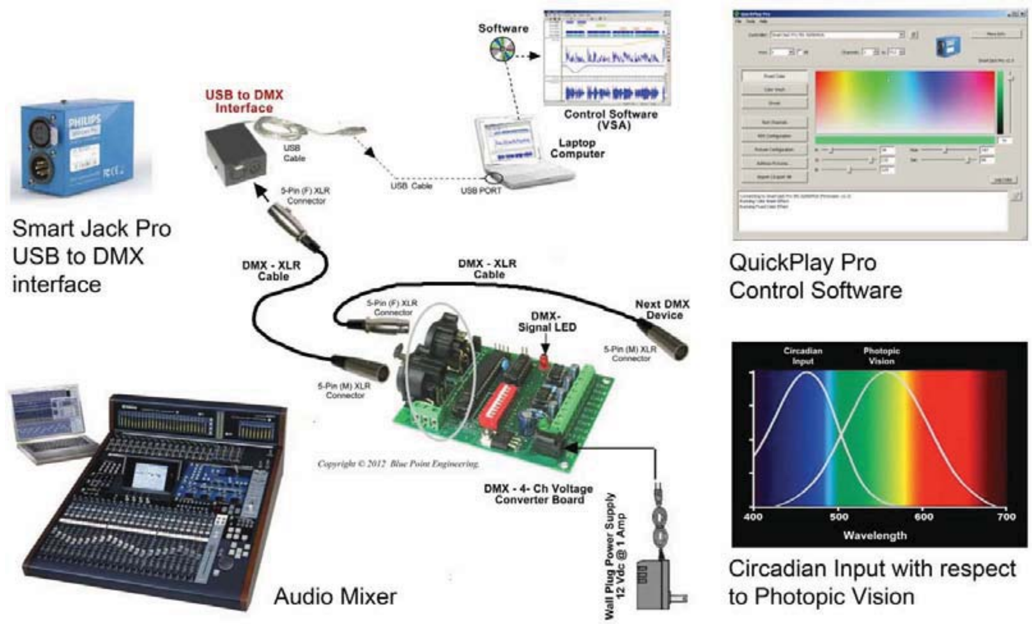

Figure 4: Lighting control system. Source: (Blue Point Engineering, Philips Lighting, QuickPlay Pro)

3.4. Current state of the art

There are a number of products on the market that claim to supply "full spectrum"[1] lighting in the form of CFL and induction lamp[2] luminaires, as well as a number of "dawn simulators". These "full spectrum" lighting products can provide consistent lighting levels using the full spectrum of *noontime* sunlight (Figure 1, metal halide and fluorescent). Some of these fixtures can be dimmable, but none of these products are capable of actually mimicking the full spectrum of natural daylight in both color temperature and light intensity. While CFL and induction lamp light sources can be energy-efficient, neither have the ability to change color throughout the day. Incandescent light is closer in color temperature to late afternoon light when blue light is preferentially scattered out of (removed) from incoming sunlight, when the late afternoon sun begins to turn red and daylight turns to orange light. On the other hand, it is possible through a combination of white and RGB (red, green, blue) LEDs to program the lights to change color throughout the day to actually mimic the full spectrum of natural daylight from dawn to dusk; to change the color from the rising sun to the setting sun and to illuminate building interiors with a low-intensity red light throughout the nighttime hours.

Energy use for this system was calculated and compared with a typical fluorescent fixture. While the LED system is a dynamic system, the calculations were based on average conditions for nighttime, daytime and noonday peak intensity for four hours per day. The fluorescent system was calculated considering an 8-hour nighttime condition of one-third illumination. Preliminary calculations indicate there would be a cost savings of 0.0538kWh/day/m^2. Considering there is close to 185,806,080m^2 of large hospital building floor space in the United States, of which up to approximately 25 percent could be circulation space in use 24/7, this could mean a significant savings in energy consumption and reduction of carbon footprint (EIA 2007).

3.5. LEDs and sustainability

Department of Energy research has shown that LED solid state lighting is more energy-efficient and longer lasting with lower lifecycle costs than other light sources (DOE 2010). Most significantly for this research project, the integrated LED luminaire has been documented by the University of Pittsburgh to be the best lighting technology from an environmental perspective, especially since LED lighting contains no mercury. The ecotoxicity of LED lighting lies primarily with the printed circuit boards and integrated circuits, as well as with the manufacturing process of the LED bulbs (Hartley 2009), both of which are a major component of this project. While the "full spectrum" lighting products currently on the market are manually dimmable, which gives the owner lighting control, these products are not automatically programmable to provide the recommended light intensity and color spectrum for time of day. These lighting systems are neither FDA-approved nor can they be prescribed by a doctor as therapy to ameliorate sleep disturbances.

CONCLUSION

Research has shown LED solid state lighting to be more energy-efficient and longer lasting with lower lifecycle costs than other light sources *and* that natural daylight controls the body's circadian rhythms and affects overall wellbeing. The objective of this project is an automatic diurnal daylight-matching LED luminaire appropriate for institutional settings. Moreover, this system satisfies the following criteria: 1) an integrated LED luminaire with changeable light source; 2) programmed to mimic natural daylighting in its full diurnal changing color spectrum and light intensity; 3) energy-conserving to operate 24 hours/day; 4) dims to the red spectrum to allow residents to go to sleep and still provide caregivers with the illumination levels they require to continue working and providing care to residents in need during the night; 5) constructed using sustainable materials; and 6) appropriate for retrofit conditions requiring minimal construction installation. This LED luminaire addresses the dual sustainability issues of energy efficiency and health/wellbeing of building occupants.

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ENDNOTES

[1] According to manufacturer Full Spectrum Solutions, “Full Spectrum Lighting is considered to be any lamp with a color temperature between 5000K and 6000K with a CRI of 90+”.
[2] BlueMax™ HD induction lamp By U.S. Patent #6,318,880 Lawrence Berkeley National Laboratory.