Programmable LED Luminaire for Maximum Entrainment and Internal Synchronization

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Abstract

Light cycles play a central role in entraining (synchronizing) circadian rhythms and maintaining internal temporal order. However, lighting systems in built environments have focused primarily on visual acuity and energy efficiency, largely ignoring lighting's temporal impacts. This oversight can lead to rhythm disruption with negative impacts on physiology and behavior. The elderly are particularly vulnerable to such disruption, especially when housed in commercial facilities. In this paper, we discuss a LED-based lighting system designed to mimic the temporal characteristics of the solar day in both intensity and wavelength. We are currently engaged in testing to determine the efficacy of the system in a dementia unit of residential nursing facility.

Author Keywords

Circadian; light cycle; entrainment; aging; dementia; LED; light intensity; wavelength

ACM Classification Keywords

D.3.2. Programming languages: Java
D.4.0 Operating Systems: Linux

Circadian Rhythm: The term circadian is Latin for 'about a day'. The term refers to self-sustaining biological rhythms with a frequency of approximately 24 hours.

Entrainment: This term refers to the ability of one rhythm to synchronize another by creating a frequency match. In the case of circadian rhythms and the day/night cycle, entrainment occurs when the day/night cycle, with a frequency of 24 hours, alters the circadian rhythm, with a frequency of only approximately 24 hours, so that both rhythms have the exact same frequency, i.e., that of the day/night cycle (24 hours).

Internal Temporal Order: Living organisms display multiple rhythms of different frequencies. When all rhythms are appropriately linked together, the organism has internal temporal order

Desynchronization: A loss of entrainment is external while internal refers to a loss of internal temporal order.

General Terms

Algorithms; Design; Human Factors; Measurement: Performance; Reliability; Verification.

Introduction

Circadian rhythms play a key role in maintaining an organism's internal temporal order. Although capable of self-sustained oscillations, circadian systems are typically synchronized (entrained) to the geophysical cycle of the Earth's rotation via the consistent alteration of daylight and darkness. Until quite recently in evolutionary time, human beings were subject to the same day/night conditions as the other organisms, leading to the evolution of an internal clock system dependent on the day/night cycle for external synchronization. However, the development of built environments with artificial lighting has created a temporally disruptive environment with potentially negative effects of both physiological and behavioral functioning.

In the external environment, light can be expected to display a gradual increase in lighting (sunrise) and powerful, sustained lighting (daylight) and a gradual decrease in lighting (sunset) followed by a profound darkness (night). These effects involve both intensity and wavelength variations in perceived lighting. Focusing on illuminance alone, a moonless overcast night may provide only about 10^{-4} lux, while full daylight provides 10,000-25,000 lux and direct sunlight 32,000–130,000 lux (http://stjarnhimlen.se/comp/radfaq.html - 10). The actual levels depend on both latitudinal location on the Earth and weather conditions, but clearly the circadian system evolved to expect a dynamic range of lighting over some 6-9 orders of magnitude.

Compare this evolutionary expectation with modern nursing home realities. In one study, Ancoli-Israel [3] reported that nursing home residents only experienced an average of 9 minutes of light over 1000 lux per 24-hour day. In another report, sixty –six institutionalized elderly were monitored for a three-day period. The mean lighting exposure was a mere 54 lux with only 10.5 minutes of exposure over 1000 lux [20]. In a survey of 53 nursing homes, illumination was considered barely sufficient or inadequate in 45% of the hallways, 17% of the activity areas and 51% of the residents' rooms [21 in 5]. It is little wonder that sleep problems and disorders are often reported for nursing home residents, even when such problems were not evident prior to admission [7,17].

Aging exacerbates the effects of artificial environments. Three factors – 1) the loss of oscillatory coherence in the circadian system [10,24]; 2) a decrease in retinal light sensitivity [4,14,23]; and 3) a yellowing of the lens, reducing the amount of light blue-green light, the most effective wavelength for entrainment, reaching the retina [5,9]– combine with poor lighting environments to create the perfect storm for external and internal desychronization and temporal disruption.

Proposed Solution –Autotuned LED Luminaire

In order to provide a more naturalistic lighting cycle, we are developing a solar day mimicking, energy-conserving integrated light-emitting diode (LED) luminaire for commercial and residential use. The initial application is for a residential nursing facility for use in the dementia unit. The luminaire is designed to be retrofitted into a standard 2′ x 2′ or 2′ x 4′ fluorescent structure often in place in a suspended acoustical tile ceiling. The luminaire design consists of several off-the-shelf components mounted into a custom-fabricated 2’ x 2’ troffer, designed to replace a standard fluorescent ceiling fixture. The components are three Philips Color Kinetics ColorBlast 12 LED fixtures with 22-degree beam angle frosted glass diffusers. An additional diffuser mounted to the underside of the troffer provides a combined beam angle comparable to traditional luminaires. Light output is 1207 lumens with a color spectrum spanning 2500 K to 6500 K, in addition to full red, green, blue (RGB) capability.

The fixture is connected with three combined power and data cables to a single Philips Color Kinetics PDS-150e power supply, which is mounted either on the top side of the troffer or to a support beam in the ceiling. The power supply is connected locally to 120 VAC or 240 VAC mains power and provides 24 VDC power and a decoded signal to each ColorBlast 12 fixture. In addition, the power supply is connected among other power supplies in a daisy-chain format to a bus of Cat 5e data cable, which carries the digital multiplex (DMX) signal from the lighting control system.

The lighting control system consists of a Philips Color Kinetics iPlayer 3 controller as well as a Philips Color Kinetics AuxBox input-output device. The iPlayer 3 runs a time-based program to control the color and intensity of each luminaire over a 24-hour period. This program is based on a schedule that closely mimics the intensity and color temperature of outdoor light throughout the day, and provides dim reddish light for safety and work purposes between dusk and dawn. The commands from the iPlayer 3 are sent out as a DMX signal to each luminaire power supply over the communications bus. The AuxBox augments the functionality of the iPlayer 3, allowing the system to output bright white light in the event of a fire alarm or triggering of an emergency switch via dry contact closure. In addition, an in-house control system is under development that better fulfills the requirements of customizability, multi-protocol signaling, remote control, and integration with other building systems.

Lighting Design Standards

Department of Health sets minimum illumination standards for skilled nursing facilities, referring to The Pennsylvania Code, Chapter 205 Physical Plant and Equipment Standards for Long-Term Nursing Facilities Section 205.68 [16]. Alternatively, ANSI/IESNA RP-28-07 *Recommended Practice for Lighting and the Visual Environment for Senior Living* recommends somewhat different levels, higher in areas where residents are active and lower is sleeping areas (for example, the PA Code requires lighting in reading areas to be 300 lux in contrast to ANSI/IESNA’s recommendation of 700 lux)[4]. Neither color temperature nor wavelength are specified in either system nor are there any true temporal considerations other than for use (reduced lighting in sleeping areas). Thus, current lighting standards have not incorporated optimal aspects of entrainment or the maintenance of internal temporal order [1,2,6,11].

Lighting Implementation Plan

There is no doubt that a sinusoidal light/dark waveform is a more powerful entraining signal than simple light pulses or a traditional square wave [11]. There is also a reasonable body of evidence indicating the efficacy of light therapy on reducing some symptoms of Alzheimer’s Disease and dementia [12,18,19,22].However, the majority of these studies have used the paradigm associated with Seasonal Affective Disorder (SAD) treatments, i.e., the use of light boxes and scheduled exposures. What is not yet known is whether or not a system which mimics both the intensity and wavelength variation of a natural solar cycle will have the predicted impact on dementia patients. To examine this question, we are working with the St. Francis Country House, a 273 bed skilled nursing facility located near Philadelphia, PA. The 4th floor dementia unit consists of fourteen three-bed, two two-bed and two one-bed rooms able to accommodate 48 residents. The solar-day luminaire is to be installed in the corridor of the southwest wing which houses two three-bed and two two-bed rooms. LED luminaires will not be installed in the residents' rooms but rooms will be modified with red lighting at night and black shades to block any incidental light from entering the rooms from street lights, etc. The end of the corridor expands into a dining area for residents. Sixteen light LED luminaire fixtures will be installed in the dining area and seven in the corridor itself (Figure 1 [8]). Residents outside of their rooms will be exposed to the solar-day mimicking lighting cycle continuously during the duration of the study.

Methods and Measures

The study will proceed in a series of steps. After obtaining Institutional Review Board (IRB) approval, consent will be obtained from those residents and/or their legal guardians. Residents will be medically screened prior to participation.

The study will begin with the collection of baseline data on cognitive status, functioning, sleep/wake cycles and daytime sleepiness at meals. Wrist actiwatches will be worn for 7 consecutive days by residents to measure sleep/wake schedules. Functioning will be measured using the Minimum Data Set Activities of Daily Living Scale (MDS-ADL [13]) as assessed by staff. Cognitive status will be measured using the Mini Mental State Examination.

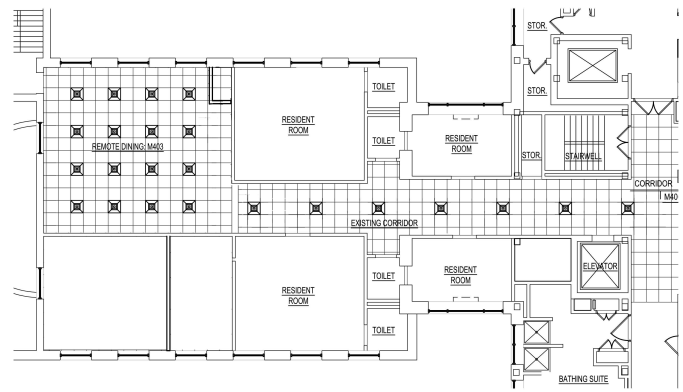

Figure 1. Lighting arrangement in the Transition Wing of the St. Francis Country House [8]

After the baseline week, the solar day mimicking LED luminaire system will be initiated providing the lighting schedule displayed in Figure 2. This schedule will continue for 30 days.

After 30 days of exposure, data on functioning and cognitive status will be collected. Activity patterns and sleep/wake cycles will be collected for 7 days. This pattern will be repeated at 90 days and 180 days after initiation of the luminaire solar day-mimicking cycle.

Data will be analyzed using standard approaches. Additionally, the impact of the lighting cycle on the global functioning of participants will be ascertained through interviews with family and/or staff members using interview questions for qualitative assessment of global functioning of participants.

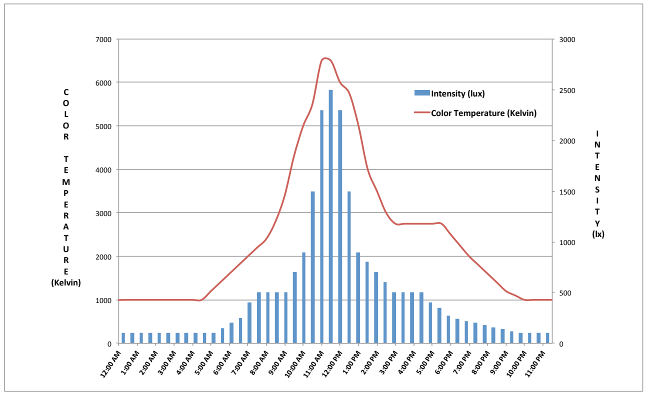

Figure 2. Lighting schedule for residents in the St. Francis Country House

Conclusion

Should the results support the hypothesis that a solar day- mimicking LED luminaire programed with the appropriate timing and wavelength variations can increase internal temporal order within residential and commercial structures, then the implications would be far-reaching. The implementation of such approaches in residential facilities and in medical facilities could result in improved treatment outcomes. Furthermore, such approaches used in home environments may reduce the need for institutionalizing patients in the early stages of dementia, improving the quality of life for those individuals.

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