White – Tunable LED Lighting: A Literature Analysis Report

Conservation and Energy Management Engineering

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Disclaimer:

The information in this report is compiled from existing sources. Our suppositions are based on reported facts and should not constitute design rules. Further research is needed to better understand the human response to white tuning illumination and establish design guidelines.

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1.0 Executive Summary

As LED lighting becomes more and more the norm people are starting to see the energy benefits of making the switch; however, LEDs are capable of providing more than just power savings. Through recent advancements in white-tunable LED technology, lights can be used not only for lighting purposes but to improve the lives of the users they affect.

Humans lived for thousands of years with only the sun as a source of light. Growing used to this day/night cycle, humans developed biological rhythms accordingly called circadian rhythms. Circadian rhythms are responsible for the production of various hormones, such as melatonin and cortisol, as well as levels of alertness and body temperature. The various levels of all these things adjust throughout the day according to an approximately 24 hour internal clock; this clock sets the frequency of circadian rhythms. Circadian rhythms use external information in the form of light to reset and to verify when to begin or stop producing hormones.

Since the dawn of electric lighting humans are no longer limited to the sun as the sole source of light. Because of this, humans can now extend their hours of work and play later, or earlier, than they ever could have in the past. However, this new form of light also has an effect on the circadian rhythms and the once near constant level of lighting expected by the body is no longer obtained. By receiving unexpected levels of light at an incorrect time of day the human body produces hormones at the incorrect time and alertness and body temperature levels are also thrown out of balance. This misalignment can result in various medical symptoms including reduced sleep and depression among other things.

Since it is unrealistic for humans to give up electric light, research has been conducted to find a solution for circadian disruption. Up until the past decade the majority of the research regarding the effect of light on the human circadian rhythm was only quantified in terms of luminance; this has since been proven inadequate. The recent discovery of intrinsically photoreceptive retinal ganglion cells (ipRGCs) in the human eye and research showing evidence of the effect of the visible spectrum has caused researchers to reevaluate their approach. These two pieces of evidence have led to research that evaluate both the luminance of the light as well as the colour on the circadian rhythm. Lighting that can be tuned in both these areas is referred to as dynamic lighting; lighting that can be set at various color and luminance levels either through manual controls or programmable controllers. White-tunable LEDs are capable of adjustments of luminance and correlated colour temperature (CCT) levels along a black body curve. This means the light can go from a reddish colour (2000 K) to a blueish colour (6000 K) and can vary from bright to dim.

After conducting a literature search of related materials, as well as examining government studies, manufacturer studies, and product brochures, the following results were found. The three main areas of focus for the effects of white-tunable dynamic lighting on occupants are health, education, and work.

In health related research the majority of work was done on patients living in extended care homes. The occupants of these homes are at great risk of circadian disruption due to the minute amount of natural light they receive. To curb the negative effects of circadian disruption caused by constant levels of electric light various CCT levels and luminance levels were evaluated. After a thorough analysis of related materials a suggested lighting routine was suggested. This routine suggest that places like extended care homes use dynamic white-tunable lighting to attempt to replicate the levels of lighting produced by the sun throughout the day. This means less intense, redder light in the morning and evening and brighter, bluer light midday. Energy savings using the suggested dynamic lighting routine versus a similar non dynamic lighting system were found to be approximately 30%.

In education related research the majority of the research was conducted on young children. Unlike people in hospital like quarters, students are less at risk of circadian disruption. Instead of replicating outdoor lighting conditions, school lighting was changed to produce certain effects in the students. Under bright bluish light cortisol and alertness levels are higher; this can result in greater focus. Conversely under warm reddish light melatonin is high and alertness is lower, this results in less stressful headspaces which are ideal for group work and creative projects. After a thorough analysis of related materials a suggested lighting routine was suggested. This routine was less a routine and more a selection of lighting options. Teachers could decide, based on the learning material, what mode to set the lighting to in order to achieve the best type of learning conditions. Energy savings using the suggested dynamic lighting routine versus a similar non dynamic lighting system were found to be less than 5%.

For work related research two areas were examined, dayshift and nightshift work. Nightshift workers are at high risk for circadian rhythm disruption due to their near complete lack of natural light. However it was found, at least for long term nightshift workers, that if conditions remain consistent the lighting that would be recommended for dayshift workers can also be recommended for nightshift workers. After a thorough analysis of related materials a suggested lighting routine was suggested. For office workers high CCT and luminance level lighting is suggested early in the morning and after lunch. In doing this workers are essentially given a “boost” to increase alertness and focus which results in greater performance. At lunch and towards the end of the day lighting CCT and luminance levels are decreased. For lunch time it is to allow the body to relax and recover; for towards the end of the day it is to allow the body to prepare to rest allowing melatonin production to begin on time. Work places can also borrow the suggested routine from education for meeting rooms. Being able to adjust the lighting for the type of meeting would likely be beneficial (i.e. Focus for presentations, Group for brainstorming sessions). Energy savings using the suggested dynamic lighting routines versus a similar non dynamic lighting system were found to be less than 5%.

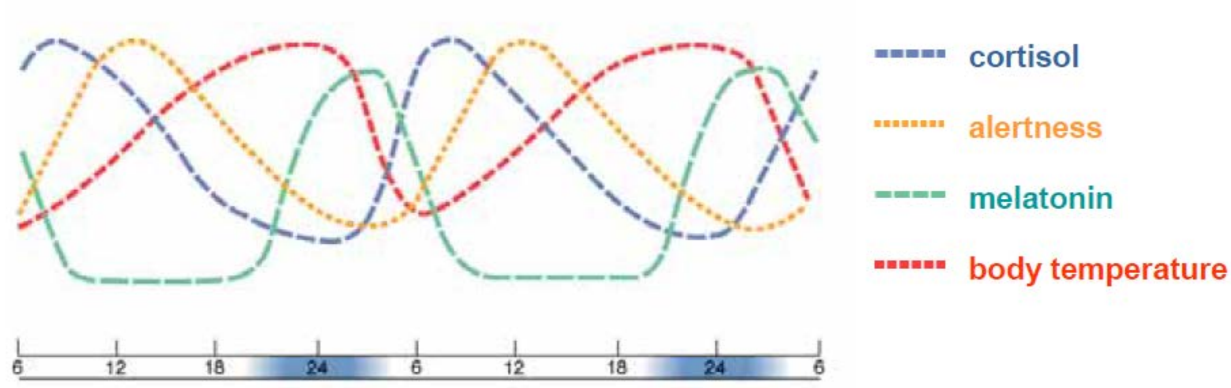
With the implementation of white-tunable lighting, positive effects have been found in various areas. As research continues, and more manufacturers continue to produce products that help to implement these systems, the positive effects that have been found will continue to become more and more prevalent. It would seem the future of white-tunable dynamic lighting is bright.

2.0 Introduction

As LED lighting becomes more and more the norm people are seeing the energy benefits of making the switch. However LEDs are capable of providing more than just power savings. Through the use of white-tunable LEDs and smart technology, lights can be used to improve the lives of the users they affect. Lights can be tuned on a brightness and colour level that can then be programmed to vary throughout the day. This report will discuss the technology of white-tunable lights, the effects they can have on circadian systems, and the sectors in which this technology can be implemented through analysis of research.

3.0 Light and Health

The earth's rotation around the sun causes a 24 hour day and night schedule. As humanity evolved, humans grew used to this cycle and developed biological rhythms accordingly [1]. These are called circadian rhythms. Circadian rhythms are responsible for the production of various hormones, such as cortisol and melatonin. Circadian rhythms also affect the body's alertness and temperature levels. How these vary throughout the day can be seen below.



Circadian rhythms of production of cortisol & melatonin, of alertness & body temperature [2]

With the advent of electric lighting humans are no longer dependent on daylight for their lighting needs; electric light has allowed for light at any time of day. This can lead to many benefits such as extended work hours but this also has a negative effect on people's circadian rhythms. Circadian rhythms are primarily set by people's consumption of light. The human body expects little to no light at night, increasing light from dawn till midday, and decreasing light towards sunset. Electric light provides constant levels of light at any time. The consumption of electric light results in a shifting or resetting of the circadian rhythm which is proving to have negative effects on the lives of everyday people.

An example of this is reduced sleep quality. Because people use electric lighting later in the day, when the body is expecting decreased light levels, adjustments in a circadian rhythm results in the body delaying production of melatonin. This results in lower overall melatonin levels which in turn decrease sleep quality. Because of these negative affects researchers have begun experiments to determine ways of correcting circadian rhythms without having to completely remove electric light from people's environments.

Up until the past decade the majority of the research regarding the effect of light on the human circadian rhythm was only quantified in terms of luminance; this has since been proven inadequate [3]. The recent discovery of intrinsically photoreceptive retinal ganglion cells (ipRGCs) in the human eye and research showing evidence of the effect of the visible spectrum has caused researchers to reevaluate their approach. These two pieces of evidence have led to research that evaluate both the luminance of the light as well as the colour on the circadian rhythm.

4.0 Dynamic Lighting

Dynamic lighting is an approach to lighting that has developed because of colour and luminance based research. With dynamic lighting systems elements of light are able to be tuned two main ways: correlated colour temperature (CCT) and intensity.

CCT is measured in Kelvin (K) and luminance is measured in Lumens (lm). CCT is the temperature value a light provides; redder colours being a lower temperature than bluer colours. CCT is usually adjusted between warm reddish light (2000 K) and cold bluish light (6500 K). Lumens are used to measure the intensity of a light; the brighter and more intense the light, the higher the lumen value.

Dynamic lighting can be used to replicate natural lighting conditions which can then be used to change and affect human circadian rhythms. This is particularly useful in areas where people do not receive adequate natural light and require electric light to reset their circadian rhythms.

There are three main types of tunable lighting for adjusting CCT and luminance:

Dimmable:

Dimmable lights are the most common type of tunable lighting. Dimmable lights use dimming switches to simultaneously increase or decrease the luminance and CCT. These systems are not ideal for circadian rhythm adjustment because they do not offer independent control over luminance and CCT.

White Colour Tunable:

White colour tunable lights are capable of CCT level changes along the black body curve; they are also, typically, able to changes luminance levels. The blackbody curve depicts how the colour levels of light change with increases in CCT; this depiction most clearly aligns with the changes seen in the sun's light throughout the day.

Full Colour Tunable:

Full colour tunable lights allow for complete control over the CCT level and, typically, luminance. While technically more dynamic, full colour tunable lights are more expensive and the effects of various colors of light (i.e. red, blue, green, etc.) are still being thoroughly researched. The benefits of these types of light do not fall under the scope of this research.

Dynamic LED lighting also provides energy savings when compared to conventional lighting systems. These savings will be calculated and discussed later in the report.

5.0 Commercially Available Products

Manufacturers have seen the interest and growth in the area of dynamic lighting and have developed products to fill this new market. Using the philosophy of Human Centric Lighting (HCL) many companies have begun to market products that focus on the effects the lights have on the occupants; many of these being dynamic lighting systems.

5.1 Luminaires

The two main manufacturers of tunable white luminaires that are commercially available in Canada are Philips and AcuityBrands. Many brands market white tunable LEDs but only luminaries with independent control of intensity and CCT can be considered for most dynamic lighting systems. Below are some examples of white tunable luminaires that could be implemented in a dynamic lighting system. All the luminaries listed have independent adjustment to intensity and CCT levels.

Philips iW Fuse Powercore:

Designed for wall grazing and flood lighting [6]. Delivers variation of CCT between 2700 K and 6500 K along the black body curve.

Philips FloatPlane:

Designed for overhead suspension and wall mounted lighting [7]. Delivers variation of CCT between 2700 K and 6500 K along the black body curve.

Philips BoldPlay:

Designed for overhead suspension and wall mounted lighting [8]. Delivers variation of CCT between 2700 K and 6500 K along the black body curve.

Acuity Brands Slot LED-Dynamic Recessed Tunable White:

Designed for overhead recessed lighting [9]. Delivers variation of CCT between 3000 K and 5000 K for the Productivity Range; for the Rhythm Range 2700 K and 6500 K.

Philips iW Fuse Powercore

Philips FloatPlane

Philips BoldPlay

Acuity Brands Slot LED-Dynamic Recessed Tunable White

5.2 Bulbs

Unlike luminaires, there are many companies, big and small, that are producing tunable LED light bulbs. These products are designed for home owners looking to make changes to their personal lighting. They tend to come with a large list of features which can include remote management, voice control, power monitoring, etc. Below are only a few of the bulbs commercially available.

Philips Hue white ambiance A19:

A bulb to be used with a Philips bridge (a hub device) [10]. Delivers variation of CCT between 2200 K to 6500 K. Includes remote management and smartphone app tuning. Changes can be made through a smartphone app that is wirelessly connected to the bridge.

TP-Link LB120:

A smart wi-fi LED bulb with tunable white light [11]. Delivers variation of CCT between 2700 K and 6500 K. Includes remote management, smartphone app tuning, and voice control. No hub is required. Connects from the bulb to a wi-fi network then through a smartphone app.

Sengled Element Plus:

A bulb to be used with the Element hub [12]. Delivers variation of CCT between 2700 K and 6500 K. Includes remote management, smartphone app tuning, voice control, and energy tracking. All changes and management can be done through a smart phone app that is wirelessly connected to the hub.

Ilumni A19 LED Smart Light Bulb:

A bulb that connects directly to a smartphone app [13]. Delivers variation of CCT between 2000 K and 8000 K. Includes smartphone app tuning and routine planning. All changes are done directly between the bulb and the smartphone app.

Philips Hue White Ambiance A19

TP-Link LB120

Sengled Element Plus

Ilumi A19 LED Smart Light Bulb

6.0 Literature Research

A literature research was conducted on materials relating light's effect on circadian systems in health, school, and office sectors. Below is a list including the journal articles, manufacturer case studies, government case studies, and product brochures found.

6.1 Journal Article Abstracts

1. *Circadian rhythms are seen at every level of biology, from single cells to complex behaviors. The timing of every biological function in mammals is governed by the master clock in the suprachiasmatic nuclei (SCN), which has an intrinsic period of slightly longer than 24 hours. The light / dark pattern incident on the retina synchronizes the SCN to the 24-hour local time, coordinating and enabling diverse biological functions to occur at the correct time of day and night for optimum species survival. Without exposure to a regular, daily pattern of light and dark, circadian rhythms become disrupted. A wide range of modern maladies, from sleep disorders to cancer, has been linked to light-induced circadian disruption. Light has, however, been defined only in terms of the human visual system, not the circadian system. Light source and systems development should consider the needs of both the visual and non-visual systems.*

   Discussed are the lighting characteristics impacting these two systems and the implications for designing light for various healthcare and medical applications.

   Figueiro, M. G. (2013). An overview of the effects of light on human circadian rhythms: Implications for new light sources and lighting systems design. Journal of Light & Visual Environment, 37(2_3), 51-61. doi:10.2150/jlve.IEIJ130000503

2. *Light is a potent stimulus for regulating circadian, hormonal, and behavioral systems. In addition, light therapy is effective for certain affective disorders, sleep problems, and circadian rhythm disruption. These biological and behavioral effects of light are influenced by a distinct photoreceptor in the eye, melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs), in addition to conventional rods and cones. We summarize the neurophysiology of this newly described sensory pathway and consider implications for the measurement, production, and application of light. A new light-measurement strategy taking account of the complex photoreceptive inputs to these non-visual responses is proposed for use by researchers, and simple suggestions for artificial/ architectural lighting are provided for regulatory authorities, lighting manufacturers, designers, and engineers.*

   Lucas, R. J., Peirson, S. N., Berson, D. M., Brown, T. M., Cooper, H. M., Czeisler, C. A., ... & Price,

L. L. (2014). Measuring and using light in the melanopsin age. Trends in neurosciences, 37(1), 1-9.

3. *Algorithmically - and sensor - controlled dynamic, daylight-quality artificial lighting provides an opportunity to restore occupants' connection to their external environment. LED luminaires can indicate sky conditions in windowless building interiors while providing high quality ambient illumination. We present methods to achieve real-time and idealized emulations of sun and sky- light specific to local geographic coordinates, orientation, and time.*

Mapel, J. K., Ellis, A. R., & Hunsinger, J. (2016). 11-3: Invited paper: Daylight-Emulating LED luminaires as daylight phase indicators and occupant Circadian-Rhythm entrainment. SID Symposium Digest of Technical Papers, 47(1), 118-121. doi:10.1002/sdtp.10612

4. *To date, most current reports on the development and optimization of artificial lighting sources have focused on the energy performance levels and limited color qualities of white light-emitting diodes (LEDs). However, these properties are insufficient in terms of representing all performance levels required when adjusting white LEDs for healthy and smart lighting. Here, we introduce essential and advanced figures of merit pertaining to circadian performance as well as vision performance and color quality. We compare all possible properties of commercialized artificial lighting, daylight and four-package white LEDs which consist of long-wavelength pass dichroic filter (LPDF)-capped, phosphor-converted red, amber and green LEDs (pc-LEDs) and a blue LED. We show that these tunable four-package white LEDs produce a tunable circadian effect for melatonin suppression/secretion, a high color quality for color perception/reproduction, high efficiency for energy savings and tunable figures of merit for the smart LED lighting market.*

Oh, J. H., Yang, S. J., & Do, Y. R. (2014). Healthy, natural, efficient and tunable lighting: four-package white LEDs for optimizing the circadian effect, color quality and vision performance. Light: Science & Applications, 3(2), e141.

5. *Light induces not only visual responses but also non-visual effects, indeed it affects performance, mood, attention and influences the synchronization of the biological clock. Duration, timing, intensity and the spectral power distribution of the light that reaches the eyes can have influence on human circadian rhythm and consequently on health. Given the important impact of the non-visual responses on people wellbeing, developing a model that allows lighting designers to predict them is a fundamental goal.*

   In this paper a case study is reported: a series of measurements were carried out in a University classroom in order to study daylight and electric light characteristics and also their impact on the human circadian system by calculating melatonin suppression. The results obtained show that not only the intensity but also the SPD of the light received by the eyes plays a significant role on circadian response and the spectral characteristics of internal and *external surfaces influence the SPD and therefore the CCT of the light that hits the eyes. Although the working behavior of the human circadian system is not completely understood, the results obtained give the designers new points of view to better evaluate lighting quality and its implications in indoor environments.*

Bellia, L., Pedace, A., & Barbato, G. (2013). Lighting in educational environments: An example of a complete analysis of the effects of daylight and electric light on occupants. Building and Environment, 68, 50-65.

6. *The near visual acuity (400 mm distance) of 27 children aged 10-11 years old was measured by a licensed optometrist under two common fluorescent lamps of CCT 3600 K and 5500 K. Acuities were measured for three lighting conditions, either both lamps providing equal task luminance or a condition where the task and room luminance from the 5500 K lamps was set 50% lower. For the equal luminance condition, the results showed visual acuity was significantly better (PB/0.001) under the higher CCT lamp with 24 of 27 children having better acuity. Paired t-tests comparing the lower luminance condition showed significantly less acuity for the 5500 K lamps at the lower luminance, but no significant difference between the 3600 K lamps at the higher luminance compared with the 5500 K lamps at the lower luminance.*

M., Martin, M., Sheedy, J., & Tithof, W. (2006). A comparison of traditional and high colour temperature lighting on the near acuity of elementary school children. Lighting Research & Technology, 38(1), 41-49. doi:10.1191/1365782806li155oa

7. *Light is universally understood as essential to the human condition. Yet light quality varies substantially in nature and in controlled environments leading to questions of which artificial light characteristics facilitate maximum learning. Recent research has examined lighting variables of color temperature, and illumination for affecting sleep, mood, focus, motivation, concentration, and work and school performance. This has resulted in artificial light systems intended to support human beings in their actualization through dynamic lighting technology allowing for different lighting conditions per task. A total of 84 third graders were exposed to either focus (6000K-100fc average maintained) or normal lighting. Focus lighting led to a higher percentage increase in oral reading fluency performance (36%) than did control lighting (17%). No lighting effects were found for motivation or concentration, possibly attributable to the younger age level of respondents as compared with European studies. These findings illuminate the need for further research on artificial light and learning.*

Mott, M. S., Robinson, D. H., Walden, A., Burnette, J., & Rutherford, A. S. (2012). Illuminating the effects of dynamic lighting on student learning. SAGE Open, 2(2), 215824401244558. doi:10.1177/2158244012445585

8. *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. Post-industrial 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.*

Ellis, E. V., Gonzalez, E. W., Kratzer, D. A., McEachron, D. L., & Yeutter, G. (2014, March). Auto-tuning daylight with LEDs: sustainable lighting for health and wellbeing. In ARCC Conference Repository.

9. *In recent years, the effects of the physical environment on the healing process and well-being have proved to be increasingly relevant for patients and their families (PF) as well as for healthcare staff. The discussions focus on traditional and institutionally designed healthcare facilities (HCF) relative to the actual well-being of patients as an indicator of their health and recovery. This review investigates and structures the scientific research on an evidence-based healthcare design for PF and staff outcomes. Evidence-based design has become the theoretical concept for what are called healing environments. The results show the effects on PF and staff from the perspective of various aspects and dimensions of the physical environmental factors of HFC. A total of 798 papers were identified that fitted the inclusion criteria for this study. Of these, 65 articles were selected for review: fewer than 50% of these papers were classified with a high level of evidence, and 86% were included in the group of PF outcomes. This study demonstrates that evidence of staff outcomes is scarce and insufficiently substantiated. With the development of a more customer-oriented management approach to HCF, the implications of this review are relevant to the design and construction of HCF. Some design features to consider in future design and construction of HCF are single-patient rooms, identical rooms, and lighting. For future research, the main challenge will be to explore and specify staff needs and to integrate those needs into the built*

environment of HCF.

Huisman, E. R. C. M., Morales, E., Van Hoof, J., & Kort, H. S. M. (2012). Healing environment: A review of the impact of physical environmental factors on users. Building and Environment, 58, 70-80.

10. ***Context:***
Cognitive decline, mood, behavioral and sleep disturbances, and limitations of activities of daily living commonly burden elderly patients with dementia and their caregivers. Circadian rhythm disturbances have been associated with these symptoms.

Objective:
To determine whether the progression of cognitive and non-cognitive symptoms may be ameliorated by individual or combined long-term application of the 2 major synchronizers of the circadian timing system: bright light and melatonin.

Design, Setting, and Participants:
A long-term, double-blind, placebo-controlled, 2-2 factorial randomized trial performed from 1999 to 2004 with 189 residents of 12 group care facilities in the Netherlands; mean (SD) age, 85.8 (5.5) years; 90% were female and 87% had dementia.

Interventions:
Random assignment by facility to long-term daily treatment with whole day bright (±1000 lux) or dim (±300 lux) light and by participant to evening melatonin (2.5 mg) or placebo for a mean (SD) of 15 (12) months (maximum period of 3.5 years).

Main Outcome Measures:
Standardized scales for cognitive and non-cognitive symptoms, limitations of activities of daily living, and adverse effects assessed every 6 months.

Results:
Light attenuated cognitive deterioration by a mean of 0.9 points (95% confidence interval [CI], 0.04-1.71) on the Mini-Mental State Examination or a relative 5%. Light also ameliorated depressive symptoms by 1.5 points (95% CI, 0.24-2.70) on the Cornell Scale for Depression in Dementia or a relative 19%, and attenuated the increase in functional limitations over time by 1.8 points per year(95%CI, 0.61-2.92) on the nurse-informant activities of daily living scale or a relative53%difference. Melatonin shortened sleep onset latency by 8.2minutes(95%CI, 1.08-15.38) or19%and increased sleep duration by 27 minutes(95%CI, 9-46) or6%.However, melatonin adversely affected scores on the Philadelphia Geriatric Centre Affect Rating Scale, both for positive affect (−0.5 points; 95%CI, −0.10 to −1.00) and negative affect (0.8 points;95%CI, 0.20-1.44). Melatonin also increased withdrawn behavior by 1.02 points (95% CI, 0.18-1.86) on the Multi Observational Scale for Elderly Subjects scale, although this effect was not seen if given in combination with light. Combined treatment

also attenuated aggressive behavior by 3.9 points (95% CI, 0.88-6.92) on the Cohen-Mansfield Agitation Index or 9%, increased sleep efficiency by 3.5% (95% CI, 0.8%-6.1%), and improved nocturnal restlessness by 1.00 minute per hour each year (95% CI, 0.26-1.78) or 9% (treatment x time effect).

Conclusions:
Light has a modest benefit in improving some cognitive and noncognitive symptoms of dementia. To counteract the adverse effect of melatonin on mood, it is recommended only in combination with light.

Riemersma-Van Der Lek, R. F., Swaab, D. F., Twisk, J., Hol, E. M., Hoogendijk, W. J., & Van Someren, E. J. (2008). Effect of bright light and melatonin on cognitive and noncognitive function in elderly residents of group care facilities: a randomized controlled trial. Jama, 299(22), 2642-2655.

11. *Behavioural and psychological symptoms, such as nocturnal restlessness and wandering, are seen in 90% of patients with dementia at some point in their course. Non-pharmacologic interventions, such as high-intensity lighting, can play an important role in managing these behavioural and psychological symptoms by impacting both the visual and the circadian system. In order to assess the effects of prolonged exposure to high-intensity light (about 1800 lx horizontal on table level) on behaviour and circadian rhythmicity of institutionalized older adults with dementia, ceiling-mounted luminaires emitting bluish (6500 K) and yellowish (2700 K) light were installed in an intervention group that was compared to a control group of traditional dim lighting equipment. The study was performed from May to August 2006. Effects of the lighting intervention were assessed by the Dutch Behaviour Observation Scale for Intramural Psychogeriatrics (GIP), and tympanic temperature measurements. In the bluish light scenario, a significant improvement in restless behaviour was observed in the intervention group, as well as a significant increase in the range of tympanic temperature. These effects were not found in the yellowish light scenario. Further evidence is found that high-intensity bluish light may play a role in managing restless behaviour and improving circadian rhythmicity in institutionalised older adults with dementia.*

Van Hoof, J., Aarts, M. P. J., Rense, C. G., & Schoutens, A. M. C. (2009). Ambient bright light in dementia: Effects on behaviour and circadian rhythmicity. Building and Environment, 44(1), 146-155. doi:10.1016/j.buildenv.2008.02.005

12. ***Objective:***
To review from an architectural lighting perspective the effects of indoor lighting on the health and well-being of people in senior living environments.

Background:
The role of circadian rhythms in people with chronic disorders continues to be a focus of laboratory research and clinical trials. Beneficial, evidence-based indoor lighting design strategies are being considered for senior living environments,

particularly for residents who have limited access to natural bright light.

Methods:
Articles published 2002–2012 reporting the results of prospective, randomized, controlled clinical trials (RCTs) were accessed using the U.S. National Library of Medicine PubMed site using the following search terms: “light, sleep, circadian, randomized, controlled, nursing home” and “light, sleep, circadian, randomized, controlled, elderly.”

Results:
The search resulted in 48 citations, of which 18 meet our pre-search criteria. Data from these RCTs indicate options such as programmable, 24-hour lighting algorithms that may involve light intensity, lighting duration, spectra (wavelength) and lighting timing sequences

Conclusions:
Valid and actionable data are available about circadian rhythms, sleep, and human health and well-being that can inform the design of lighting for long-term care. Evidence-based architectural design of a 24-hour light/dark environment for residents may mitigate symptoms of circadian disruption; evidence-based management of darkness is as important as evidence-based management of light. Further research is needed into the long-term circadian health needs of night staff members in order to understand the effects of shift work while, at the same time providing the highest level of care.

White, M. D., Ancoli-Israel, S., & Wilson, R. R. (2013). Senior living environments: evidence-based lighting design strategies. HERD: Health Environments Research & Design Journal, 7(1), 60-78.

13. *Lighting design for office buildings has focused largely on providing sufficient light for visual performance, minimal glare, good colour rendering and energy conservation. Little attention has been given to understanding how light affects the non-visual systems, including circadian regulation that affects sleep and mood. Circadian light–dark and activity–rest patterns of individuals working in a building designed to provide daylight availability in the space were obtained in winter and summer. Measures of objective and subjective sleep and self-reports*

    of mood were also obtained from participants. Results show a significant increase in light exposure during summer. Sleep quantity and quality were also significantly higher in summer than in winter. Strategies to increase circadian light exposures in buildings should be a consideration in architectural design.

Figueiro, M. G., & Rea, M. S. (2016). Office lighting and personal light exposures in two seasons: Impact on sleep and mood. Lighting Research & Technology, 48(3), 352-364.

14. *This paper addresses the question: ‘‘What is happening when we change the lighting at an industrial workplace?’’ and develops a new approach for looking at*

the effects of a change of lighting at the workplace on performance. Installing new lighting in the workplace may influence the performance of people working there by way of several mechanisms. In this paper the mechanisms are described: visual performance, visual comfort, visual ambience, interpersonal relationships, biological clock, stimulation, job satisfaction, problem solving, the halo effect, and the change process. The importance of these mechanisms is discussed and the results of old field studies in industrial environments have been put together to illustrate the effect of lighting change in industry.

Juslén, H., & Tenner, A. (2005). Mechanisms involved in enhancing human performance by changing the lighting in the industrial workplace. International Journal of Industrial Ergonomics, 35(9), 843-855.

15. *Light can be used to increase alertness, evoke relaxation and suppress sleepiness. Therefore, it can be deployed to support the well-being and performance of people in working places. These so-called 'non-visual' or 'biological' effects have become an increasingly important topic in lighting design over the last few years. Research on the physical effects of light on our body, as opposed to effects on visual perception and emotion, is still ongoing. This paper will discuss the implementation of current research results into practical applications.*

Furthermore, this article will discuss opportunities and benefits for lighting designers to apply this research by suggesting methods of application in lighting solutions for various work places. Those are driven by biological aspects of lighting, but take into account visual and emotional attributes, to aim at overall well-being in work places.

Knoop, M. (2006). Dynamic lighting for well-being in work places: Addressing the visual, emotional and biological aspects of lighting design. In Proceedings of the 15th international symposium lighting engineering. Lighting Engineering Society of Slovenia, Bled, Slovenia (pp. 63-74).

16. *The effects of good lighting extend much further than we used to think. Recent medical and biological research has consistently shown that light entering the human eyes has, apart from a visual effect, also an important non-visual biological effect on the human body. As a consequence, good lighting has a positive influence on health, well-being, alertness, and even on sleep quality. Our better understanding of the diversity in lighting effects teaches us that new rules governing the design of good and healthy lighting installations are required.*

Thanks to the recent discovery of a novel photoreceptor in the eye and its probable distribution within the eye we can now begin to define these new rules. These will guide us to dynamic lighting installations: that is to say dynamic in lighting level and dynamic in tint of whiteness of the lighting colour.

Van Bommel, W. J. (2006). Non-visual biological effect of lighting and the practical meaning for lighting for work. Applied ergonomics, 37(4), 461-466.

17. *A field study was performed to examine the effects of correlated color temperature (CCT) and lumen output of fluorescent lighting on office occupants' visual comfort, brightness perception, satisfaction, and self-reported productivity. Twenty-six participants were recruited (mean age = 38.8 years; age range = 23-55 years). Ten of them had daylight access in their personal work areas. Four lamp types were selected to create luminous conditions organized as a 2 x 2 factorial design, comprising two levels of CCT (i.e., 3500 and 5000 K) and lumen output (i.e., 2330 and ~3000 lm). Each condition lasted two weeks. Under each condition, participants adapted during the first week. During the second week they completed ecological momentary assessments (EMAs) three times daily using smart phones. Two of the daily EMAs included questions about lighting. Participants also completed a web-based survey on the last day of each condition. The results from the EMA (60.0% response rate) and web-based (77.2% response rate) surveys were generally consistent, indicating that CCT significantly affected spatial brightness perception, visual comfort, satisfaction, and self-reported productivity. The luminous conditions at 5000 K (visually cooler) were rated to be brighter than those at 3500 K (visually warmer), especially when higher lumen output was in place. However, the increase in spatial brightness perception came with lower satisfaction, worse visual comfort, and worse self-reported productivity. The conditions at 5000 K were judged to be too cool, especially for those who had daylight in their work areas. The results of this study do not support the spectrally enhanced lighting (SEL) method advocated by the U.S.*

Department of Energy (DOE) as an energy savings strategy. Even when higher CCT resulted in higher spatial brightness perception, occupants' visual comfort and satisfaction were compromised.

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too cool, especially for those who had daylight in their work areas. The results of this study do not support the spectrally enhanced lighting (SEL) method advocated by the U.S.

Department of Energy (DOE) as an energy savings strategy. Even when higher CCT resulted in higher spatial brightness perception, occupants' visual comfort and satisfaction were compromised.

Wei, M., Houser, K. W., Orland, B., Lang, D. H., Ram, N., Sliwinski, M. J., & Bose, M. (2014). Field study of office worker responses to fluorescent lighting of different CCT and lumen output. Journal of Environmental Psychology, 39, 62-76.

6.2 Government and Manufacturer Case Studies

1. *Key results from the trial installation at the ACC Care Center included the following:*

    - *Energy savings for the tunable white LED luminaires used in the corridors was 68% relative to the fluorescent system based on the LED system's reduced power and the automatic dimming implemented.*
    - *Illuminance levels in resident rooms and bathrooms were inadequate with the older fluorescent system but exceeded IES recommendations for the over 65 age group with the LED system.*
    - *Color consistency for the tunable white LED luminaires used in the corridors, nurse station, family room, and administrator's office was very good among luminaires and very good over the dimming range.*
    - *The combination of spectral tuning and dimming with the LED systems in the residents' rooms, the adjacent corridor, and the nurse station provided the opportunity to stimulate the ipRGCs (intrinsically photosensitive retinal ganglion cells) during the times of day when melatonin suppression is desirable (morning and mid-day), and to reduce stimulation of the ipRGCs during times of day when melatonin production is desirable (evening and night).*
    - *The amber LED lighting installed under the beds and in the bathroom handrails, controlled by motion sensors, proved very effective for providing low-level nighttime lighting that supported safe navigation while likely minimizing the stimulation of the ipRGCs.*
    - *Although this pilot study involved a very small number of rooms and residents, ACC Care Center staff documented important health-related benefits that may have been (at least in part) attributable to the lighting changes. For example, target behaviors such as yelling, agitation, and crying were reduced by an average of 41% for the three residents. Nursing staff noted that all three residents had been consistently sleeping through the night since the installation, and that psychotropic and sleep*

medication use had been significantly reduced for one of the residents whose room was included in the trial installation.

DOE 2016. Tuning the Light in Senior Care: Evaluating a Trial LED Lighting System at the ACC Care Center in Sacramento, CA.

2. *The project began when Veldvest approached Philips for some lighting advice. It learned about a recent study carried out by the University of Hamburg, which showed that light can reduce restless behaviour in classrooms. As Veldvest was interested in improving the lighting in schools, it was a great opportunity to trial SchoolVision lighting in local classrooms.*

SchoolVision lighting was installed in two classes at Wintelre school, with two classes at Veldvest De Rank Primary School in Veldhoven serving as a control group. This allowed researches to compare the performance of students in classrooms with and without Schoolvision.

The innovative SchoolVision system aims to create the ideal classroom atmosphere for learning. It lets teachers choose between four pre-set lighting scenarios, 'Normal', 'Energy', 'Focus' or 'Calm'. These settings can be used to calm children down when they are very energetic, wake them up when they are listless, or help them concentrate during challenging tasks. Both children and teachers enjoyed the new lighting, and teachers observed an improved level of concentration.

Philips. Case Study: Wintelre Primary School, Wintelre, the Netherlands. http://www.lighting.philips.com/main/cases/cases/education/wintelre

3. *SchoolVision was put to the test in an independent study by the government of Hamburg, Germany and the Universitätsklinikum Hamburg-Eppendorf. A total of 166 pupils and 18 teachers took part in the year-long scientific experiment, which recorded significant improvements in student performance.*

Compared to children under normal lighting, the children studying under SchoolVision showed improvements in concentration, attention span, and behaviour. In addition, they read faster and made fewer mistakes.

The figures speak for themselves:

- *Reading speed – 35% increase*
- *Frequency of errors – 45% decrease*
- *Hyperactive behaviour – 76% decrease*

School Vision Lighting. Retrieved March 07, 2017, from http://www.lighting.philips.com/main/systems/packaged-offerings/office-and-industry/schoolvision

4. *HealWell was shown to have beneficial effects for patients and staff, thus confirming the positive impact that light can have, as shown in previous studies.*

The HealWell lighting solution resulted in:

- *Improved patient and staff satisfaction*
- *Longer sleep duration for patients*
- *Shorter time to fall asleep for patients*
- *Enhanced mood of patients, as derived from the HADS*
- *(Hospital Anxiety and Depression Scale) depression scores*

HealWell. Retrieved March 07, 2017, from http://www.lighting.philips.com/b-dam/b2b-li/en_AA/systems/healwell/healwell-brochure-int.pdf

5. ***The Solution:***
The directors of the clinic opted for a comprehensive lighting solution from Philips to light each part of the new building in the best possible and coordinated way. The "Personal Light" concept was chosen for the patient, treatment and consulting rooms. This enables patients and staff to adjust the lighting to suit their requirements and to achieve the desired atmosphere. The intensity and colour of the light can each be adjusted separately.

Light colours of between 2700 Kelvin (warm white) and 6500 Kelvin (daylight white) can be selected. These values correspond to the natural light encountered in the course of the day and enable the melatonin and cortisol levels to be selectively adjusted to produce either a calming or an invigorating response. "Personal Light" is best implemented using the Savio product family. The clinic went for the ultra low-profile recessed lights that can be installed inconspicuously in the ceiling. Their patented OLC microlens optics produces a homogeneous and non-glare beam of light. An unusual light and colour concept was implemented in the corridors: whenever someone mentions the name of an area of Europe, such as Provence, East Anglia or Tuscany, an image of that area always springs to mind. The colour associations of these positive images have been employed in the design of the lighting. The "Ireland" corridor, for example, glows with rich green tones, whereas "Tuscany" features warm reds and earthy colours. The Rotaris lights also make a positive contribution through the concentric circles that characterise their design. To draw attention to the artworks on the walls, a third of the lights are equipped with adjustable Fugato downlights. The office lighting for employees has also been modernised. The minimalist design and optimum light distribution of the Arano lights brighten up the working day in the office.

Benefits: The well-being of the patients was at the forefront during the design stage and the Philips lighting solution fits the bill perfectly. The corridors throughout the clinic exude a warm and pleasant atmosphere, far removed from the sterility of traditional hospitals – something that strikes you as soon as you enter the department. Recent research indicates that patients who are allowed to play an active role in the design of their environment feel much more comfortable *and secure. In Oberhausen, they can now adapt their individual spaces according to their own ideas and moods. The lighting options also have major benefits for the therapy. Cold white light tends to have an invigorating effect on people and improves attention levels, whereas a warm white light is more calming. "Personal Light" allows every therapist to adapt the rooms to their requirements.*

Philips. Case Study: Psychiatry in Oberhausen, Germany
http://images.philips.com/is/content/PhilipsConsumer/CaseStudies/CSLI20141119_065-ECT-global-psychiatry-oberhausen.pdf

6.3 Product Brochures

1. *For white light, IntelliHue's enhanced spectrum allows for:*

    - *Precise color tuning in an expansive range extending from 2000 K (firelight) to 10000 K (blue sky) along the black-body curve*
    - *Precise tinting and shading of white light points in a generous region extending above and below the black-body curve (+/- 0.06 Duv)*
    - *An extremely high level of color consistency (<2 SDCM) in tandem with Chromasync, rendering color variations virtually imperceptible*

    You can fine-tune the white-light output of IntelliHue fixtures for an array of effects and applications, including:

    - *Matching the hues of fluorescent and incandescent lighting sources in an installation*
    - *Blending lighting with daylight, or following the daylight cycle from cooler color temperatures in the morning to warmer color temperatures in the evening*
    - *Allowing occupants of a space to adjust the color temperature, tint, and intensity of lighting to increase comfort and productivity*
    - *Adjusting the color appearance of light for changing retail displays, or to encourage desired occupancy behavior in indoor spaces*

    IntelliHue Technology Overview. Retrieved March 07, 2017, from
    http://www.colorkinetics.com/ls/guides-brochures/PCK-Technology-Overview-IntelliHue.pdf

2. *USAI Lighting Color Select® proprietary tunable white LED technology unlocks the potential of Personalized Lighting®, replacing a variety of sources as well as recreating the feel of natural daylight with one fixture type. By allowing end-users to change the LED color temperature from 6000K down to 2200K—and everything in between—while independently adjusting intensity from 100% down to 0.1% using either standard roomside dimmers or programmable control*

systems

Color Select. Retrieved March 07, 2017, from http://www.usailighting.com/stuff/contentmgr/files/0/3902799291705fa35c9e2ad6d0b7d708/download/color_select_brochure_ca_036b.pdf

3. *Channels of warm, neutral, and cool white LEDs produce color temperatures ranging from 2700 K to 6500 K with the greatest possible light intensity at all color temperatures. Fixture brightness can be varied while maintaining constant color temperature.*

Philips Color Kinetics. Retrieved March 07, 2017, from http://www.colorkinetics.com/ls/intelliwhite/

4. *The dynamic feature of Philips tunable white solutions allow you to automatically mimic daylight patterns by adjusting color temperature and brightness levels with respect to the time of day for optimal visual comfort*

Philips Tunable White Lighting Solutions. Retrieved March 07, 2017, from http://www.usa.lighting.philips.com/products/product-highlights/tunable-white-technology.html

5. *At its core, cycled light encourages a deeper, biophilic connection to nature – a connection that's often missing from indoor environments. Tunable White fosters a sense of passage of time and enables the creation of scenes and modes that can be aligned with key activities that require occupants be more focused, relaxed or energetic. Because Tunable White supports sleep/ wake cycles and promotes an intellectually stimulating learning environment. It is best used in spaces where occupant experience and performance are important, like school classrooms or college campuses. Tunable White is perfect for Healthcare, Office, Corporate Interiors, Education, Retail, Hospitality and Recreation applications. Tunable White features four ranges: Rhythm, from 2700K to 6500K; Productivity, from 3000K to 5000K; Layers, from 2000K to 5000K; and Atmosphere, from 1800K to 4300K*

Tunable White. Retrieved March 07, 2017, from http://www.acuitybrands.com/products/lighting/featured-technology/mainstream-dynamic/tunable-white

7.0 Sectors for Use

Many researchers have begun testing various schedules and patterns of light, in various sectors, in order to determine the most effective CCT and lumen levels for certain situations and periods of the day. The three main areas that are being researched are health, education, and office sectors.

In each of the following sections a recommendation will be made for a lighting routine. The recommendation will be a schedule in terms of CCT and intensity percentage; intensity percentage is the percentage of the highest intensity that is being used. These terms were used instead of lumens because the lumen value is highly dependent on the situation, location, and brand used.

A shorthand was used for the legends in the graphs seen throughout this section regarding where the values were sourced from; AVG indicates the average, CS indicates a government or manufacturer case study, JA indicates a journal article, and PB indicates a product brochure. The number associated with sources indicates the number associated with it in Section 6 (ie. JA1 is “An overview of the effects of light on human circadian rhythms: Implications for new light sources and lighting systems design”).

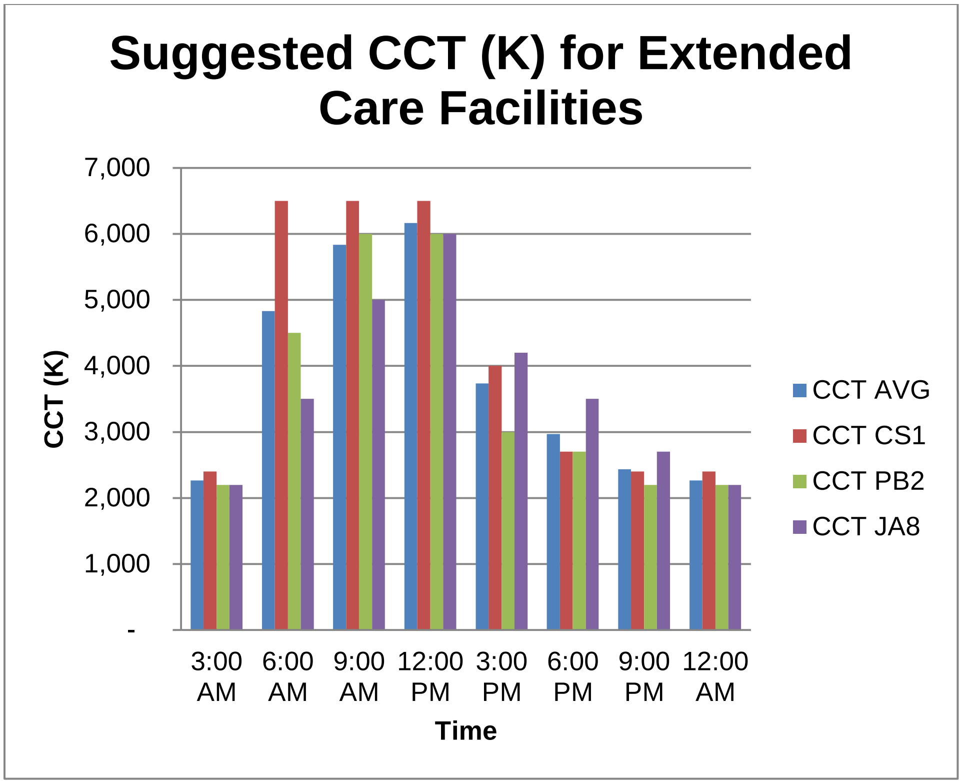
7.1 Health

7.1.1 Extended Care

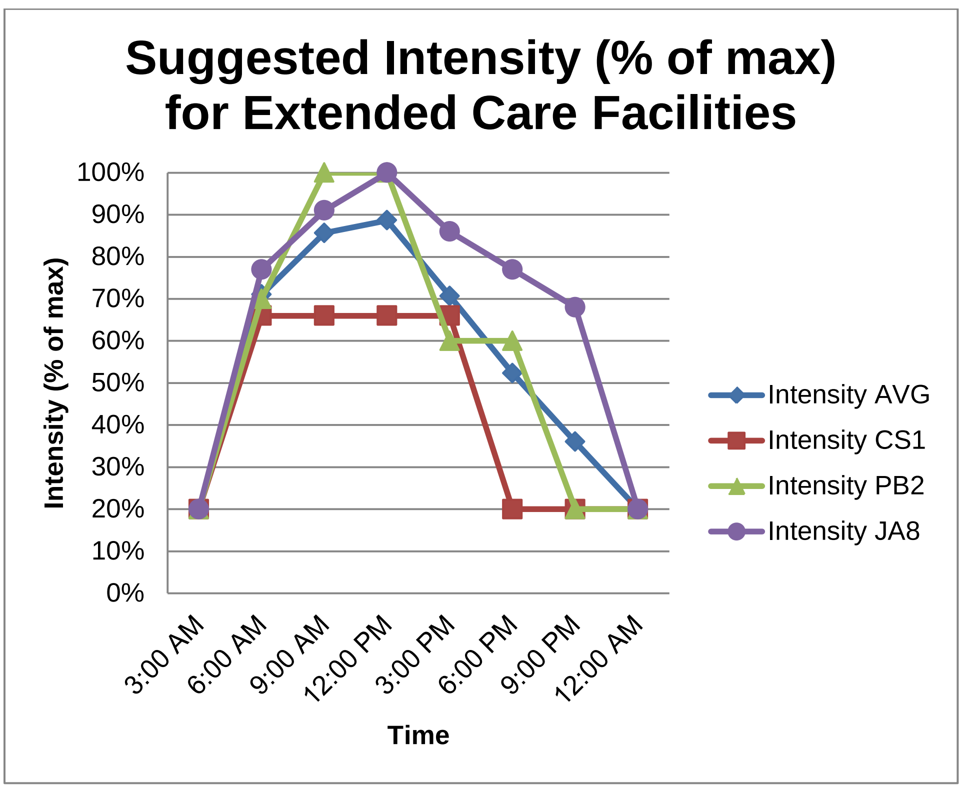
Medical institutions house patients for extended amounts of time and during this time most patients are not exposed to an adequate amount of natural light. Adjustments to the current lighting can result in reduced symptoms and will allow for circadian realignment. Research has been conducted to see how light can affect patients and whether or not the effects can be used to their benefit.

7.1.1.1 Suggested Routine for Extended Care Patients

Most journal studies, manufacturer case studies, and magazine articles [1, 3, 5-6, 9, 14-15, 19-23, 28, 31-34] suggest that replicating a natural daylight rhythm would have the most positive effect on patients. By attempting to realign circadian rhythms the sleep patterns, as well as other symptoms commonly suffered by people in extended care, would be best treated. Using resources that provided the clearest indication of lighting levels throughout the day [19,28,33] the following two graphs were generated.

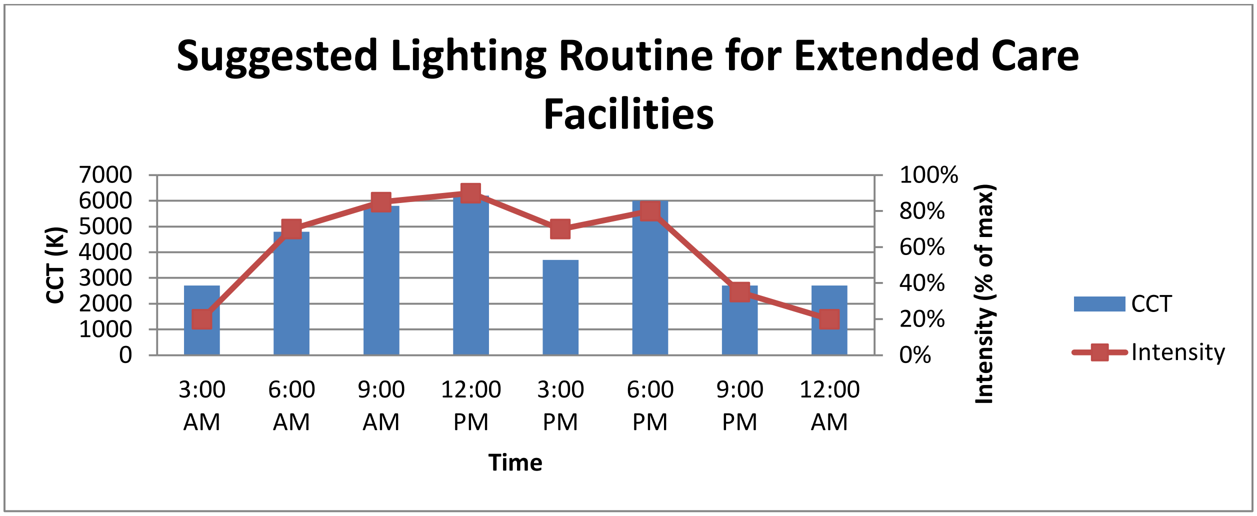


Suggested CCT for Extended Care Facilities



Suggested Intensity (%of max) for Extended Care Facilities

The above graphs show a sinusoidal like shape. The graphs suggest that both CCT and intensity should be low very early in the day, rise until noon, and then decrease towards the evening. Using educational considerations garnered from other sources [1, 3, 5-6, 9, 14-15, 20-23, 31-32, 34] as well as the above graphical information, a final suggested lighting routine was developed.



Suggested Lighting Routine for Extended Care Facilities

This routine attempts to simulate outdoor natural lighting in regards to CCT and intensity while providing low level light through the night in hallways and bathrooms. Manufacturer limitations were also taken into account when developing this routine; most manufacturers do not provide CCT levels below 2700 K so 2700 K was made the minimum lighting level [5-9, 33-34]. A 6PM spike in CCT level was also added; this is to attempt to provide patients with a better overall sleep [35]. Elderly people tend to wake up earlier due to having very early chronotypes. This means that they are more likely to wake up at an inopportune time and have restless sleep. By providing a CCT boost later in the day a shift in the circadian clock can be achieved thereby delaying the patients waketime.It should be noted that the spaces in which nightshift workers are working should not follow this schedule; instead it should follow the schedule in “Suggested Lighting Routine for Nightshift Workers”. Lights in patient rooms would be off when sleeping.

7.1.1.2 Energy Savings for Extended Care Facilities

Energy savings were calculated using a comparison between similar lighting systems; the standard (non tunable) Philips Boldplay LED and the tunable white Philips Boldplay LED [8]. The standard system used constant levels of intensity and CCT over the course of 24 hours while the tunable white system followed the suggested routine over a 24 hour period. A power savings of approximately 30% was found when using the tunable white system with the suggested routine over the standard system.

7.2 Education

7.2.1 Primary Schools

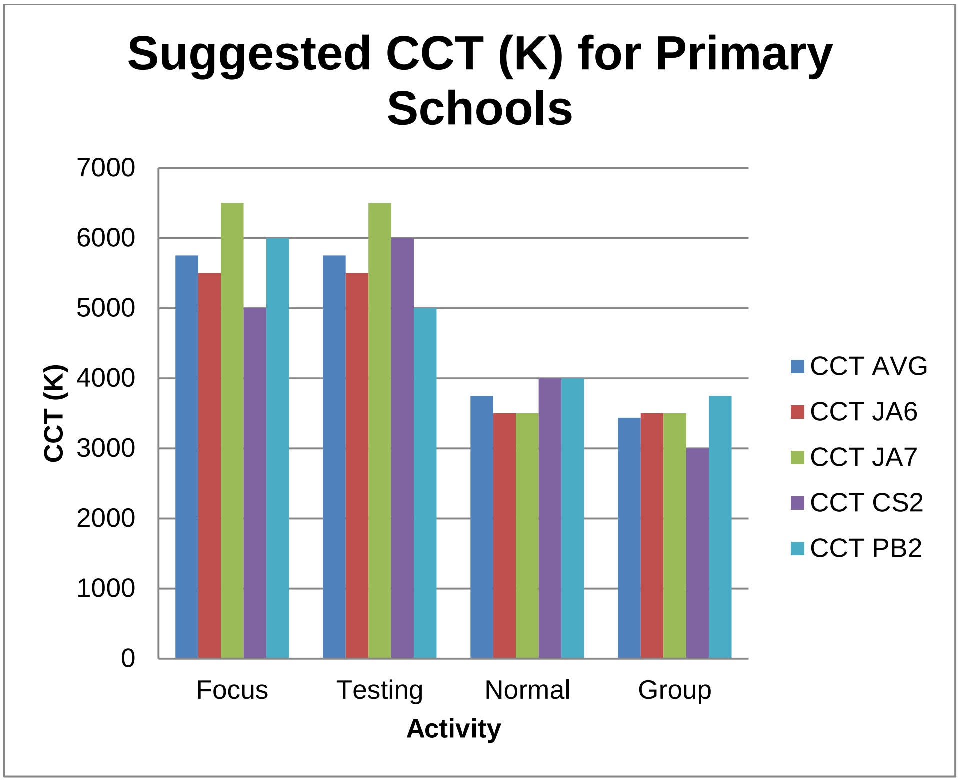
The focus of the majority of the research concerning lights effect on students has been performed on children in grades 3 through 5 [1, 3, 5-6, 9, 14-18, 29-30, 33-34]. This is likely due to the fact that at this age students tend to stay in one classroom all day instead of shifting rooms like older aged students. The goal of dynamic lighting in schools is not to replicate outdoor lighting but instead use the varied conditions of lighting to produce desired effects such as increased focus.

7.2.1.1 Suggested Routine for Primary Schools

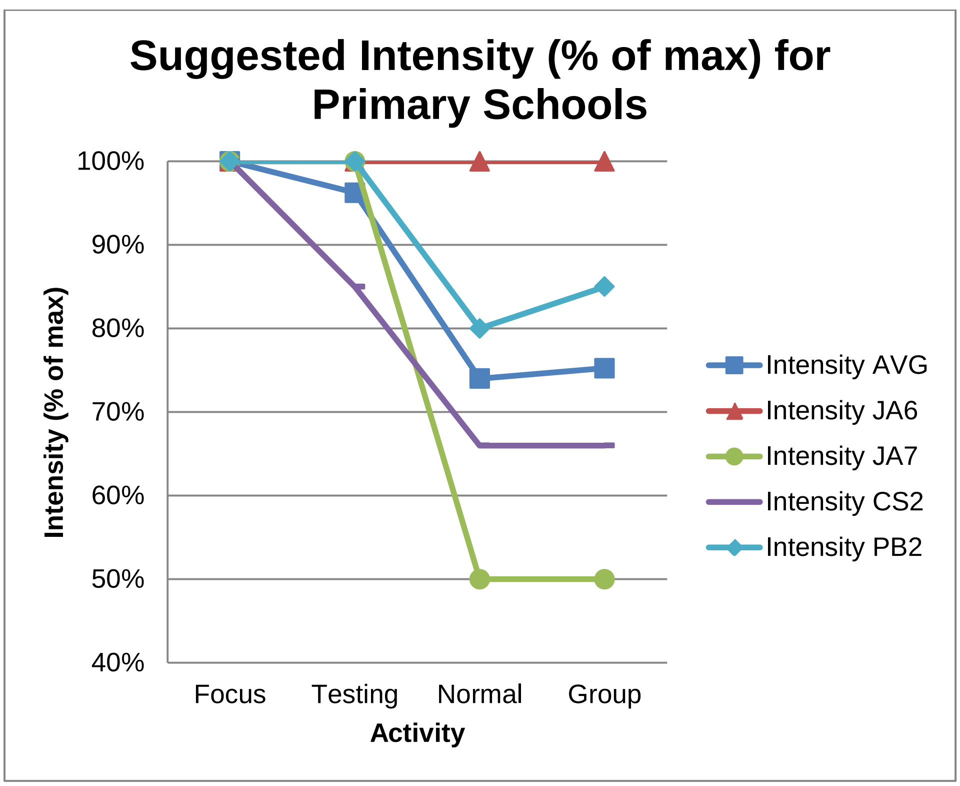
Unlike health industries where the goal of dynamic lighting is to replicate a 24 hour daylight routine, educational lighting is typically tuned by activity. This suggested routine has been adapted for four types of learning situations: Focus, Testing, Normal, and Group.

- Focus lighting: to be used when covering complicated material; it can also be used to refocus distracted students.
- Testing lighting: similar to focus but the intensity level is reduced; allows for focus but also creative thinking.
- Normal lighting: used for standard activities.
- Group lighting: to be used in more interactive segments, optimized for co-operation and creativity.

Using resources that provided the clearest indication of lighting levels throughout the day [17-18, 29, 33] the following two graphs were generated.

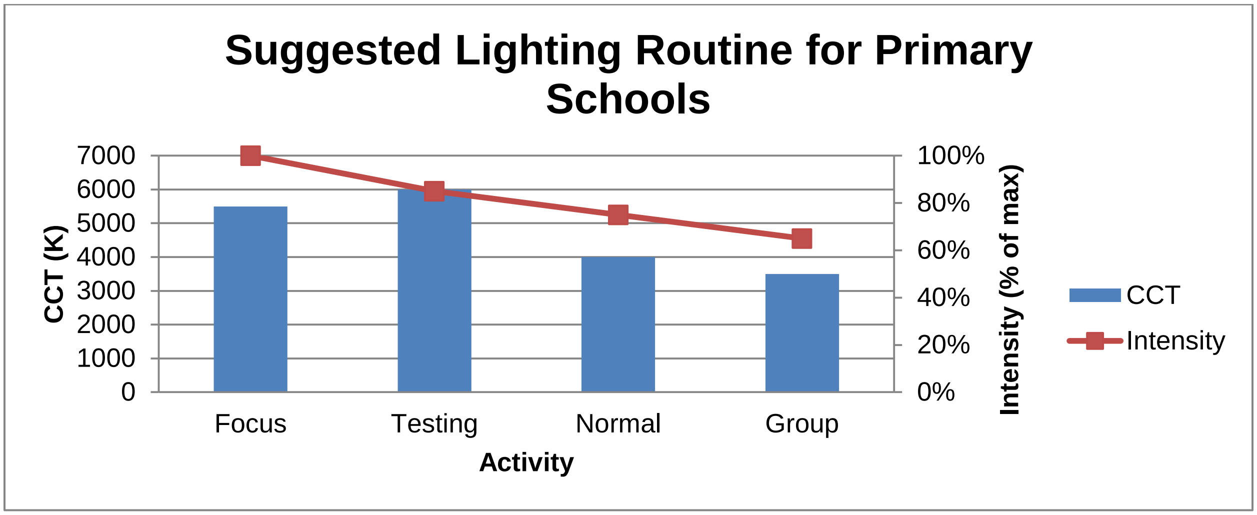


Suggested CCT (K) for Primary Schools



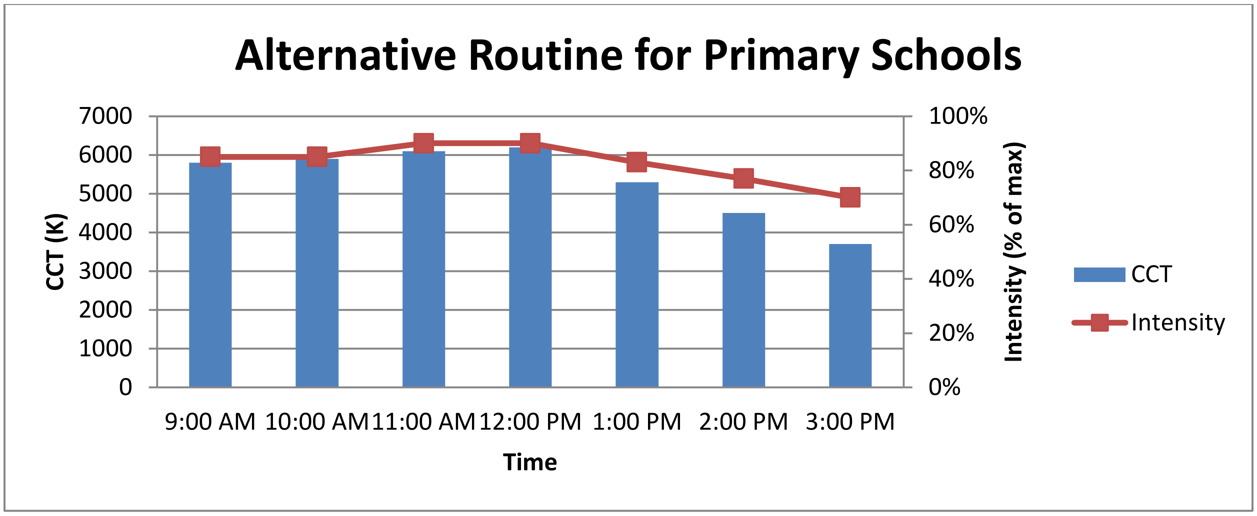
Suggested Intensity (% of max) for Primary Schools

The above graphs show very little difference between Focus and Testing, they also show very little difference between Normal and Group. Evidence shows that under increased intensity lighting, creativity tends to decrease, because of this, adjustments were made to testing and group work to allow for more creative thought during those activities [2]. Using educational considerations garnered from other sources [1, 3, 5-6, 9, 14-16, 29-30, 34] as well as the above graphical information, a final suggested lighting routine was developed.



Suggested Lighting Routine for Primary Schools

Teachers would adjust the lighting throughout the school day to accommodate the situation. Although this research was performed on younger children the results would carry over for older students as well. Alternatively the routine below uses values extrapolated from "Suggested Routine for Extended Care Facilities" for use in a classroom where dynamic changes are not possible. This routine would also have positive effects but instead of changing by activity this routine works to simulate outdoor light to achieve positive effects.



Alternative Lighting Routine for Primary Schools

7.1.2.2 Energy Savings for Primary Schools

Energy savings were calculated using a comparison between similar lighting systems; the standard (non tunable) Philips Boldplay LED and the tunable white Philips Boldplay LED [8]. The standard system used constant levels of intensity and CCT over the course of the school week while the tunable white system followed the suggested routine over the same period. A power savings of less than 5% was found when using the tunable white system with the suggested routine over the standard system.

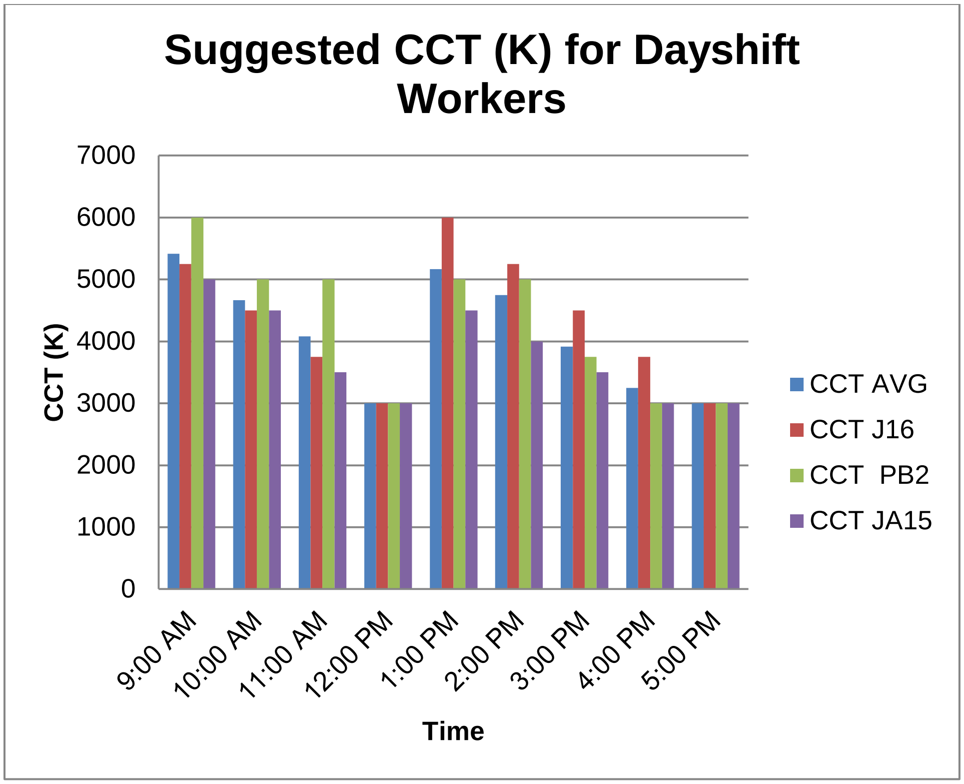
7.3 Work

7.3.1 Dayshift Workers

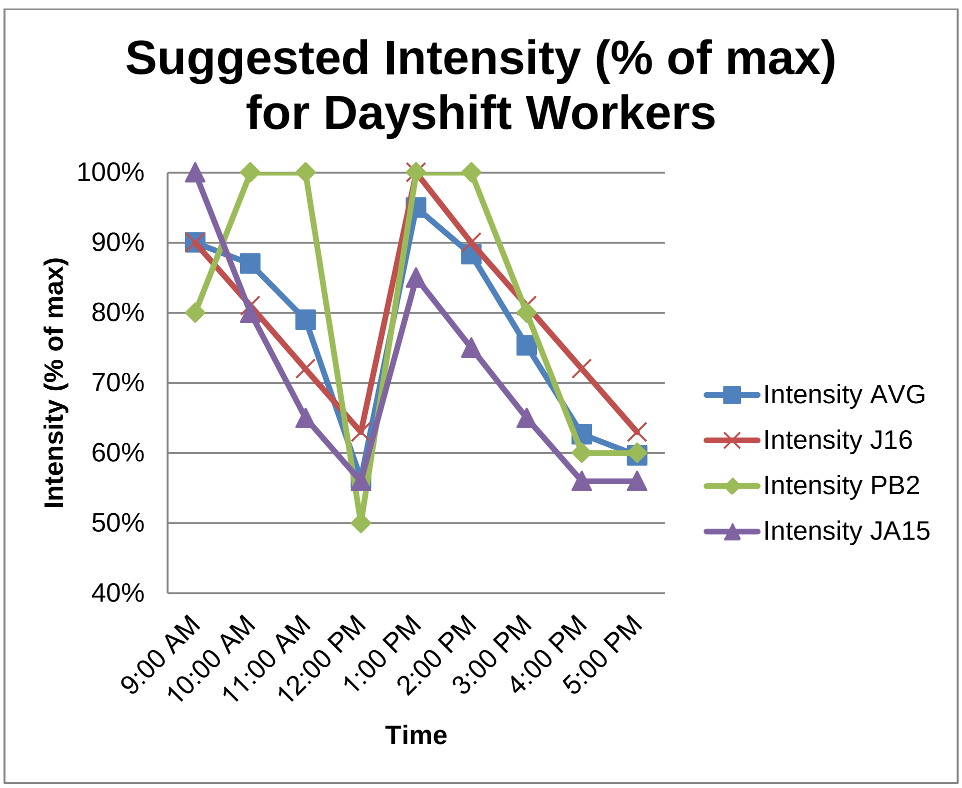
The majority of the North America's population work hours between 8 AM and 6 PM. Due to most workers being kept inside under constant lighting levels throughout the day, circadian rhythm disruption can tend to occur [1-3, 5-6, 9, 14-15, 24-27, 33-34]. By making changes to the lighting routine dayshift workers can increase their overall work while also increasing their overall sleep quality.

7.3.1.1 Suggested Routines for Dayshift Workers

The goal of lighting for dayshift workers is to provide optimal lighting to complete work while also achieving maximum focus at key points in the day. Using resources that provided the clearest indication of lighting levels throughout the day [2, 26, 33] the following two graphs were generated.

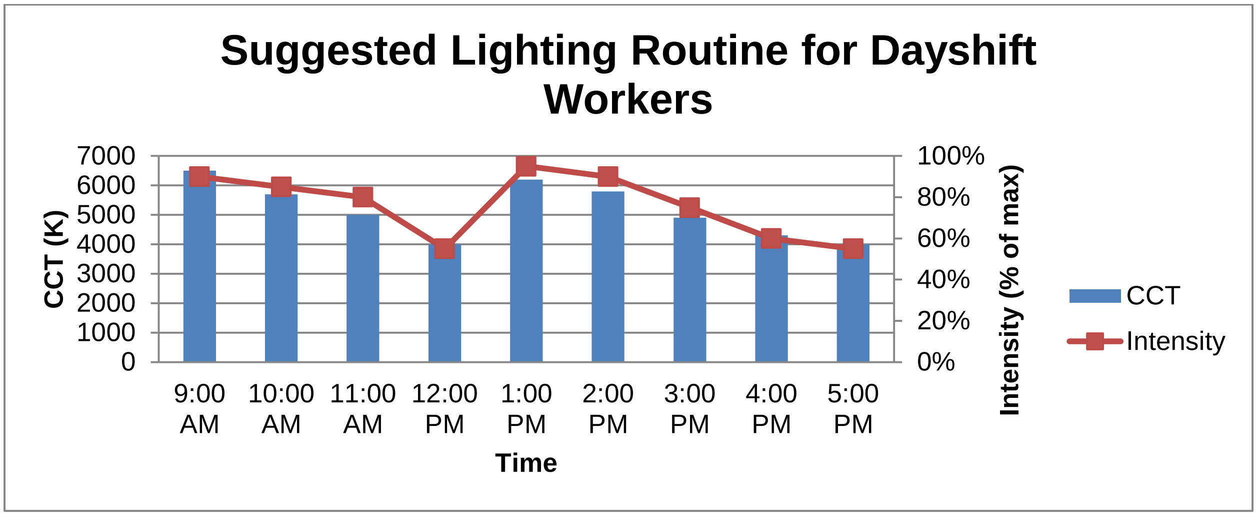


Suggested CCT (K) for Dayshift Workers



Suggested Intensity (% of max) for Dayshift Workers

The above graphs show high levels of CCT and intensity early in the day, a decrease towards noon, a spike at 1 PM, and a decrease towards 5 PM. This routine allows for increased productivity early in the day and a boost of alertness after lunch to also increase productivity. Lower level CCT and intensity lighting is provided after meal break and towards the end of the shift to allow workers to relax and unwind. By reducing the light levels towards the end of the day workers melatonin will be produced earlier resulting in increased overall sleep quality. Using educational considerations garnered from other sources [1, 3, 5-6, 9, 14-15, 24-25, 27, 34] as well as the above graphical information, a final suggested lighting routine was developed.



Suggested Lighting Routine for Dayshift Workers

This routine can be adjusted to fit any work hours, not strictly 9 AM – 5 PM. All CCT values were increased by 1000 K. Because the reviewed tests were constrained by the technology used at the time, it was suggested to increase the maximum CCT levels when the techonology was available. For meeting rooms a lighting routine similar to that of the "Suggested Routine for Primary Students" could also be implemented. Adjustments could be made depending on the type of meeting; a presentation could use Focus and a brainstorming session could use Group.

7.3.1.2 Energy Savings for Dayshift Workers

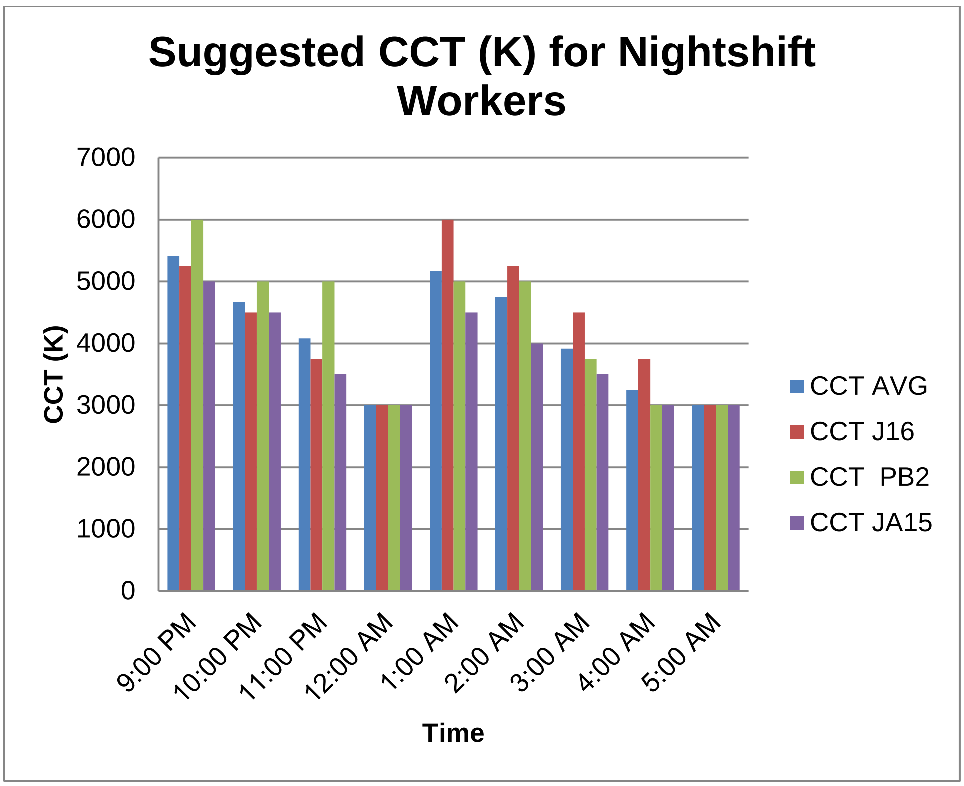
Energy savings were calculated using a comparison between similar lighting systems; the standard (non tunable) Philips Boldplay LED and the tunable white Philips Boldplay LED [8]. The standard system used constant levels of intensity and CCT over the course of an average work shift while the tunable white system followed the suggested routine over the same period. A power savings of less than 5% was found when using the tunable white system with the suggested routine over the standard system.

7.3.2 Nightshift Workers

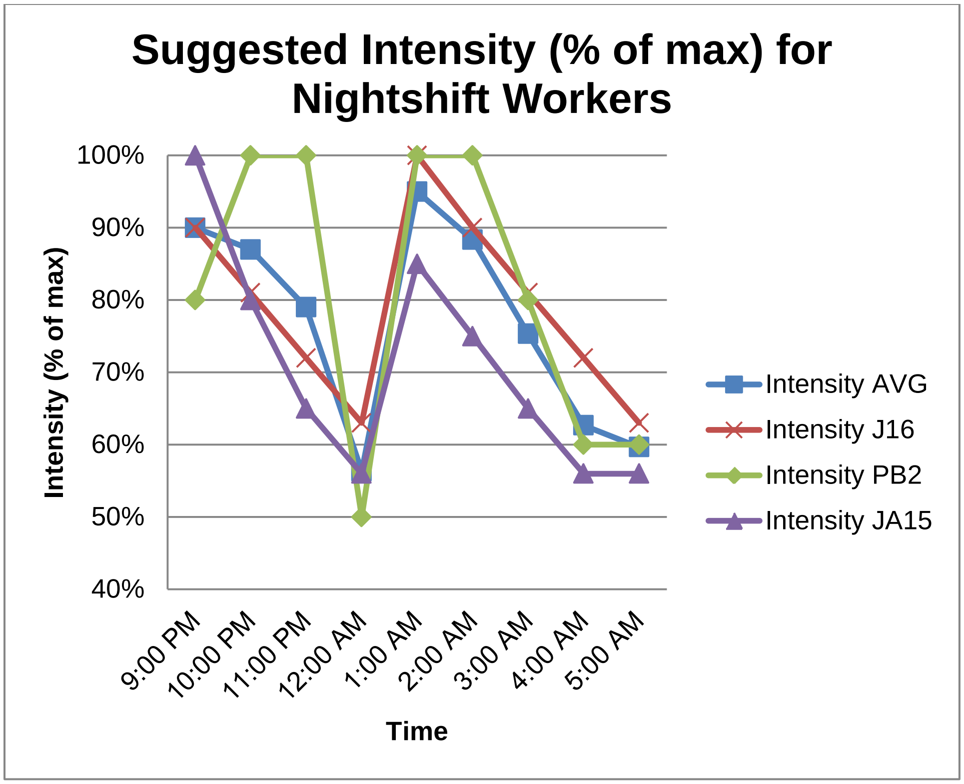
Nightshift workers are at the highest risk of to suffer symptoms caused by circadian rhythm disruption. In order to reduce these effects adjustments to the provided lighting is required. Since nightshift workers do not have access to daylight to reset their circadian rhythms this job is left solely to electric lighting.

7.3.2.1 Suggested Routines for Nightshift Workers (Long Term)

The suggested routine for nightshift workers is the same as the routine suggested for dayshift workers [1-3, 5-6, 9, 14-15, 24-27, 33-34]. In order for nightshift workers to avoid the effects of circadian rhythm disruption nightshift workers must be exposed to the same type of light as those who work the dayshift. Before this routine is implemented it is suggested that a lighting routine be developed to adapt nightshift workers circadian rhythms to be the inverse of those of dayshift workers.

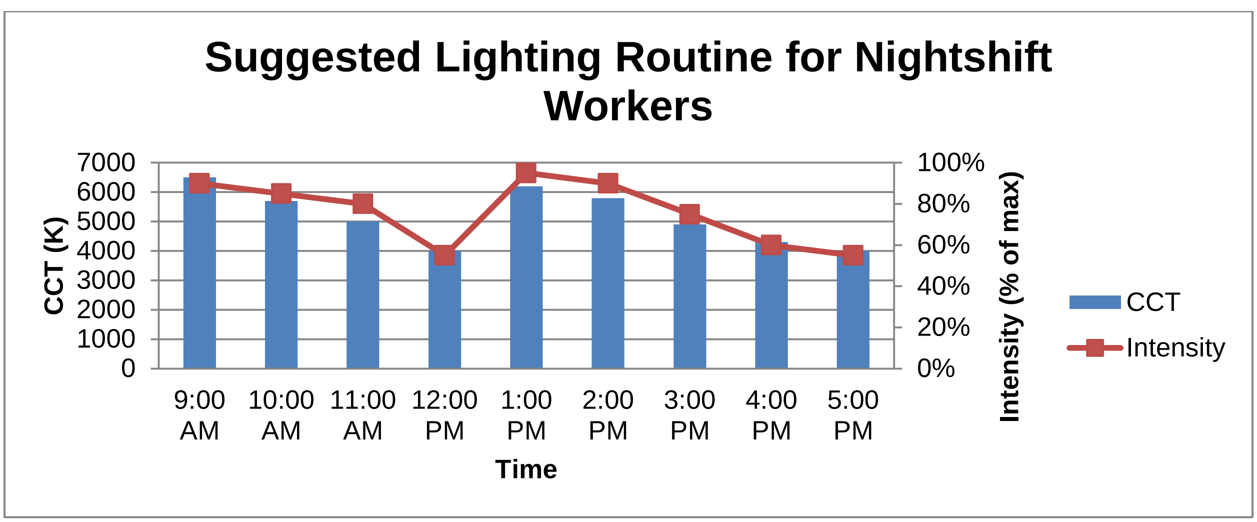


Suggested CCT (K) for Nightshift Workers



Suggested Intensity (% of max) for Nightshift Workers

Like the previous section, the above graphs show high levels of CCT and intensity early in the shift, a decrease towards midshift, a spike at 1 AM, and a decrease towards 5 AM. This routine allows for increased productivity early in the shift and a boost of alertness after the meal break to also increase productivity. Lower level CCT and intensity lighting is provided after meal break and towards the end of the shift to allow workers to relax and unwind. Using educational considerations garnered from other sources [1, 3, 5-6, 9, 14-15, 24-25, 27, 34] as well as the above graphical information, a final suggested lighting routine was developed.



Suggested Lighting Routine for Nightshift Workers

This routine can be adjusted to coincide with other night shift hours, not strictly 9 PM – 5 AM. Like dayshift work, meeting rooms could use a lighting routine similar to that of the "Suggested Routine for Primary Students". Adjustments could be made depending on the type of meeting; a presentation could use Focus and a brainstorming session could use Group. It is very important that nightshift workers block out daylight on their way home from work; this can be done with bluelight blocker glasses. Routines that use red light instead of the suggested routine are being researched. The alerting effect of the red light may be able to provide the same results but further research is needed to confirm this.

7.3.2.2 Energy Savings for Nightshift Workers

Energy savings were calculated using a comparison between similar lighting systems; the standard (non tunable) Philips Boldplay LED and the tunable white Philips Boldplay LED [8]. The standard system used constant levels of intensity and CCT over the course of 24 hours while the tunable white system followed the suggested routine over a 24 hour period. A power savings of less than 5% was found when using the tunable white system with the suggested routine over the standard system.

8.0 Conclusions

The effect of CCT and luminance on various sectors and the effects they have on occupants have been researched and the positive effects found have paved the way for dynamic lighting. Through dynamic lighting routines people's circadian rhythms have been able to be adjusted back to levels that result in better sleep and overall health. Dynamic lighting may also be used to affect circadian rhythms to produce desired behaviours.

High CCT and luminance level lighting were found to have a focusing effect both in classrooms and in workplaces. This was expected as midday conditions exhibit high level CCT and luminance and this is when alertness levels are at their highest, cortisol levels are also high at this time of day. Under low CCT and luminance level lighting a calming effect was seen in classrooms and hospital patients. This was also expected due to these levels of lighting simulating times of day when melatonin levels were higher and alertness levels were lower.

Knowing both of these effects combined with the information necessary to replicate daylight conditions, various suggested routines were suggested to increase the overall wellness or effectiveness levels of the occupants. Energy savings were only found to be significant in the health sector. However the non-energy benefits of dynamic lighting should be considered when thinking of adopting a new lighting system.

More research is still continuing in this field and as this research comes in new and exciting advantages of dynamic lighting are bound to be found.

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