IMPACTS OF TUNING AMBIENT ILLUMINATION ON SLEEP QUALITY, MOOD, AND COGNITIVE PERFORMANCE IN OLDER ADULTS

BY

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DISSERTATION

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ABSTRACT

Population aging is one of the most urgent demographic matters of the 21st century. As a person ages, health expenses usually rise so as to increase vulnerability, especially where social and economic protections are lacking. Thus, the need for increased research on factors to support late-life health is more crucial than ever before. Older adults are at higher risk for sleep dysfunctions, depression, and cognitive impairments as aging is associated with several physical, biological, and social changes. Proper lighting condition is one of the non-pharmacological solutions that could potentially play an important role in improving health and well-being in older adults. In addition to the visual impact, light causes extensive emotional and biological aspects that influence circadian rhythms, sleep, mood, and cognitive performance.

Appropriate lighting design should consider both visual and non-visual effects of light. Research suggests that a healthy lighting condition should provide individuals with exposure to light with the right spectrum and illuminance level at the right time; namely, lighting conditions during the daytime and nighttime are to be different. Hence, designers need to have a whole-day approach towards lighting. Timing and duration of exposure are two factors that are usually not considered in the process of lighting design. This study aimed to evaluate the effects of two whole-day ambient lighting interventions on sleep quality, mood, and cognitive performance in older adults. Both lighting interventions were designed to create a direct/indirect ambient illumination that provided a high illuminance level (500 lux) in the morning (8:00 – 12:00), followed by gradually lower illumination throughout the rest of the day, reaching 100 lux in the evening (after 20:00). One lighting condition (L1) delivered a constant Correlated Color Temperature (CCT) of 2700ºK. In the other lighting condition (L2), the CCT was changing in a range of 6500ºK – 2700ºK from morning towards evening. We recruited 21 healthy older adults (mean age = 78.81 years; 16

females and 5 males), from three senior residential communities in Saint Louis, Missouri, and Chicago, Illinois. Lights were placed in the living rooms of the participants around their most favorite seating spot for 18 days. The study was designed as a counterbalanced crossover experiment, with two baseline measurements (before and after the interventions) and 18 days of interventions. Participants were exposed to each lighting condition for nine days. We employed wrist-worn actigraphy measures (41 days) and standardized measures of sleep quality, mood, and cognitive performance before, during, and after interventions. As hypothesized, we found improvements in objective and subjective sleep metrics, mood, and cognitive functions after exposure to both lighting conditions; there were significantly more improvements for the L2 intervention. This research found promising evidence that a whole-day lighting scheme with varying intensity and CCT, tailored to meet circadian and visual performance needs of older adults, could be an effective design solution to create a healthy and healing living environment in senior livings and promote sleep, mood, cognitive functions, and hence the quality of life in their senior residents.

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TABLE OF CONTENTS

GLOSSARY OF ABBREVIATIONS

ADRD – Alzheimer disease and related dementia

ANOVA – analysis of variances

AS – adopted standard

AT – active time

B1 – Baseline 1 (pre-assessment)

B2 – Baseline 2 (post-assessment)

Baseline – mean of Baseline 1 and Baseline 2

BLT – bright light therapy

CCT – correlated color temperature

DSD – daytime sleep Duration measured by Actigraphy

DSST – digit symbol substitution test

DV – dependent variable

EEG – electroencephalography

ES – the European Standard for Light and Lighting of Indoor Work Places

ESS – Epworth sleepiness scale

GDS – geriatric depression scale

HQDLR – high quality daylighting room

IDV – independent variable

ipRGC – intrinsically photoreceptive retinal ganglion cell

KSS – Karolinska sleepiness scale

L1 – lighting intervention 1 (varying intensity and constant color of 2700ºK)

L2 – lighting intervention 2 (varying intensity and color)

LQDLR – low quality daylighting room

MMSE – mini-mental state examination

NA – negative affects

NSD – nighttime Sleep Duration measured by Actigraphy

PA – positive affects

PANAS – positive and negative affects scale

PROMIS – the patient-reported outcomes measurement information system

PSQI – Pittsburgh sleep quality index

QL – health-related quality of life

REM – rapid eye movements

RM ANOVA – repeated measures analysis of variances

RT – rest time

SCN – suprachiasmatic nucleus or nuclei

SDist – sleep disturbance

SE – sleep efficiency measured by actigraphy

SF-8 – Short Form-8

SOL – sleep onset latency measured by actigraphy

SPD – spectral power distribution

SQ – sleep quality

SRImp – sleep-related impairments

TMT-A – trail making test A

TMT-B – trail making test B

TWL – tunable white lights

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: GENERAL INTRODUCTION

1.1. Background to the Problem

According to the United Nations (2015), population aging is one of the most urgent demographic matters of the 21st century. As life expectancy increases, the population of older people (over age 60) has risen, both in numbers and as a proportion of the whole population. With around 205 million in 1950, older people formed just less than 5% of the world's population. In 2015, there were around 900 million older people (12.3%). This number is expected to reach 2 billion, about 21.5% of the world population, by 2050. It is anticipated that by 2050, the percentage of people over the age of 60 will exceed that of 15-years-olds and younger (Christensen et al., 2009). As a person ages, health expenses usually rise so as to increase vulnerability, especially where social and economic protections are lacking. The prevalence of age-related diseases, including atherosclerosis, neoplastic disease, Alzheimer's, and Parkinson's, can create a societal burden. Thus, the need for increased research on factors to support late-life health is more crucial than ever before.

Among many factors, sleep plays a critical role in older adults' quality of life. Although there are many complaints about sleep problems by older people, there has not been proportionate attention researching these complaints. Research shows that more than 50% of institutionalized older adults complain about at least one chronic sleep disorder (Monjan, 2013). Chronic insomnia impacts about a third of the senior population in the United States (Scholtens, van Munster, van Kempen, & de Rooij, 2016a). Failure to address the root problem and to find an effective and applicable solution contributes to increasing prescription and over-the-counter sleep-aid use. Among other issues, poor sleep quality among older adults is associated with higher levels of depression (Chang et al., 2014), anxiety (Marcks, Weisberg, Edelen, & Keller, 2010) and falls

(Stone et al. 2008), as well as lower levels of cognitive and memory performance (Niu et al., 2016; Waller et al., 2016; Yaffe, Falvey, & Hoang, 2014), and well-being (Ribeiro Do Valle, Valle, Valle, & Fior, 2013). Furthermore, poor sleep quality increases seniors' odds of developing dementia (Tranah et al., 2011). Thus, poor sleep is a risk factor for lower quality of life for seniors.

Despite the importance of sleep, physicians are not necessarily trained to recognize sleep disorders in seniors. Moreover, they might assume that sleep disorders are an inevitable part of aging, an assumption increasingly questioned by many researchers (Harrington & Lee-Chiong, 2007; Monjan, 2013). There is now firm evidence that it is not only age-related processes that bring about sleep disorders but also environment and lifestyle factors.

Therefore, we need to move beyond research that merely aims to find some pharmacological solutions to improve sleep in older adults. Instead, research that focuses on the environmental needs of older adults and the impacts of physical environments on their lifestyle, health, and well-being is needed.

This chapter will discuss circadian rhythms, the circadian effects of light, lighting design for circadian rhythms, and age-related changes in circadian rhythms and visual systems. Then, it will provide an overview of this research including research objectives, aims, rationale and need for the study, and studies assumptions and limitations.

1.2. Circadian Rhythms: Overview of Mechanisms and Processes

As the earth rotates around its axis, it provides a consistent and predictable 24-hour cycle of the light and dark over its surface. All eukaryotic organisms in the world adapt to this unstoppable daily pattern by developing biological rhythms that repeat at approximately 24-hour intervals (Figueiro, 2013). Mammals manifest this adaptation through the time-based organization of behavior into periods of sleep and wake or rest and activity. Mammals that use vision as their primary sense to perceive the surrounding environment typically have a diurnal pattern (active during the day and sleep at night). In contrast, mammals that employ audition and olfaction as primary senses are nocturnal (active at night and sleep during the day) (Moore, 1997).

These biological rhythms of sleep and wake are called circadian rhythms. The word circadian derives from two Latin words, “circa” meaning approximately and “diem” meaning day, thus circadian rhythm means a rhythm that repeats itself at about every 24 hours.

Circadian rhythms are produced and synchronized by a specific neural system called the Circadian timing system (CTS). CTS is an internal clock (pacemaker) located in the Suprachiasmatic Nuclei (SCN). This internal clock is responsible for providing an extensive series of biological cycles including metabolism, hormone secretion, and cardiac function (Kondratova & Kondratov, 2012; Moore, 1997). It enables the organism to entrain these cycles to its particular photic function (diurnal or nocturnal) and location on Earth (Figueiro, 2013).

Since SCN is a self-sustaining oscillator, it can keep its daily activity patterns for weeks while isolated and cultivated. It means that if humans or animals are kept in an environment without time cues, the cycles of rest and activity behavior and consequently, the rhythms remain but with a period that is different from 24 hours. It is now well-known that SCN in humans has a cycle which is slightly longer than 24 hours. To ensure that humans’ behavioral and physiological rhythms are in synchrony with the daily rhythms in the environment, this cycle should be reset and synchronized regularly. This process is called entrainment.

In humans, two rhythms are commonly used to estimate the timing of circadian rhythms: the circadian rhythms of core body temperature and the circadian rhythms of the melatonin production. Melatonin is a hormone produced by pineal gland in human brain and fluctuates with circadian rhythms (Crowley & Eastman, 2017). Levels of melatonin have a positive correlation with sleep feeling. In other word, melatonin levels increase in the evening near individual's sleep time and stay consistent during the nighttime and while one is asleep. Early in the morning and near one's habitual wake-up time, melatonin levels decline and reach to their nadir during the daytime (Lewy, Lefler, Emens, & Bauer, 2006). In addition, in a normally entrained condition, sleep timing is significantly related to the timing of the circadian rhythms of body temperature with a negative correlation (Lack, Gradisar, Van Someren, Wright, & Lushington, 2008). The minimum core body temperature occurs 5-6 hours after one's habitual sleep time while sleepiness circadian rhythms are at their maximum level (such as melatonin level) (Czeisler et al., 1992). One's habitual wake up time happens 1-3 hours after minimum core body temperature while it begins to rise (Lack & Lushington, 1996).

Circadian rhythms govern the internal coordination of various oscillators within and among several organ systems to improve the overall health of an organism and provide it with the optimal response to its environment (Gery & Koeffler, 2010; Green, Takahashi, & Bass, 2008; Kyriacou & Hastings, 2010; M. E. Young, 2006). A large body of research have proven that dysfunction of circadian system in humans negatively influences humans' health and well-being (Carvalho-Bos, Riemersma-van der Lek, Waterhouse, Reilly, & Van Someren, 2007; Cerny & Penhaker, 2009; Marcks et al., 2010) and increases the risk of metabolic syndromes, cardiovascular diseases, and cancer, as well as mental illnesses such as depression (Mcclung, 2011) and anxiety (Ramsawh, Stein, Belik, Jacobi, & Sareen, 2009).

1.3. Light and Circadian Rhythms

Light is a fundamental need for humans. It is now well-established that light is not only necessary to fulfill adequately visual tasks, but it also has several powerful non-visual effects on humans such as sleep quality, mood, and behavior through neuroendocrinal pathways other than the visual system. Light is the main stimulus that regulates circadian rhythms, as well as seasonal cycles and neuroendocrine responses in many species including humans (Corbett, Middleton, & Arendt, 2012). In fact, light is a rhythm regulator or Zeitgeber (lit. "time giver"). Zeitgeber is an environmental agent or event that provides the cue for setting or resetting a biological clock. The light received through signals from a recently discovered class of photoreceptors in the retina, referred to as Intrinsically Photosensitive Retinal Ganglion Cells (ipRGCs) (Gooley, Lu, Chou, Scammell, & Saper, 2001; Hannibal et al., 2001; Schantz, Provencio, & Foster, 2000) synchronizes the rhythmic activity of the SCN. There are several clinical studies that have demonstrated that light therapy is effective for treating seasonal affective disorders, sleep problems, and circadian disruptions (Ashkenazy, Einat, & Kronfeld-Schor, 2009; Bellia, Bisegna, & Spada, 2011; Bellia, Pedace, & Barbato, 2013; Eagles, 2009).

Light could be broken down into five main characteristics: (1) quantity, (2) spectrum, (3) distribution, (4) duration of exposure, and (5) timing. These light characteristics influence the circadian system differently from the way they influence the visual system.

(1) Quantity: Higher level of illumination (or light quantity or intensity) is required to impact the circadian system to stimulate than the visual system. The human visual system operates across a large range of light levels from starlight to sunlight, or approximately from 1lx to 120,000 lx. For instance, while the visual performance is near its maximum at a typical illuminance level of 500 lx (on the working plane), this amount of light is only near the threshold of circadian system activation (Rea & Figuero, 2011). Hence, relatively low light levels (rarely brighter than 300 lx), which are typical of indoor lighting, cannot bring about significant circadian effects (Bellia et al., 2011; Daurat et al., 1993; Kozakov, Franke, & Scho, 2008; van Bommel, 2006).

(2) Spectrum: While the spectral response of the visual system has a peak sensitivity of 555nm (yellow-green light), the spectral response of the ipRGCs and hence circadian system is most sensitive short light wavelength with a peak at approximately 490nm (blue light) (Corbett et al., 2012).

(3) Distribution: Whereas the visual system deals mostly with the intensity of light falling or reflecting off a given surface, circadian rhythm is influenced primarily by light falling onto the eyes. Hence, the illuminance levels on the vertical plane and at the eye level matter more so than those on the working plane.

(4) Duration of Exposure: It is estimated that the visual system can fully process light as short as 80 milliseconds. In contrast, it takes several minutes (usually more than 30 minutes) for the circadian system to respond to a light exposure (Rea, Figueiro, & Bullough, 2002). For instance, 50% melatonin suppression by a "white" light with the CCT of 5500K and 1000 lx corneal intensity at night took about 33 minutes for a circadian response (McIntyre, Norman, Burrowes, & Armstrong, 1989).

(5) Timing: The minimum amount of light needed for the human visual system to perform varies slightly over the 24-hour day (Tassi, Pellerin, Moessinger, Hoeft, & Muzet, 2000). This means that visual performance does not depend on the time of the day. In contrast, the circadian system's response to a lighting condition is strongly related to the timing of the light exposure. Light can have a small or large impact on the circadian system, which result in either phase advance or phase delay, depending upon when during the circadian cycle the eyes detect the light (Rea & Figuero, 2011).

Another influential factor related to the impacts of lighting on the circadian clock is the history of light exposure, which is not a characteristic of the light itself. In fact, the sensitivity of the circadian system to light appears to change depending upon previous light exposures. For example, a person who had been in a dim room all day long would show greater response to a given light at night (e.g., more melatonin suppression, greater alertness levels) than would an individual who had experienced very high sunlight levels during the day (Hebert, Martin, Lee, & Eastman, 2002).

Much research has examined the effectiveness of various light characteristics on human circadian systems and sleep quality, with a focus on quantity and spectrum. Studies reported a significant association between the quantity of light exposure and sleep quality and/or related parameters in all age groups. In a cross-sectional survey on 72 office workers carried out by Kozaki et al. (2012), office workers who spent most of their working hours inside the building were exposed to less illuminance level (490 – 550 lux) and reported a significantly higher levels of sleep difficulties compared to those work outside the office and were exposed to higher lighting levels (700 – 750 lux) (Kozaki, Miura, Takahashi, & Yasukouchi, 2012).

Spectral distribution of the light source is another light characteristic evaluated with respect to sleep quality and other related parameters. In most studies, Correlated Color Temperature (CCT) has been considered as an indicator of the spectral distribution. However, it should be noted that sometimes CCT is not a precise measure to assess the actual spectrum of the emitted light. However, studies failed to address the difference between CCT and spectrum in relation to the non-visual effects of light. It has been reported that exposure to blue-enriched light (usually CCT of 5000ºK or above) shift the circadian system and is associated with melatonin suppression. However, reddish and yellowish light (usually CCT of 3000ºK or lower) with a typical light intensity (< 300 lx) does not show any impacts on circadian systems and hence sleep quality. Kraneburg et al. (2017) studied the influence of 7 various CCTs (1600ºK, 1950ºK, 2750ºK, 3900ºK, 6100ºK, 7100 ºK and 14000ºK, 200 lux) on 17 subjects (20 – 27 years old) in two experiments that were conducted during the daytime. The findings showed that the CCT of the light source significantly affected melatonin suppression in adult subjects where higher CCTs were associated with more melatonin suppression. Suppression was almost negligible under the CCTs that were less than 2750ºK. No information with regards to spectrum of the tested lighting conditions were provided (Kraneburg, Franke, Methling, & Griefahn, 2017). This revealed that, depending on the spectrum, the CCT of the light source might be an influential factor in the circadian effects of light.

In addition to intensity and spectrum, timing of light exposure is among the variables evaluated in the literature. Timing plays a fundamental role in designing the optimal lighting solution as circadian system response to a specific lighting condition varies in the daytime compared to nighttime. For instance, bright blue light before body temperature nadir delays circadian phase and after nadir advances it (White, Ancoli-Israel, & Wilson, 2013). A cross-sectional study by Auger et al. (2012) on 38 subjects (10 – 18 years) suggested that later sleep onset times is associated with increased evening light exposure (Auger, Burgess, Dierkhising, G, & Slocumb, 2012). The optimal time for delivering lighting with proper intensity and spectrum to stimulate circadian rhythms depends on an individual's circadian cycle and relation to a model rhythm that is in sync with the natural light/dark cycle (White et al., 2013). However, in general, research on the association between lighting and sleep quality among different age groups recommends that to meet human biological needs, an optimum environmental lighting design should provide bright blue light during the daytime (usually early in the morning) and then both illumination and CCT are to decrease gradually towards night to deliver a dim and yellow light.

As previously mentioned, duration of exposure is another influential parameter on how a lighting condition impacts circadian rhythms and sleep. This factor is usually evaluated in conjunction with lighting intensity and/or spectrum. In general, it is stated that longer duration of exposure is required for lower light intensities to obtain the same circadian effect. For instance, it has been reported that 2 hours of exposure to blue enriched light with 2500 lux intensity have the same impact as 30 minutes of exposure to the same light with 10000 lux intensity (Turner, Van Someren, & Mainster, 2010). Also, 50% melatonin suppression can occur after 28 minutes of exposure to a 3000 lux lighting condition with CCT of 5500 K or 33 minutes of exposure to the same light but with 1000 lux intensity (Turner et al., 2010). However, duration of exposure is effective only if sufficient light intensity is available. For instance, for any duration of exposure, we can never obtain 50% melatonin suppression with 100 lux intensity (Rea & Figueiro, 2016).

Spatial distribution of light is the parameter that, unfortunately, has been neglected in the literature. No study has assessed the impacts of spatial distribution of light on circadian system or sleep. Moreover, the studies on other light parameters rarely provide any exact information about the distribution of the light intervention and tested environment. These studies usually limit their description of lighting to illuminance levels (most of the time on the working plane) and/or CCT which are not sufficient to comprehend lighting distributions. Therefore, this should be the subject of future studies.

As mentioned, all these characteristics play a significant role on how a lighting condition impacts the human circadian system. Unfortunately, so far, no study has had the intention to compare the effectiveness of these parameters (e.g., CCT versus intensity or timing versus duration of exposure). Studies usually examined them as separate variables in comparison to a control condition or combined them in one intervention and evaluated their collective impacts. However, by reviewing literature and comparing the findings, we may conclude that light intensity (or quantity) has the highest effect on circadian system and therefore sleep quality. In fact, studies that examined the impacts of light intensity showed more significant and firmed results compared to those that investigated other parameters. After intensity, timing and duration of exposure seem to be the most effective ones due to specific behavior of our circadian system towards lighting. For instance, even very bright light condition cannot influence our circadian system in five minutes. Also, our circadian system's response to the same lighting condition is completely different in the morning from evening time. CCT or spectrum comes after these three characteristics. Although, the effects of light spectrum on sleep and circadian system is evident, spectrum is influential only when a certain amount of light level is available. For instance, exposure to a blue-enriched white light (>6500ºK) with 100 lux corneal intensity does not provide enough circadian stimulus (obtained CS value = 0.16 while at least 0.3 is recommended). We need at least the corneal intensity of 250 lux to make sure that this specific lighting has circadian effects (CS value for the 250 lux = 0.31) (calculated by the CS calculation tool which will be explained later).

1.4. Lighting Design for Circadian Rhythms Stimulation

Currently, there is no agreement for the proper minimum light level threshold or optimum spectrum to ensure effective circadian stimulus in buildings, or for the duration at which the effects of light exposure saturate. However, we can extract the following principles from the literature related to circadian lighting design:

- High levels of bright blue illuminance (high intensity + high CCT (or blue-enriched spectrum)) early in the morning to phase advance the circadian clock.

- Medium to high levels of illuminance (medium to high intensity + medium CCT (neutral white)) in the afternoon to increase alertness without exerting substantial phase shifting effects on the circadian clock
- Dimmed illumination (low intensity + low CCT (yellowish white light)) in the evening to avoid disruption of circadian rhythms and unwanted phase delay.

Given these principles, one can conclude that light emitted from the sun possesses all required characteristics for stimulating and synchronizing humans' circadian system. The variable characteristics of daylight offer individuals illumination with proper intensity and spectrum at the best time. Many studies have demonstrated that daylight exposure significantly improves mental and physical health, sleep, physical activity, and performance (Boubekri et al., 2014; Hoffmann et al., 2008; Mirrahimi, Ibrahim, & Surat, 2012; Wallace-Guy et al., 2002). However, due to inconsistent weather conditions, improper architectural design, and amount of time spent indoors, the natural regulating effects of daylighting are not always available; therefore, the standards for electrical lighting systems must be quite high to replace the important influences of natural light on circadian rhythms.

In the past decade, lighting industry has focused on finding a lighting technology to simulate daylighting indoors. Tunable White Lights (TWL) is a recent lighting technology invented to serve this purpose. TWLs enables alternations of lighting intensity and CCT to simulate daylighting in indoor environments and suit individual and environmental needs. It is hypothesized that this new lighting technology provides occupants with a healing lighting condition that improves their sleep quality, well-being, and overall health; however, no firm scientific evidence has been demonstrated.

1.5. Circadian Lighting Metrics

Circadian lighting metrics emerged to study the potential circadian effects of various lighting conditions through quantifying light exposure in biologically meaningful units. These metrics enable the measurement and circadian performance evaluation of existing lighting conditions as well as design of new ones.

Several researchers have proposed metrics to quantify circadian effectiveness of the various light sources at a specific illuminance level. Circadian Stimulus (CS) is a recent metric developed by Professor Mark Rea and his colleagues at the Lighting Research Center (LRC) based on published studies of nocturnal melatonin suppression using illuminations of various SPDs. This metric measures the effectiveness of a light source with a specific SPD in providing circadian stimulus ranging from 0 (no effect) to 0.7 (maximum suppression level achievable after one-hour of exposure) (Rea et al. 2012; Rea, Figueiro, Bullough, & Bierman, 2005). Studies report that exposure to a CS of 0.3 or greater at the corneal for at least one hour in early mornings would be sufficient to promote circadian entrainment in various populations (Rea & Figueiro, 2016; P. D. Sloane et al., 2014; C. R. Young et al., 2015). CS may need to be increased if the duration of exposure is shorter (Figueiro, 2008). The CS metric can be applied to convert various light sources to units of Circadian Lux (CLA) for relative comparison using a publicly available circadian stimulus calculator that can be accessed on http://www.lrc.rpi.edu/programs/lightHealth/.

Equivalent Melanopic Lux (EML) is a more recent metric developed after Enezi et al. (2011) and Lucas et al. (2014) to measure the biological impacts of light on humans. As a metric, EML is weighted to the ipRGC's response to light and translates how much the spectrum of a light source stimulates ipRGCs and influences the circadian system. Figure 1 illustrates the spectral efficiency function of the melanopsin-containing ipRGCs (black curve), referred to as the melanopic spectral efficiency function (C (λ)). The melanopic spectral efficiency function can be used to quantify melanopic illuminance which is reported in units of EML. To calculate EML, photopic lux (corneal illuminance level at the vertical plane) is multiplied by the melanopic ratio (R) of the light source. Melanopic ratio is the ratio of melanopic lux to photopic lux for a given light source. Melanopic ratio of a light source can be calculated using the online tool developed by Lucas et al. (2014) and available at: http://lucasgroup.lab.manchester.ac.uk/research/measuringmelanopicilluminance/.

The introduction of EML as a unit enables designers to distinguish the relative "circadian efficacy" of various light sources (e.g., daylight vs. fluorescent) that might create the same visual effects. EML is used by WELL Building Standard to measure sufficient lighting for circadian stimulus. WELL requires exposure above various EML threshold depending on the space type, ranging from 125 EML (learning areas), to 200 EML (work areas), to 250 EML (break rooms), for at least 4 hours a day for a 32-year old individual.

It should be mentioned that both these circadian lighting metrics are emerging and yet to be validated. In this study, we merely used these metrics to test our proposed whole-day lighting schemes against the circadian lighting design recommendations available in literature and standards.

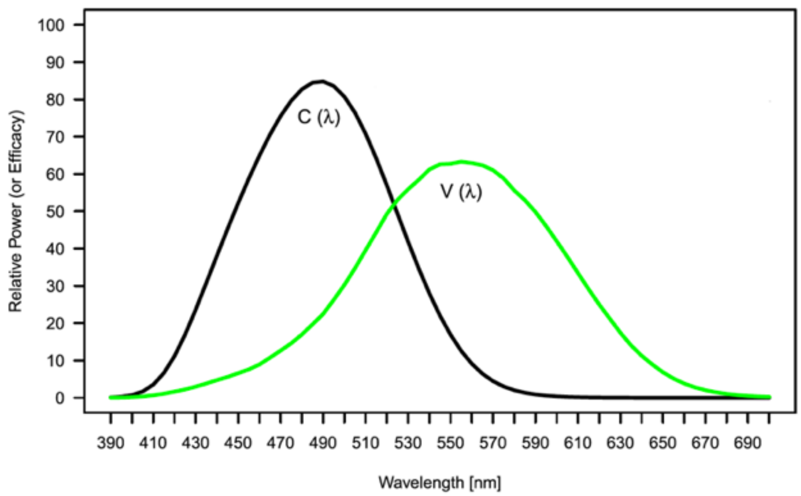


Figure 1. Comparison of the spectral efficiency function of the melanopsin-containing ipRGCs (C (λ), black curve) and the visual (photopic) system (V (λ), green curve)

1.6. Age-related Changes that Impact Circadian Rhythms and Sleep

There are several factors that bring about sleep difficulty for geriatric groups including health problems, medication side effects, and specific sleep disorders (Daneault et al., 2012). However, drastic changes in performance of the circadian system with aging is the main factor that has been observed as a significant cause of sleep disorder even among healthy older adults who do not suffer from any medical, psychiatric, or specific sleep disorders (Hofman & Swaab, 2006) (Boudreau, 2013; Hofman & Swaab, 2006; Monjan, 2013).

1.6.1. Changes to the Aging Circadian system

The biological process of aging impacts the activity of multiple biological systems including the circadian clock (Stone, Ensrud, & Ancoli-Israel, 2008; Willis, 2014). Performance weakening of circadian rhythms through aging has been investigated in many studies for several years in various model organisms such as invertebrates (Joshi, 2008; Koh, Evans, Hendricks, & Sehgal, 2006; Rezával et al., 2008; Zheng, Yang, Yue, Alvarez, & Sehgal, 2007), rodents (Froy, 2011), primates (Zhdanova, Masuda, Rosene, & Killiany, 2011), and human (Monk, 2005; Skene & Swaab, 2003).

Studies on the circadian pacemaker, the main component of the circadian system, have indicated that SCN deteriorates with aging and specifically after the age of 80 (Skene & Swaab, 2003; Swaab, Fliers, & Partiman, 1985). In fact, with aging, the rate of neuronal activities in SCN are reduced and consequently, less robust and synchronized circadian rhythms are generated (Cohen-Zion & Ancoli-Israel, 2014). In addition, a reduced circadian rhythm amplitude after the age of 50 has been reported (Hofman & Swaab, 2006). Studies on animals have shown that with aging the amplitude of the sleep-wake cycle (Davis et al., 1998; Valentinuzzi, Scarbrough, Takahashi, & Turek, 1997) as well as the amplitude of multiunit electrical activity in SCN (Farajnia et al., 2012) are reduced. With regards to human circadian rhythms, it has been found that aging decreases the amplitude of the rhythms of melatonin and other hormones (Coevorden et al., 1991; Mu¨nch et al., 2014; Zeitzer et al., 1999) as well as temperature amplitude (Boivin et al., 2020; Carrier, Monk, Buysse, & Kupfer, 1997; Weitzman, Moline, Czeisler, & Zimmerman, 1982).

Moreover, aging influences the circadian or sleep-wake biological phase. As people age, the circadian phase gradually moves earlier or advances (Duffy, Zitting, & Chinoy, 2015). The gradual advancing in older adults' rest-activity phase results in modifications in sleep-wake's timing. Thus, a common condition among geriatric groups is advanced sleep phase syndrome (ASPS). Older adults who suffer from ASPS, usually feel tired earlier in the evening and wake up earlier in the morning and they are not able to fall back to sleep (Cohen-Zion & Ancoli-Israel, 2014). It is evident that compared to young individuals (20-30 years old), the circadian rhythms of the core body temperature are earlier in older adults (>60 years old) (Kim et al., 2014). In fact, although inconclusive, aging has been demonstrated as a risk factor for ASPS due to the advanced phase of the circadian rhythms of melatonin and body temperature (Zisapel, 2001) (Sack et al., 2007). As discussed before, waking usually occurs 1-2 hours after the minimum core body temperature. Thus, ASPS might be a consequence of earlier core body temperature troughs (E. J. W. Van Someren, 2000). Moreover, the time intervals between the minimum of core body temperature and waking time decreases as people age (Duffy, Zeitzer, & Czeisler, 2007). The timing of melatonin rhythms is also reported to move earlier with aging (Kripke, Elliott, Youngstedt, & Rex, 2007; Tozawa et al., 2003). All these modifications in circadian systems that occur throughout the aging process in human's body lead to deterioration of circadian rhythms, reduced sleep efficiency, and alteration of hormone productions.

1.6.2. Changes in Aging Circadian Entrainment

The process of interaction among various independent rhythmical systems with each other is called "entrainment" (Clayton, 2012). There are several types of independent rhythmical systems and all include some form of periodic or semi-periodic oscillatory activities. However, they need to be able to be sustained independently in the absence of other rhythmical systems (Clayton, 2012). The pendulum clock is a classic instance of entrainment which is synchronized when suspended from a support (Rosenblum, Pikovsky, Kurths, Schafer, & Tass, 2001). There are several mechanical examples of this phenomenon. Nonetheless, entrainment also extends to some biological instances including resetting circadian clock through external cues such as light (especially sunlight), social interaction, and physical activities.

The process of aging is also associated with reduced exposure to external cues or zeitgebers that provide entrainment signals to maintain proper timing of circadian rhythms. It has been observed that older adults experience a shortage of adequate zeitgebers such as bright light (the most important time cue), social interactions, and physical activities (Cochen et al., 2009; Roenneberg & Merrow, 2007). Research constantly demonstrates that older adults living in institutions are often alone, inactive, and immobile (Mozley et al., 2000), spend high proportion of their day in bed and frequently nap during the day which impacts their sleeping patterns (Gordon & Gladman, 2010; Neikrug & Ancoli-Israel, 2010), and seldom engage in activity (Ibrahim & Dahlan, 2015). Sanchez et al. (1993) found that older adults living in assisted living facilities are exposed to bright light for only 35 minutes a day. This number drops to only 2 minutes a day for senior residents of nursing homes (Ancoli-Israel, Parker, Sinaee, Fell, & Kripke, 1989). The human body needs at least 1 hour of exposure to bright light to be able to synchronize circadian rhythms effectively. Necessary duration of exposure differs for different ages as well as various light intensity and characteristics (Rea et al., 2005).

1.6.3. Age-related Changes in the Eyes

age-related changes that occur in the structure and function of eyes lead to a decline in the amount of light reaching the retina and consequently impact the circadian timing system (Schieber, 2006). Visual performance weakens in seniors due to changes in the aged eyes and cognition. A functionally important change in the eye occurring with age is a reduction in pupil size (known as senile meiosis). As retinal illumination and pupil area are correlated, the amount of light reaching the retina reduces as humans age. The retina of a 20-year-old receives 3 times more light than that of a 60-year-old and 6 times more than that of an 80-year-old individual (Haegerstrom-portnoy & Morgan, 2007). Senile meiosis is not the only age-related problem that diminishes the amount of light reaching the retina and affecting retinal responses to light. As humans age, absorption in the crystalline lens increases which is known as “lens yellowing” (Lupi, Semo, & Foster, 2012). This occurs mostly due to exposure to ultra violet light. Research employing electroretinography

(ERG), a test of retina function, shows a 50% reduction in cone response to light among seniors compared to young adults (aged 15–24 years). Thus, retinal sensitivity to light weakens through aging (Daneault et al., 2013a). "Lens yellowing" selectively reduces transmissions of short-wavelength light (blue light) which is essential to synchronize biological rhythms (Najjar et al., 2014). A study conducted by Kessel, Siganos, Jørgensen, & Larsen (2011) on around 1000 Danish adults demonstrated that the age-related increase in yellowing of the lens led to greater sleep disturbance reported by participants. Furthermore, research established that aging is also associated with changes in retinal functions in human eyes by reducing the number of intrinsically photosensitive retinal ganglion cells (ipRGCs) in blind mice (Semo, Lupi, Peirson, Butler, & Foster, 2003). Photoreceptor cells, ipRGCs, located in the retina of mammals, regulate various interactions between biological functions and external luminous stimuli, thus a reduced number of them results in less light transmission between eyes and brain.

1.7. Statement of the Problem

Considering the physical and biological impacts of light, it is evident that the proper lighting plays a critical role in improving the living environment and promoting quality of life in older adults (Lu, Park, & Ahrentzen, 2019). However, lighting for older adults has not received much considerations by researchers and designers. The limited number of studies that evaluated the impacts of lighting on sleep quality, mood, and cognitive functions in older adults indicated mixed results. In most of these studies, lighting intervention includes a light box, and not an ambient lighting, which exposes subjects to an extra lighting source with specific characteristics (e.g., blue-enriched light) for only a few hours without considering the impacts of other lighting sources that seniors are exposed to throughout the day (Fetveit & Bjorvatn, 2005; Herljevic, Middleton, Thapan, & Skene, 2005; Royer et al., 2012a).

On the other hand, studies reported poor lighting conditions in senior livings in terms of light levels and spectrum (Bakker, Iofel, & Lachs, 2004; De Lepeleire, Bouwen, De Coninck, & Buntinx, 2007; Eilertsen, Horgen, Kvikstad, & Falkenberg, 2016; Hegde & Rhodes, 2010). According to these studies, light levels in senior living facilities are not even sufficient to meet older adults' visual needs. Most of the conventional lightings provide a constant illuminance level and spectrum (or CCT) during the day and night. Such lighting conditions do not necessarily provide efficacious stimulation of the circadian rhythms. This issue is even more salient for older adults who spend over 94% of their time indoors where the natural light regulating effects of daylighting are usually absent.

Therefore, we can conclude that current lighting conditions in senior living facilities are not well-designed to meet the visual needs of older adults living in assisted living facilities, to properly regulate their circadian rhythm and improve their health and wellbeing. An appropriate ambient lighting condition in senior living facilities would be a whole-day lighting scheme that provides older adults with variable illuminance and spectrum throughout the day which simulate daylighting in the indoor environment to respond to their visual and circadian needs.

1.8. Research Aims and Hypotheses

The intention of this study is to evaluate the impacts of variable illuminance levels and spectrum (and CCT) applied by TWLs on improving sleep quality, mood, cognitive functions, and consequently quality of life in older adults. The project focuses on defining two whole-day lighting schemes by using TWLs, which provide a range of illuminations, and CCTs that are changing throughout a day.

It is hypothesized that the whole-day lighting scheme is an appropriate lighting solution to compensate for age-related changes in circadian systems and accommodate older adults' circadian lighting needs through providing a suitable illuminance level and spectrum at the right time. Hence, applying a whole-day lighting scheme can help synchronize older adults' circadian rhythms, which will result in better outcomes for sleep, mood, cognitive performance, and thus quality of life.

Throughout this study, we try to find answers to the following questions: "Do the current lighting conditions in the living spaces meet older adults' visual and circadian lighting needs?", "Is there any significant difference between sleep quality, mood, and cognitive performance of older adults living in spaces with high quality daylighting compared to those with low quality daylighting condition?", "Does applying a variable whole-day lighting scheme improve older adults' sleep quality, mood, cognitive performance, and quality of life?", "Does adding tuning spectrum to the ambient illumination provide any addition benefit for older adults?" In this regard, the specific aims of this study include:

Aim 1- Understand the associations between the lighting condition in living spaces and subjective and objective sleep quality, as well as cognitive function, subjective mood, and quality of life of older adults.

Hypothesis: We hypothesize that there is a strong association between the lighting condition in living spaces and objective and subjective sleep quality, subjective mood, cognitive function, and quality of life among older adults.

Aim 2- Explore the impacts of a whole-day lighting scheme with variable illumination (bright illumination in the morning and dimmed in the evening) and constant CCT (and so SPD) applied by TWLs on sleep quality, mood, cognitive performance, and quality of life in older adults through a nine-day lighting intervention.

Hypothesis: We hypothesize that applying a range of illuminations that provide bright morning lighting to evening dimmed lighting with constant CCT of 2700ºK (and so SPD) improves objective and subjective sleep quality of older adults and benefits mood, cognitive performance, and health-related quality of life.

Aim 3 - Investigate the beneficial influences of adding tuning spectrum to the ambient lighting quality through exploring the effects of a whole-day lighting scheme with variable illuminations and variable CCTs (as suggested in section 1.3) applied by TWLs on sleep quality, mood, cognitive performance, and quality of life in older adults through a nine-day lighting intervention and compare the results with aim 2.

Hypothesis: We hypothesize that exposure to a whole-day lighting scheme with a range of illuminations and variable CCTs (and so SPDs), as suggested in section 1.3., improves objective and subjective sleep quality of older adults and benefits mood, cognitive performance, and health-related quality of life; moreover, compared to the lighting scheme with variable illumination and constant CCT of 2700ºK, the proposed lighting schedule in aim 3 provides higher levels of enhancement with regards to the above-mentioned variables. Therefore, we hypothesize a range of illuminations and CCT should both be used to improve older adults' sleep quality, mood, cognitive performance, and quality of life.

1.9. Significance and Innovation

The outcome of this study will be an optimum whole-day lighting strategy which includes adequate illuminance levels, CCT, timing, and duration of exposure to meet older adults' circadian lighting needs and visual performance requirements. This lighting arrangement can be easily applied by using TWLs in older adults' dwellings as well as communal rooms and other interior public spaces such as corridors in senior facilities. Hence, this study promotes architectural lighting design in senior livings through providing ambient lighting conditions in the dwelling units of older adults that promote health and well-being. The innovation of this study comes from our comprehensive approach towards architectural lighting design. In this comprehensive approach, lighting is considered as a significant ambient quality that not only assists occupants with their everyday visual tasks, but also has a long-term impact on their physical, psychological, and physiological health, thus their quality of life.

To accomplish a comprehensive lighting design, instead of applying a short-term lighting intervention similar to previous studies, we designed a whole-day lighting scheme that provides varying light intensity and color in response to daytime and nighttime lighting needs. Moreover, while most of the previous studies were conducted in laboratory settings, the current study occurs in the real living settings of the subjects who volunteered to participate in this study. This provides real value to the collected data and eliminates bias that might occur in the laboratory context. To our knowledge, this is the first study that examines the impacts of a whole-day lighting intervention on sleep quality, mood, and cognitive performance in older adults in their real living environments. As older adults spend most of their time indoor (usually in the dwelling units) and under the electrical lighting conditions, the findings of this study have the potential to impact a large portion of the older population.

In addition, this study is the first that tests the potential benefits of TWLs for older populations in a real residential environment. This is particularly important for the lighting industry as the findings of this study is scientific evidence to develop TWLs or other future lighting technologies.

The findings also provide even more firm evidence with respect to the significant role that lighting in living spaces plays in health and well-being in older adults. This increases architects' awareness and encourages them to consider lighting more seriously in the design of residential buildings and especially in those for the older population.

Moreover, this study can forward and assist the process of building automation and smart housing by providing primary information to utilize the smart lighting systems at an optimum level. Architects, lighting designers, and facility managers can utilize the proposed whole-day lighting scheme as a preset for programing smart lights in senior livings and older adults' homes in general.

Finally, findings of the study can be used as scientific evidence to improve lighting standards in general as well as those related to long-term care facilities (e.g., nursing homes and assisted living facilities). Current lighting standards mainly provide recommendations for horizontal illuminance levels (for visual performance) and neglect the other parameters associated with the circadian effects of light such as CCT (and so SPD), duration of exposure, timing, and corneal illumination. The final outcome of this study could be a reliable source to enhance lighting recommendations and requirements which can later be utilized by architects and lead to better indoor environmental quality.

CHAPTER 2: REVIEW OF LITERATURE

This chapter provides an overview of the literature concerning lighting and sleep quality, mood, and cognitive functions in older adults. Although this dissertation study evaluates the effects of ambient lighting conditions, studies investigating environmental lighting for older adults are limited. Therefore, a review of the literature investigating the effects of Bright Light Therapy (BLT) on older adults is included as information in those studies has implications for the study of the ambient lighting.

2.1. Lighting and Older Adults' Quality of Life

The World Health Organization (1995) defines "Quality of Life" as "*living conditions associated with the corresponding goals, expectations, standards, and concerns of each individual living in different cultural systems*." (Whoqol Group, 1995). The quality of life is influenced by each person's abilities and proficiencies as well as opportunities and facilities to support people's desires and demands to achieve their various life goals (Azri, Dahlan, Masuri, & Isa, 2016). The universal concept of quality of life illustrates a concern with regard to improvement and alteration of overall conditions of humans' qualities of life through enhancement of the physical, moral, and social environment (Zachariae & Bech, 2008). Quality of life among older adults living in institutional settings is reported as poor (Higgins & Mansell, 2009; Rashid, Ong, & Yi Wong, 2012). Research demonstrates that health status, social interactions, and sleep quality are three main factors that affect older adults' quality of life (Eyigor, Eyigor, & Uslu, 2010; Netuveli, Wiggins, Hildon, Montgomery, & Blane, 2006; Ribeiro Do Valle et al., 2013). Sufficient sleep timing and quality is necessary for human beings as it maintains the body's circadian clock and restores energy for daily activities. Consequently, sleep is an essential factor in affecting the quality of life (Dam et al., 2008). Researchers argue that poor sleep quality influences alertness, memory, cognitive performance, mood, and emotional balance (Al-Jawad, Rashid, & Narayan, 2007; Phillips & Ancoli-Israel, 2001) as well as physical health, and consequently reduces the quality of life.

Lighting has a prominent effect on sleep quality and thus can impact the quality of life of older adults by improving their sleep quality and through it their memory and cognitive functions, as well as reducing stress, anxiety, and depression.

Very few studies have examined the associations between light exposure and older adults' quality of life. In most of these studies, quality of life was measured by questionnaires as a secondary outcome related to mood, health, and sleep quality. The only study that assessed quality of life directly related to light was conducted by Grandner, Michael A., Kripke, Daniel F., Langer (2005). In this study, the relationship of habitual light exposure to the quality of life for older women was assessed by means of self-report questionnaires designed for use as part of the Women Health Initiative (WHI). Findings demonstrated that the increased light exposure, especially in the morning, is related to improved quality of life. Although this study reported a significant correlation between light and quality of life, the causal mechanism of the relationship between these two variables might be bidirectional in nature or follow complex pathways. For instance, it is possible that those who receive more light will experience enhancements in functioning and, reciprocally, those with better functioning might receive more light. However, the positive effects of morning bright light exposure on health-related quality of life have been reported in a more controlled study by Friedman et al. (2009) where the quality of life was measure by using SF-36 questionnaires after 12 weeks of exposure to bright light (4000 lux) in the morning. These results are also aligned with the findings of a study by Rubiño, Gamundí, Akaarir, & Cañellas (2017).

2.2. Lighting and Older Adults' Sleep Quality

2.2.1. Bright Light Therapy

Bright Light Therapy (BLT) is considered as a Complementary and Alternative Medicine (CAM) approach and has been increasingly applied in a variety of sleep and psychiatric conditions including circadian-related sleep disorders and Seasonal Affective Disorder (SAD) (Wu et al., 2015). BLT was introduced and tested for the first time in 1984 by Rosenthal and colleagues as an intervention to treat SAD (Rosenthal et al., 1984). BLT is usually administrated with a light box; however, other devices such as visors, masks and dawn simulators have been also employed in a few studies (Levitt, Lam, & Levitan, 2002; R. Loving, Kripke, & Shuchter, 2002; Wirz-Justice, 2009). Although very few studies have investigated light treatment by means other than light boxes, a comprehensive review by Tuunainen, Kripke, & Endo (2004) suggests that light boxes seem to be more effective compared to the other tested alternatives. Light boxes usually emit bright white light from a variety of light sources such as fluorescent, incandescent, and Light Emitting Diodes (LEDs). The intensity and spectral distribution of the emitted light varies depends on the characteristics of the light source. In order to use a light box, the patient needs to sit in front of it for a prescribed period of time (usually between 30 to 120 minutes) and long enough to take advantages of the bright light exposure. Exposure to bright light suppresses melatonin production and contributes to the stimulation of the circadian rhythms (Ancoli-Israel, Martin, Kripke, Marler, & Klauber, 2002; Maanen, Marie, Heijden, & Oort, 2016). In general, the administration time for BLT is morning (7 AM–9 AM) or evening (7 PM–9 PM), although a few studies have delivered treatment during the mid-day (Gammack, 2008). BLT might potentially cause headache, nausea, dry skin, and eye symptoms such as dryness, sensitivity, and vascular injection of eye tissues

(Terman, 2007). Moreover, in healthy older adults, BLT might bring about irritability, anxiousness, and agitation (Genhart, Kelly, Coursey, Datiles, & Rosenthal, 1993).

Given the significant effectiveness of light exposure on sleep quality, a number of studies have investigated the efficacy of BLT in improving sleep problems such as insomnia and ASPS among older adults. These studies have reported inconsistent results, with some studies showing positive impacts while others found minor or no impacts (see Table 1). Although the reasons for these inconsistencies are not completely clear yet, they might occur as a result of a large variety in tested sleep problems, variety in studied groups (e.g., age, physical and mental conditions), and differences in study design and treatment administration. Particularly, there is a considerable variability in the design and methodology employed in the study of community-dwelling and institutionalized older adults in terms of measurement tools as well as administrated light treatment duration (number of treatment days and daily treatment duration), timing, and characteristics such as illuminance levels and spectral distributions.

All these factors could influence the efficacy of the BLT in treating sleep problems among older adults. For instance, an influential factor is the quality of the study design. Studies without a control group (Fetveit, Skjerve, & Bjorvatn, 2003; Kohsaka et al., 2000; Skjerve et al., 2004) might find larger effects than randomized controlled trials (R. Loving et al., 2002; R. T. Loving, Kripke, Knickerbocker, & Grandner, 2005), as the latter control for placebo effects.

In addition, duration of BLT administration appears to be a factor that influences sleep outcomes. In a very recent study by Rubiño et al. (2017) on 37 older adults, they show that 60 minutes of morning exposure to bright light (10000 lux) significantly improved subjective insomnia by 25% when measured by the Oviedo Sleep Scale. However, in another study by (Wu, Sung, Lee, & Smith (2015) with a similar protocol (10000 lux BLT) but 30 minutes of exposure, no statistically significant improvement in sleep quality of the treatment group in comparison with the control group was found.

Moreover, the illumination of the tested BLTs varies between 400 lux and 10000 lux. Low light levels appear to show no impacts on improving sleep quality of older adults particularly due to the age-related changes in the eyes. As an example, Royer et al. (2012a) reported no significant changes in daytime sleepiness of participants after 4 weeks of 30 minutes BLT exposure with the illumination level of 400 lux. 400 lux is relatively low illuminance. Reviewing literature suggests that BLT with the illuminance level of over 6000 lux might be beneficial to older adults' sleep quality if all other factors are administered properly. In addition to light levels, the spectral distribution of the BLT is another important factor in determining the beneficial impacts of BLT. A few studies have considered this factor and compared the effectiveness of blue-enriched and green lights with red light (Gasio et al., 2003; Leggett, Conroy, Blow, & Kales, 2017; Münch, Linhart, Borisuit, Jaeggi, & Scartezzini, 2012). However, all these studies examined the effectiveness of spectral distributions in combination with light intensity and not as an individual factor and thus the actual effect of spectral distributions administered by BLT on older adults' sleep quality is not clear yet. Considering the high potential of light therapy for sleep disorders among older adults, it is fundamental to obtain insight in the general and specific influences of the lighting therapy on various sleep problems and to identify factors that impact its efficacy. However, as administration of BLT might be problematic for older adults especially those diagnosed with dementia and Alzheimer's, delivering all potential benefits of light through environmental lighting condition could be introduced as an applicable and optimal lighting solution to treat sleep disorders among older adults.

Table 1. Studies on the impacts of BLT on sleep quality of older adults

Citation	DP Variables	Measures	Light Intervention			Sample	Findings
			Lux level	CCT °K / Color	Duration		
(Kohsaka et al., 2000)	Sleep Structure	Sleep Dairy OSA Sleep Inventory	6000 lux	N/A	30 mins / Everyday / 4 Weeks	5	Morning bright light exposure significantly decreased time in bed, the number of awakenings, and rapid eye movement fragmentations.
(Gasio et al., 2003)	Circadian Disruptions Sleep	Actigraphy	0.001 lux to 210 lux	White light	24 hours / everyday / 3 weeks	9	Dawn-Dusk Simulation of light induced a small advance in the circadian rest–activity cycle by inducing an earlier onset of the most restful period of the night.
			<5 lux	Red light	3 weeks	4	
(Fetveit et al., 2003)	Sleep Efficiency	Actigraphy	6000 - 8000 Lux	N/A	2 hrs/ Everyday / 2 Weeks	11	Sleep improved substantially with bright light exposure. Waking time within nocturnal sleep was reduced by nearly two h, and sleep efficiency improved from 73% to 86%.
(Kirisoglu & Guilleminault, 2004)	Sleep Latency Total sleep time Fatigue	Sleep Log Actigraphy ESS, SDQ	10000 lux	N/A	20 mins / everyday / 60 days	46	20 minutes of bright light treatment leads to a lesser treatment response than 45 min at 3-month follow-up and to a return toward baseline at 6-month follow-up that was not seen with a 45-min exposure.
(Skjerve et al., 2004)	Sleep Disturbance	Actigraphy	5000 - 8000 lux	N/A	45 mins / everyday / 4 weeks	10	There was an advance of the activity rhythm acrophase.
(Loving, Kripke, Elliott, Knickerbocker, & Grandner, 2005)	Sleep Onset Sleep Duration	Actigraphy	1200 lux	Green Light	1 hours / everyday / 4 weeks	17	There was no significant effect on sleep onset time or sleep offset time, nor did total sleep time vary significantly by treatment.
			10 lux	Red light	1 hours / everyday / 4 weeks	16	
(Loving, Kripke, Knickerbocker, et al., 2005)	Sleep Quality	Urine Sample Saliva Sample Actigraphy	8500 lux	N/A	1 hr / 3 times a day	40	No significant improvement in sleep quality and timing
			<10 lux	N/A	1 hr / 3 times a day		
(Figueiro et al., 2008)	Sleep	Blood Sample Saliva Sample	10.4 ± 2.6	Red (peak wavelength = 630 nm)	90 mins	12	After 1 h of light exposure, the light-induced nocturnal melatonin suppression level was about 35% for the low light level and about 60% for the high light level.
			53 ± 15.5	Blue (Peak Wavelength = 474 nm)	90 mins		

Table 1 (cont.)

(Friedman et al., 2009)	Subjective Sleep Objective Sleep	Actigraphy Daily Sleep Logs Spielman Insomnia Symptom Questionnaire ESS Sleep Hygiene Questionnaire Horne-O¨ stberg Morningness/ Eveningness Questionnaire	4000 lux	N/A	45 mins Morning or 45 mins evening / everyday / 4 Weeks	26	Scheduled light exposure was able to shift the circadian phase predictably but was unrelated to changes in objective or subjective sleep measures.
			65 lux	N/A	45 mins Morning or 45 mins evening / everyday / 4 Weeks	25	
(Most, Scheltens, & Van Someren, 2010)	Sleep Efficiency Sleep-Wake Rhythm	Athens Insomnia Scale Dutch Sleep Disorders Questionnaire PSQI Actigraphy	10000 lux	N/A	30 mins Morning and 30 mins evening / 2 years	36	N/A (it is a study protocol)
			300 lux	N/A	30 mins Morning and 30 mins evening	36	
(Lieverse et al., 2011)	Sleep Efficiency	Actigraphy Saliva Melatonin Levels	7500 lux	>5000 (pale blue)	60 mins/every day/3 weeks	45	BLT improves sleep efficiency.
			50 lux	<1000 (red light)	60 mins/every day/3 weeks	44	
(Münch et al., 2011)	Circadian Phase Alertness	EEG KSS	N/A	4100 (White light)	2 hr / evening / 3 days	10	Evening light exposure could benefit older adults with early evening sleepiness, without negatively impacting the subsequent sleep episode.
			N/A	Blue-enriched Light	2 hr / evening / 3 days	N/A	
(Friedman et al., 2012)	Objective Sleep Subjective Sleep	Actigraphy ESS Blake–Gomez Sleep Hygiene	4200 lux	Bright White	30 mins / morning every day / 2 weeks	27	The results suggest that a brief, 30-min exposure to bright light in the morning was not sufficient for improving sleep in older individuals with memory problems or their caregivers.
			90 lux	Red Light	30 mins / morning every day / 2 weeks	27	
(Royer et al., 2012a)	Sleep Circadian Rhythms	ESS	400 lux	Blue Light	30 mins / mon-Fri / 4 Weeks	15	No significant changes were detected in reports of daytime sleepiness
			75 lux	Red light	30 mins / mon-Fri / 4 Weeks		

Table 1 (cont.)

(Duffy, Scheuermaier, Münch, & Ronda, 2013)	Sleep Efficiency Sleep Duration	Observation Sleep Dairy	N/A	4100 (White light)	2 hr / evening / 3 days	10	There was no significant change in sleep efficiency or the duration of any sleep stage between baseline nights and the nights following the light exposures.
			N/A	Blue-enriched Light	2 hr / evening / 3 days		
(Wu et al., 2015)	Sleep Disturbance	Daily Sleep Recording Sheet	10000 lux	N/A	30 mins / morning/ 3 times a week / 4 weeks	34	There was no significant difference in sleep disruption between the experimental group and control group.
(Leggett et al., 2017)	Objective Sleep Subjective Sleep	Actigraphy Sleep Dairy PSQI	506 lux	Blue-Green (500 nm)	30 mins / everyday / 2 weeks	11	Objective and subjective sleep quality were improved.
(Rubiño et al., 2017)	Sleep	Oviedo sleep	10000 lux	N/A	60 mins/ everyday / 2 weeks	37	The exposure to bright light during morning time causes significant improvements in sleep quality and insomnia
(Mohanty & Patra, 2019)	Sleep	PSQI Sleep Dairy	10,000 lux	Cool	30 minutes/ every day/ 2 weeks	48	A highly significant increase in global score of quality of sleep was found.

2.2.2. Ambient Lighting

Given the fact that older adults spend the majority of their time indoors along with the issues associated with using BLT, improving environmental lighting appears to be an effective solution to meet visual and circadian lighting needs of older population. This approach becomes more popular from a research, practical, and ethical point of view (van Hoof, Aarts, Rense, & Schoutens, 2009).

Studies that exposed community-dwelling and institutionalized older adults to ambient bright light through ceiling mounted luminaires indicated positive short-term and long-term effects including reduced nocturnal unrest, reduced fragmented sleep, a more stable sleep-wake cycle, and more sleep quality and efficiency (see Table 2) for both healthy and ADRD participants.

These studies employed various research methods and study design and used a large variety of tools to measure sleep-related parameters. Almost all studies included objective outcome measurements such as wrist actigraphy (Mishima, Okawa, Shimizu, & Hishikawa, 2001; Riemersma-van der Lek, Swaab, Twisk, Hol, Hoogendijk, & Van Someren, 2008; Wakamura & Tokura, 2001). There are a few studies that measured salivary and urinary melatonin as well as blood melatonin (Obayashi, Saeki, Iwamoto, Okamoto, et al., 2013; Sander, Markvart, Kessel, Argyraki, & Johnsen, 2015). Measuring subjective sleep parameters by questionnaires is also used in some other studies individually or in combination with objective measures. Pittsburg Sleep Quality Index (PSQI) is the most common questionnaire used in this respect.

Most of these studies concentrated on the illuminance levels and spectrum (or CCT) as the main lighting characteristics associated with older adults' sleep quality. Riemersma-van der Lek et al. (2008) conducted a long-term double-blinded experiment on 189 older adult subjects (85.8 ± 5.5) to test the effects of 15 months of daily, whole day bright (1000 lux) or dim (300 lux) light exposure applied through indirect ceiling mounted luminaires on sleep duration, nocturnal restlessness, and sleep efficacy of older adults. They found that exposure to bright light would improve sleep efficacy and duration by 3.5% and 2% respectively over time. This experiment is the only recent study that assessed a long-term trial of the ambient light bright light on senior populations.

Sloan et al. (2007) examined the impacts of high-intensity bright light (2500 lux) in public areas of long-term care facilities on sleep patterns and circadian rhythms of 66 participants with dementia. Participants were exposed to either morning bright light (3 hours), evening bright light (3 hours), or whole day bright light (8 hours). This study is especially significant in that in addition to illuminance levels, it examined the effects of timing as an area of scientific controversy. The results of this study suggested that, compared to evening, morning and whole-day bright light exposures are more beneficial to improve the sleep quality of older populations. Throughout the intervention, morning and whole-day ambient bright light exposure significantly increased night-time sleep (16 minutes for morning exposure and 14 minutes for whole day exposure), and it was more effective in patients with severe or very severe dementia; moreover, while morning bright light produced on average 29 minutes of phase advance, evening bright light caused an average of 15 minutes phase delay. These findings are aligned with other studies which showed the clinical advantages of morning light exposure on institutionalized older adults (Figueiro et al., 2019; Formentin et al., 2020; Skjerve et al., 2004). Therefore, light exposure should be provided during the daytime to take advantage of ambient bright exposure in promoting circadian entrainment among older adults. It has been reported that evening exposure to bright light is associated with sleep disruption. In a large, community-based, cross-sectional study on 857 older adult participants, Obayashi et al. (2014) found a significant association between the increasing illumination at night and poorer sleep quality, decreased sleep efficiency, prolonged sleep-onset latency, increased wake-after-sleep onset, shortened total sleep time, and delayed sleep-mid time.

Spectral distribution of the light source (or CCT) is another factor evaluated with respect to sleep quality of older adults. van Hoof et al. (2009) conducted an experiment on 42 older adults (mean age: 85.6) to test the influences of prolonged exposure to bright light (~1800 lux at horizontal plane and on working level) on behavior and circadian rhythms of institutionalized older adults with dementia. In this regard, ceiling-mounted luminaires emitting bluish (6500K) and yellowish (2700K) light were installed in an intervention group that was compared to a control group of traditional dim lighting equipment. Findings showed a significant improvement in the restless behavior of the intervention group exposed to blue light. This effect was not observed in the yellowish light scenario. These results revealed that in addition to intensity, the spectrum and CCT of the light source is another influential factor in the circadian effects of light in older adults; however, this study measured only subjective restless behavior and did not provide any evidence with regards to objective and subjective sleep quality, duration, timing, and efficiency. The associations between sleep efficiency and duration with spectral distribution of the light was investigated by Figueiro et al. (2015). In this study, researchers examined the effectiveness of a lighting intervention with short wavelength spectral distribution (CCT of 9325 K) on circadian stimulation and objective and subjective sleep efficiency of 35 ADRD older adults. The intensity of the tested light was 400 lux at the vertical plane (120 lux at the horizontal plane). They reported that four weeks of bright blue light exposure resulted in significantly greater circadian entrainment, higher sleep efficacy, and longer sleep durations among ADRD older adults. Although less compelling and showing only a 2% increase in sleep efficiency, these results were consistent with those observed by Figueiro et al. (2014), Figueiro, Plitnick, & Rea (2016), and Figueiro, Lesniak, & Rea (2011).

In a more recent study, Van Lieshout-van Dal, Snaphaan, & Bongers (2019) evaluated the exposure to a dynamic lighting on sleep quality of thirteen older adults with AD. During the day, the participants received gradual illumination levels ranging from 600 lux at 8 a.m., 1100 lux between 10 a.m. to 2 p.m. and 600 lux after 5 p.m. During the day, the light was blue-enriched with color temperature was around 6500 K During the evening, the color temperature had a warmer, around 1800 K. Three biodynamic lighting armatures were placed in the common area for a period of three weeks and then removed for the same period. Results showed a significant reduction in the frequency of night-time bed leave moments (11 to 5) and day time naps (16 to 7). These results were aligned with those of found by Mariana et al. (2017) as well as with the conclusion of a review study by White et al. (2013) which included 18 cited studies that dynamic lighting interventions might decrease symptoms of circadian disruption in older adults and improve their sleep quality.

Whereas these studies confirmed the positive effects of morning bright blue light exposure on improving sleep of seniors, Sander et al. (2015) reported no significant results. In this study, the effects of a 3-week exposure to bright-blue-enriched indoor ambient light (5100 K) were compared to that of blue-suppressed light (2800 K) on subjective and objective sleep quality of older adults in their private homes. The light levels were kept the same for both lighting conditions (240-280 lux). The results were no significant differences between the two indoor lighting conditions in sleep or rest duration, sleep quality, and other circadian parameters such as morning-evening types and melatonin concentration. One explanation for these findings might have something to do with the level of the light, which could have been too low to find a difference. Moreover, participants of this study were healthy older adults who independently lived in their private homes. This group of people are still mobile and could have activities outside the house where they could be exposed to daily natural light. Exposure to daily sunlight might have nullified the impacts of the lighting intervention.

All these studies seem to suggest that a properly designed light/dark pattern could improve sleep efficiency of older persons, including those with AD, through consolidation of their circadian rest/activity rhythms. The results of previous studies suggest that a proper lighting solution for older adult should provide them with higher ambient light levels (e.g., >120 lux at the horizontal plane) with more short wavelength contents (e.g. 6500K or higher) during the day, while the evening lighting system should provide lower ambient light levels (e.g., <300 lux at the horizontal plane) and use light sources with less short-wavelength content (e.g. 2700 K). However, more detailed studies are required to determine precise lighting exposure timing, duration, intensity, and spectral distribution of the source, and to propose a 24-hour lighting schedule for older adults.

Table 2. Studies on the impacts of ambient lighting on older adults' sleep quality.

Citation	DP Variables	Measures	Light Intervention			Sample	Findings
			Lux level	**CCT °K / Color**	**Duration**		
(Shochat, Martin, Marler, & Ancoli-Israel, 2000)	Percent Sleep and Wake Number of Naps	Actigraphy	N/A	N/A	N/A	66	The median light level was 54 lux and a median of only 10.5 min were spent over 1000 lux. Higher light levels predicted fewer night-time awakenings.
(Mishima et al., 2001)	Melatonin levels Sleep Onset Sleep Efficiency Sleep Duration	Blood Samples Actigraphy	2500 lux	N/A	4 hours/ everyday / 4 weeks	10	Supplementary exposure to 4 h (1000 to 1200 h, 1400 to 1600 h) of midday bright light significantly increased melatonin secretion in older adults and improves their sleep quality and duration.
(Wakamura & Tokura, 2001)	Sleep Quality	Actigraphy Saliva Sample	3000 lux	N/A	5 hours / everyday / 1 week	7	The findings suggest that diurnal bright light exposure for hospitalized older adults improves their sleep quality.
(Riemersma, 2002)	Sleep Efficiency rest-activity rhythm	Actigraphy	1000 lux	N/A	Whole day / 6 weeks	6	Overall interaction effect of light and melatonin, increasing the stability and amplitude of the rest-activity rhythm by 8%, lowering nocturnal restlessness by 22%, and improving sleep efficiency by 3%.
			375	N/A	Whole day / 6 weeks	6	
(Riemersma-van der Lek, Swaab, Twisk, Hol, Hoogendijk, & Van Someren, 2008)	Sleep Quality	Actigraphy	1000 lux	N/A	10 am - 6 pm/ 1 year	98	The treatments significantly reduced sleep fragmentation and improved sleep durations.
			375	N/A	Whole day / 6 weeks	6	
(Philip D. Sloane, Md, Figueiro, & Cohen, 2008)	Sleep Onset Sleep Duration	Actigraphy	2500 lux	N/A	2.5 hours morning and evening exposure 8.5 hours all-day exposure	66	Night-time sleep increased significantly in participants exposed to morning and all-day light. Morning light produced a mean phase advance of 29 minutes and evening light a mean phase delay of 15 minutes.

Table 2 (cont.)

(van Hoof, Schoutens, & Aarts, 2009)	Circadian Rhythms	The Dutch Behavior Observation Scale for Intramural Psychogeriatric (GIP)	1800 lux	6500	3 weeks	16	High intensity light with a high CCT (6500 K) improves circadian rhythmicity in institutionalized older adults with dementia
			1800 lux	2700	3 weeks	10	
(van Hoof, Aarts, et al., 2009)	Circadian Rhythms	The Dutch Behavior Observation Scale for Intramural Psychogeriatric (GIP)	500 lux	17000	9	12	The 17,000 K lighting scenario did not improve circadian rhythms. In contrary, it even resulted in worsened observed behavior.
			500 lux	2700	9		
(Missildine, Bergstrom, Meininger, Richards, & Foreman, 2010)	Sleep Quality	Actigraphy	N/A	N/A	N/A	48	No significant correlation was found between sleep and lighting.
(Figueiroa, Hamnera, Higginsb, Hornickb, & Rea, 2011)	Circadian Disruption	Dimesimeter	N/A	N/A	N/A	13	lower levels of light exposure and greater levels of circadian disruption were seen during the winter than during the summer
(Obayashi, Saeki, Iwamoto, Okamoto, et al., 2013)	Sleep Duration	Urinary Melatonin	N/A	N/A	N/A	516	There is significant association between Sleep duration, insomnia, and night time illuminance level.
(Obayashi, Saeki, & Kurumatani, 2014)	Objective and Subjective Sleep Quality	PSQI Actigraphy	N/A	N/A	N/A	857	Exposure to light at night is significantly associated with both subjectively and objectively measured sleep quality in a community based elderly population.
(Obayashi, Saeki, Iwamoto, et al., 2014a)	Sleep onset	Actigraphy	N/A	N/A	N/A	192	Exposure to evening light prolongs subsequent sleep-onset latency in older adults.
(Akei Ichimori, Tsukasaki, & Koyama, 2015)	Subjective Sleep Quality	PSQI	N/A	N/A	N/A	44	No significant associations between illuminance levels and subjective sleep quality
(Figueiro et al., 2015)	Circadian Rhythms Sleep efficiency	Daysimeter Actigraphy PSQI	400 lux	9325	3 weeks	34	The lighting intervention significantly increased circadian entrainment and sleep efficiency.

Table 2 (cont.)

(Sander et al., 2015)	Sleep Duration	PSQI Saliva Sample Actigraphy	280 lux	5100	6 hours / everyday / 3 weeks	29	No significant differences were found between the two indoor lighting conditions in sleep or rest duration measured by diary and Actiwatch, or sleep quality measured with the Pittsburg Sleep Quality Index.
			240 lux	2800	6 hours / everyday / 3 weeks	25	
(Tsuzuki, Mori, Sakoi, & Kurokawa, 2015)	Sleep Quality	Actigraphy	N/A	N/A	N/A	8	Increased lighting level before the sleep prolongs the bedtime and wake time after sleep onset, and became wake-up time earlier. Increased lighting levels during the sleep period mount up the wake time after sleep onset and impaired the sleep efficiency index.
(Karami, Golmohammadi, Heidaripahlavian, Poorolajal, & Heidarimoghadam, 2016)	Sleepiness Day and night melatonin	blood samples KSS	Daylight	N/A	9:00 – 10:00 and 16:00 – 17:00 everyday daylight exposure for 6 weeks		Daylight exposure could delay sleep phase and correction of circadian rhythm in elderly. Anxiety.
(Nioi, Roe, Gow, Mcnair, & Aspinall, 2017)	Sleep	Actigraphy	N/A	N/A	N/A	16	
(Mariana G. Figueiro et al., 2019)	Circadian Rhythms Sleep efficiency	Daysimeter Actigraphy PSQI	600 lux	5000	4 weeks	46	The lighting intervention tailored to maximally entrain the circadian system can improve sleep in patients with dementia.
(Van Lieshout-van Dal et al., 2019)	Bed Leave Daytime Napping	Bed Sensors	600 lux at 8:00, 1200 lux at 10:00 – 14:00, 600 lux at 17:00	Daytime: 6500 Evening: 1800	3 weeks	13	During exposure the average frequency of night-time bed leave, and daytime napping significantly decreased.

2.3.Lighting and Older Adults' Mood and Depression

Depression is a common symptom among older adults with the estimated prevalence of 5% - 15% among community-dwelling older adults (Taylor, 2014). According to the American Geriatrics Society (2003), depression occurring with dementia is the most common disorder for older adults residing in nursing homes. Depression can bring about psychological distress, functional impairment, and consequently poorer overall health outcomes (Wu et al., 2015). In addition, it has been demonstrated as a risk factor for cardiovascular diseases (Ariyo et al., 2000). Depression among older adults is associated with cognitive impairment and could approximately double the risk of dementia (Saczynski et al., 2010). Moreover, these depressive symptoms could place more stress on caregivers in both institutional and home settings (Hickman, Barrick, Williams, Rose, et al., 2007).

Researchers argue that light with correct characteristics could be as effective as medication in the treatment of depression if it is employed at the right time and with sufficient duration (Akei Ichimori et al., 2015; Tuunainen et al., 2004). Most of these studies examine the effectiveness of Bright Light Therapy (BLT) for treating depression. BLT showed positive impacts on treating depression as an adjunct in combination with antidepressant medicine (Martiny, Lunde, Unden, Dam, & Bech, 2005), particularly when administered in the morning hours (Golden et al., 2005). A meta-analysis of BLT in the treatment of mood disorders published by Golden et al. (2005) reported predominantly positive benefits of BLT. They reported that BLT significantly decreased depression symptom severity with an effect size of 0.84. In addition, BLT showed minimal side effects on patients (Gallin et al., 1995; Pail et al., 2011).

Several studies support the effectiveness of Bright Light Therapy (BLT) for treating depression in older adults (see Table 3). However, the characteristics of applied BLT in these studies are varied in terms of illumination levels, spectrum (or CCT), duration of exposure, and timing. In one study, 60 hospitalized individuals (mean age 75 years) were randomized to 50 minutes of 5000 lux morning bright light versus control for 5 consecutive days. Geriatric Depression Scale (GDS) scores were similar at baseline between treatment and control groups. With BLT, GDS scores dropped significantly among participants in the treatment group but did not change in control group (Y. F. Tsai, Wong, Juang, & Tsai, 2004). Moreover, in a placebo-controlled study, 14 participants (mean age 84 years) received 5 days of bright light (10000 lux), dim light (300 lux), or no light therapy for 30 minutes each day. GDS scores decreased significantly during the BLT but did not change during the dim- or no-light period. After BLT, 50% of the participants no longer scored in the depressed range (Sumaya, Rienzi, Deegan, & Moss, 2001). Similar results were reported in other studies (Leggett et al., 2017; Rubiño et al., 2017; Skjerve et al., 2004) where researchers investigated the effects of high intensity light on treating depression on older adults. Although these studies employed similar study design, they examined various duration of exposure to BLT from 30-180 minutes a day for 5 to 50 days. No study compared the effectiveness of duration of exposure on the treating effects of BLT.

Whereas the above-mentioned studies focused merely on the light intensity of BLT, a few other studies added Spectrum and/or CCT as another beneficial factor that might positively impact depression in the aged population. Komatsu et al. (2010) examined the effects of bluish and reddish BLT exposure on behavioral and psychological symptoms of dementia (BPSD) in 8 Alzheimer Disease (AD) older adults (mean age = 80) living in geriatric healthcare facilities. Subjects received either blue (12,000K) or red (2,400K) light with a consistent intensity of 2000 lux from light-emitting diodes and were measured before the eyes in gaze direction from 9:00 am to 9:30 am during the occupational therapy. Results of this study showed that bright light exposure in the morning significantly improved BPSD symptoms among older adults with AD. In another study by Lieverse et al. (2011), the efficacy of BLT with high intensity blue light on depressive symptoms in older adults was investigated in a double-blind, placebo-controlled randomized study. Throughout this experiment, 45 senior participants in the treatment group were exposed to 1 hour of early morning BLT with pale blue light and the intensity of 7500 lux for three weeks. The other 44 participants in the control group received red light with the intensity of 50 lux with the same timing and duration of exposure. Findings of this study indicated that blue BLT with higher intensity produces continuing improvement in mood of older adults. These results suggest that higher CCTs and blue-enriched light can add to the efficacy of high-intensity BLT in the process of depression treatment.

Although several studies supported the effectiveness of bright light on reducing depression among geriatric groups, there are a few studies that reported no impacts (R. T. Loving, Kripke, Elliott, et al., 2005; Royer et al., 2012b; Wu et al., 2015). The conflicting findings of these studies suggest the need for further investigation. A significant impediment to further research on bright light therapy in older adults is that these individuals typically require constant reminders to remain seated and awake in front of a light box long enough to benefit from the bright light exposure. This is even more challenging for seniors with dementia or AD. These constraints limit such research to the subpopulation of individuals who will remain seated. Perhaps more importantly, it also creates a secondary, unintended component to the treatment interaction with staff who provide reminders to stay seated. An alternative way to deliver bright light therapy is providing an ambient of high-intensity, low-glare overhead lighting (Hickman, Barrick, Williams, Zimmerman, et al., 2007). This approach relies on passive exposure, permitting older adults to engage in their normal activities without restricting movement, and removes the interaction bias inherent in light box studies in this population.

Reviewing literature suggests the positive impacts of ambient indirect overhead bright light on enhancing mood and treating depression among older adults. The effectiveness of illuminance levels in the ambient indoor environment is important for both the treatment and prevention of depression (Shochat et al., 2000). Researchers demonstrated a significant negative correlation between daytime ambient illuminance levels of over 400 lux and depression scores among older adults (Ichimori, Tsukasaki, & Koyama, 2013). Although 400 lux is a significantly low illuminance compared to those used for light therapy, it seems that over 400 lux might be an appropriate daytime illuminance to maintain mental health of seniors if duration of exposure is sufficiently long. Despite the beneficial impacts of daytime ambient bright light, night time illuminance exposure is reported to have a positive association with the risk of depression among older adults (Obayashi, Saeki, Iwamoto, Okamoto, et al., 2013), possibly due to circadian phase delay and impaired sleep quality.

The beneficial effects of daytime bright light on depression and mood of senior population have also been demonstrated in recent randomized controlled studies (Dowling, Graf, Hubbard, & Luxenberg, 2007; Figueiro et al., 2019; Karami et al., 2016). Findings of these studies show that the long-term application of whole day ambient bright light in residential settings could reduce depressive symptoms by a relative 19% in older adults. However, these studies merely evaluated the effectiveness of light intensity, and no data were provided with respect to the light intervention's spectrums and CCTs, whereas these two factors might be associated with symptoms of depression among older people.

Nevertheless, thus far, studies on the effects of CCTs and spectrum on depression symptoms among older adults indicated no statistically significant correlation. This might be due to insufficient sample size, participants’ mental and physical conditions (e.g., ADRD patients), methodological issues, and the incorrect application of light intervention. For instance, in the study by van Hoof et al. (2009), they compared the usefulness of 17000 K lighting intervention on improving mood and behavioral symptoms of older adults with a 2700 K control condition. However, the intensity of light in the control condition was higher than the intervention condition and no significant improvement was found.

Although the association between lighting and depression is evident, more research is required to investigate the optimal characteristics of the light to maintain behavioral health of older adults. As all lighting characteristics such as intensity, spectrum, timing, and duration might have some interactive influence, it is suggested that future studies focus on the combination of these factors to examine their interaction and find the optimum lighting solution. Moreover, considering the limitations of BLT and senior populations, it is fundamental to develop ambient lighting solutions to increase the efficiency.

Table 3. Impacts of lighting on older adults' mood and depression.

Citation	Variables	Measures	Lighting	Light Intervention			Sample Size	Findings
				Lux level	CCT °K / Color	Duration		
(Skjerve et al., 2004)	Mood Agitation	CMAI BEHAVE-AD	BLT	5000 - 8000 lux	N/A	45 mins / everyday / 4 weeks	10	Behavioral symptoms were improved
(Tsai, Wong, Juang, & Tsai, 2004)	Depression	GDS	BLT	5000 lux	N/A	50 mins / 5 days	30	Depressive symptoms were significantly reduced in the experimental group at post-test but no significant decline was found in the control group.
				N/A	N/A	N/A	30 - Control	
(Loving, Kripke, Knickerbocker, et al., 2005)	Mood Depression Sadness	GDS SIGH-SAD-SR HDRS	BLT	8500 lux	N/A	1 hr / 3 times a day	41	16% improvement in GSD and HDRS measures.
				<10 lux	N/A	1 hr / 3 times a day		
(Loving, Kripke, Elliott, et al., 2005)	Mood	GDS	BLT	1200 lux	Green Light	1 hours / everyday / 4 weeks	17	Mood improved on average 23% for all subjects, However, no significant statistical differences were found between treatment and placebo groups.
				10 lux	Red light	1 hours / everyday / 4 weeks		
(Dowling et al., 2007)	Depression	NPI-NH	BLT	2500 lux	N/A	1 hour morning / Mon-Fri/ 10 weeks	29	Analyses revealed that light therapy significantly reduces depression scores for both morning and evening groups.
				2500 lux	N/A	1 hour evening / Mon-Fri / 10 weeks	24	
(Riemersma-van der Lek et al., 2008)	Depression	Cornell Scale for Depression in Dementia	Ambient Lighting	1000 lux	N/A	10 am - 6 pm/ 1 year	98	Light ameliorated depressive symptoms by 1.5 points on the Cornell Scale for Depression in Dementia.
				300 lux	N/A	10 am - 6 pm/ 1 year	91	

Table 3 (cont.)

(Sloane et al., 2008)	Depression	CSDD PHQ-9	Ambient Lighting	400 lux	13000	3 hours in the morning	17	For both the CSDD and the PHQ-9, the intervention condition was associated with a statistically significant improvement compared to usual light, but the contrasts of intervention condition to control condition were not significant.
				400 lux	2700	3 hours in the evening	17	
(van Hoof et al., 2009)	Mood	The Dutch Behavior Observation Scale for Intramural Psychogeriatric (GIP)	Ambient Lighting	1800 lux	6500	3 weeks	16	High intensity light with a high CCT (6500 K) may positively influence restless behavior.
				1800 lux	2700	3 weeks	10	
(van Hoof et al., 2009)	Mood	The Dutch Behavior Observation Scale for Intramural Psychogeriatric (GIP)	Ambient Lighting	500 lux	17000	9 Days	12	The 17,000 K lighting scenario increased the scores for depressive/sad behavior and anxious behavior.
				500 lux	2700	9 Days	10	
(Most et al., 2010)	Depression	GDS	BLT	10000 lux	N/A	30 mins Morning and 30 mins evening / 2 years	36	N/A (it is a study protocol)
				300 lux	N/A	30 mins Morning and 30 mins evening / 2 years	36	
(Lieverse et al., 2011)	Depression (MMD)	HDRS	BLT	7500 lux	>5000 K (pale blue)	60 mins/every day/3 weeks	45	BLT produced continuing improvement in mood
				50 lux	<1000 K (red light)	60 mins/every day/3 weeks	44	
(Royer et al., 2012a)	Depression	GDS	BLT	400 lux	Blue Light	30 mins / mon-Fri / 4 Weeks	15	No significant changes were detected in reports of depression
				75 lux	Red light	30 mins / mon-Fri / 4 Weeks	13	

Table 3 (cont.)

(Ichimori et al., 2013)	Depression	GDS	Ambient Lighting	NA	N/A	N/A	24	A significant negative correlation was found between time exposed to light over 400 Lux and depression scores.
(Ichimori, Tsukasaki, & Koyama, 2015)	Depression	GDS	Ambient Lighting	N/A	N/A	N/A	44	Depression scores were significantly related to age, level of required support, and illuminance.
(Figueiro et al., 2015)	Depression	GDS Cornell Scale for Depression in Dementia (CSDD)	Ambient Lighting	400 lux vertical	9325 K	3 weeks	34	The lighting intervention significantly reduced symptoms of depression in the participants with ADRD.
(Obayashi, Saeki, Iwamoto, et al., 2014b)	Depression	GDS	Ambient Lighting	N/A	N/A	N/A	516	These results suggested that exposure to light at night in home settings is significantly associated with depressive symptoms in older adults.
(Wu et al., 2015)	Depression	GDS	BLT	10000 lux	N/A	30 mins / morning/ 3 times a week /4 weeks	34	The depression level of participants in the experimental group was decreased significantly. However, there was no significant difference in depression scores between the experimental group and control group.
(Leggett et al., 2017)	Depressive Symptoms	PHQ-9	BLT	506 lux	Blue-Green (500 nm)	30 mins / everyday / 2 weeks	11	Depressive symptoms declined through the intervention period
(Rubiño et al., 2017)	Depression	GDS	BLT	10000 lux	N/A	60 mins/ everyday / 2 weeks	37	The exposure to bright light during morning time causes significant improvements in mood.
(Mariana G. Figueiro et al., 2019)	Circadian Rhythms Sleep efficiency	Daysimeter Actigraphy PSQI	Ambient Lighting	600 lux	5000	4 weeks	46	The lighting intervention tailored to maximally improve mood in patients with dementia.

2.4.Lighting and Older Adults' Memory and Cognitive Functions

The influences of an aging circadian system on memory and cognitive function might be both sleep-dependent and sleep-independent. It is difficult to distinguish between them. As an example, sleep is important for memory consolidation, hence the disruption of normal sleep patterns as a result of age-related changes in the circadian system could be one of the contributors to memory impairment (Kyriacou & Hastings, 2010; Pace-Schott & Spencer, 2011). The association between sleep and cognitive performance has been investigated objectively by use of actigraphy in a few large population-based studies. These studies suggested that shorter total sleep duration, longer sleep-onset latencies, fragmented sleep, and lower sleep efficiency are related to lower cognitive performance among older adults (T Blackwell et al., 2006; Terri Blackwell et al., 2011).

Considering the strong associations between sleep and cognitive functions, studies investigating the impacts of lighting on sleep quality might provide us with data about the relationship between lighting and cognitive performance. Although the number of these studies are limited, they suggest that lighting with the right characteristics might improve memory and cognitive functions among healthy older adults and those with dementia (see Table 4). Graf et al. (2001) tested whether bright light therapy (BLT) is capable of improving cognitive functions in ADRD older adults through a balanced, placebo-controlled parallel-group design. Twenty-three participants with ADRD were randomly assigned to either evening bright (3000 lux) or dim (100 lux) light. Effects of light on cognitive functions were assessed before and after light therapy using Mini-Mental State Examination (MMSE) scores. Participants treated with bright light showed a statistically significant increase in MMSE total scores after light therapy. This effect was not found for those exposed to the dim light. Results suggested that short-term evening BLT may exert beneficial effects on cognitive functioning in older adults with dementia. In a more recent study, Rubino et al. (2017) also reported that 1 week of 60 minutes morning BLT (10000 lux) enhanced cognitive and memory functions of older adults diagnosed with low to moderate cognitive impairment. These results are aligned with findings from an earlier study by Ito et al. (1999) where morning BLT improved MMSE scores of 27 ADRD participants after 4 weeks of treatment. However, the findings from these studies do not support the hypothesis that the phase-shifting outcomes of BLT expound the improvement of cognitive performance. Higher cognitive and memory function could occur because of other biological mechanisms than phase-shifting effects of light such as alerting effects of BLT (Massie, Campbell, & Williams, 1995; Murphy & Campbell, 1996).

One important drawback of the above-mentioned studies is the disregard of lighting spectrum and CCTs as potential influential factors on cognitive and memory functions. None of these studies reported the CCTs of the light intervention. Moreover, as is mentioned previously, compared to ambient lighting, BLT would provide less benefits due to the need for timed seating in front of a light box. Hence, it is more desirable to study and develop ambient lighting conditions as a relatively straightforward environmental modification to improve older adults' cognitive performance.

Studies on the association of ambient lighting and cognitive functions suggest that higher levels of ambient illumination (>1000 lux) could have a strong direct and independent benefit on improving cognitive performance and mainly on working memory and concentration (Riemersma-van der Lek, Swaab, Twisk, Hol, Hoogendijk, & Someren, 2008) (Kretschmer, Schmidt, & Griefahn, 2013). However, no evidence has been reported regarding the impacts of light spectrum and CCTs.

The only study that specifically compared the effectiveness of light spectrum is conducted by Royer et al. (2012). This double-blinded, placebo-controlled study exposed 28 institutionalized older adults to either 30 minutes of 400 lux of blue light or 75 lux of red light for 4 weeks. Findings suggested that high intensity blue light exposure leads to significant cognitive improvements among older adults as measured by the MicroCog Assessment of Cognitive Functioning. However, as the intensity and lighting spectrum both are different in the intervention condition compared to control, it is not clear if the treating effects of lighting intervention are a result of higher intensity or blue spectrum or perhaps the interaction between these two variables. Further studies are required to investigate the effectiveness of these variables on cognitive and memory functions of older adults separately in order to develop optimal lighting solutions.

Table 4. Impacts of lighting on older adults' memory and cognitive performance.

Citation	Variables	Measures	Lighting	Light Intervention			Sample Size	Findings
				Lux level	CCT °K / Color	Duration		
(Graf et al., 2001)	Cognitive Functions	MMSE	BLT	3000 lux	N/A	2 hours / everyday / 10 days	13	Participants treated with BLT (Not DLT) showed a statistically significant increase in MMSE total scores after light therapy.
				100 lux	N/A	2 hours / everyday / 10 days	10	
(Riemersma-van der Lek et al., 2008)	Cognitive Functions	MMSE	Ambient Lighting	1000 lux	N/A	10 am - 6 pm/ 1 year	98	Light attenuated cognitive deterioration by a mean of 0.9 points on the Mini-Mental State Examination.
				300 lux	N/A	10 am - 6 pm/ 1 year	91	
(Most et al., 2010)	cognitive performance	MMSE	BLT	10000 lux	N/A	30 mins morning and 30 mins evening / 2 years	36	N/A (it is a study protocol)
				300 lux	N/A	30 mins morning and 30 mins evening / 2 years		
(Royer et al., 2012a)	Cognitive Functions	MicroCog Assessment of Cognitive Functioning	Ambient Lighting	400 lux	Blue Light	30 mins / mon-Fri / 4 Weeks	15	Blue light treatment led to significant cognitive improvements compared with placebo red light
				75 lux	Red light	30 mins / mon-Fri / 4 Weeks	13	
(Kretschmer et al., 2013)	Concentration Working Memory Divided Attention	KLT-R TAP Divided Attention test	Ambient Lighting	3000 lux	N/A	4 hours / 3 night	16	It becomes evident that bright light has a strong direct and independent effect on cognitive performance, particularly on working memory and concentration.
				300 lux	N/A	4 hours / 3 night	16	
(Rubiño et al., 2017)	Cognitive Performance	MMSE	BLT	10000 Lux	N/A	60 mins/ everyday / 2 weeks	37	The exposure to bright light during morning time causes significant improvements in Cognitive Performance.

CHAPTER 3: METHODOLOGY

This section describes research design, variables, participants, and lighting interventions as well as data collection and data analysis procedures.

3.1. Study Design

We utilized a counterbalanced crossover design to examine the impacts of changing illuminance levels and CCTs on sleep quality, mood, and cognitive performance in older adults. In this design, each participant acted as their control; hence, extraneous variables such as the difference in health status, age, visual acuity, gender, and living conditions remained constant. This means that differences observed were more likely due to the effects of lighting conditions rather than individual differences among participants. Moreover, having each participant served as their own control eliminated the need for a control group; thus, fewer participants and less time were required to complete the study.

As two lighting interventions were tested, we counterbalanced the study to reduce the bias that could result from the order of which an intervention was provided. In this regard, participants were randomly assigned to two groups with a different intervention order.

3.2. Environment

We received written consent from the managers of three independent livings located in Saint Louis, MO, and Chicago, IL, to recruit residents for the study (two in Saint Louis). Figure 2, Figure 3, and Figure 4 illustrate pictures of these senior livings. We carried out the study in these two cities because of our strong working relationships with design firms, lighting manufactures representatives, and developers. Furthermore, the research costs significantly reduced as we were offered free technical assistance and service (e.g., lighting setups, control commissioning, moving) for the study by Meglio & Associates (Signify Lighting Representative in Saint Louis, MO) and Chicago LightWorks (Signify Lighting Representative in Chicago, IL). No specific inclusion and exclusion criteria were applied in selecting the independent living facilities or participants' accommodations types. The study was conducted in twenty dwelling units (fourteen in Saint Louis) including two single-family houses and 18 apartments between 650 – 1700 sqft.

Figure 2. Affordable Senior Community I, Saint Louis, MO

Figure 3. Affordable Senior Community II, Saint Louis, MO

Figure 4. High-end Senior Community, Chicago, IL

3.3. Participants

Recruitment for the study was conducted through holding presentations and distributing flyers to the residents of the above-mentioned independent livings. Residents of the communities were 54 years of age or older who resided independently in the villas and apartments within these communities.

3.3.1. Inclusion and Exclusion Criteria

Inclusion criteria included English speaking older adults 65 years of age or older residing in senior communities. Community-dwelling older adults are less mobile and spend most of their time inside the building and are exposed to the ambient lighting conditions of their rooms. This group of older adults are less likely to receive daylight exposure; thus, the quality of artificial lighting in their living environments might be critical for their sleep quality, mood, and cognitive functions. That is why, for the purpose of this study, we selected this group of the older population.

Furthermore, potential participants should show no evidence of moderate to major ADRD based on the Montreal Cognitive Assessment (MoCA) criteria (score of 26 and higher).

Exclusion criteria included any evidence of moderate to major dementia based on the Montreal Cognitive Assessment (MoCA) test (score of 25 or lower), blindness, and current use of light therapy. Moreover, potential participants were excluded if they spent most of their daily time (more than 5 hours) outside their private residential units or if they had planned upcoming travel out of the time zone during the study participation period. There were no inclusion or exclusion criteria based on sleep and mood (e.g., depression, anxiety).

3.3.2. Study-Wide Recruiting Methods

A total of 33 individuals signed up for the study. However, after initial screening nine individuals were excluded. The initial screening included a screening interview survey followed by the MoCA test for cognitive diagnosis to determine eligibility. During this process individuals were excluded due to evidence of moderate to major dementia (n = 3), upcoming travel (n = 1), and blindness (n = 1). We also excluded four individuals as they spent most of their day time out of their living environments for various reasons.

Eligible participants were scheduled for a visit at their apartment where details of the study were reviewed. From 24 eligible individuals, 21 remained in the study. The other three eligible individuals withdrew from the study for personal reasons. The participants were not told about the specific objectives of the study; however, they had been informed that the study was about the effects of lighting on sleep, mood, and well-being. The Institutional Review Board of the University of Illinois at Urbana-Champaign (UIUC) approved the research study, and all volunteers gave informed written consent as required by UIUC regulations and standards.

Following completion of the screening questionnaires and obtaining informed consent forms, participants were requested to wear an actiwatch to monitor their activity/rest cycle and light exposure for 41 days. They were asked to start wearing the actiwatch nine days prior the intervention session. We provided participant with the actiwatch two days prior the actigraphy starts so that they could acclimate to wear the new device. Moreover, the initial assessment of participants' subjective sleep, mood, cognitive performance, and health-related quality of life were conducted in this step.

All these procedures except the initial screening (Inclusion/Exclusion, Consent Form, and Cognitive Diagnosis) were repeated three more times on day 17th, 26th, 41st of the study, twice during the lighting interventions, and once 14 days after the lighting intervention period. All meetings with the participants were held in the participant's living room at their favorite seating spot. We also kept meeting time constant for all sessions, as DVs may vary throughout the day. For instance, if the baseline measurements for one participant were conducted at 10:00 hr, we repeated all the other measurements at 10:00 hr.

3.4. Procedures Involved

This data collection process took 41 days for each participant and included five sections: (1) Baseline Measurement 1 (B1), (2) Lighting Intervention 1 (L1), (3) Lighting intervention 2 (L2), (4) washout period, (5) Baseline Measurement 2 (B2).

The Duration of B1 section was nine days and encompassed a pre-test assessment of variables and nine days of actigraphy under the conventional lighting conditions in the participants' dwelling units. The first two days of this section were for participants to acclimate with the new device on their wrist and hence not considered in the data analysis. Thereafter, we supplied the lighting in the participants' homes (lighting intervention installation) and performed in-home lighting assessments. The process of lighting setup and measurements took for 2-3 hours for each participant. Participants were exposed to each lighting intervention for another nine days (Intervention session) while they continued wearing the actiwatch. We measured subjective variables and cognitive performance on the last day of each intervention. Here again, the first two days of each intervention section were for participants to adapt to the new lighting condition and thus not accounted for in the actigraphy data analysis. Furthermore, as it was a counterbalance study design, the 21 participants were randomly divided into two groups (group A and group B) that experienced different orders of lighting interventions.

Following the intervention sessions, there was a one-week washout period during which the experimental lights were removed from the participants' living room and the original lighting conditions were returned to the participants' living room. B2 section began right after the washout period and lasted for seven days. This section included 7-day of actigraphy and the post-intervention assessment of subjective variables and cognitive performance which were performed on the last day of B2 section. Table 5 shows the procedures involved in the data collection.

Table 5. Data Collection Procedures.

Section	Procedures	Data Collection Period				
		1 - 9	10 - 18	19 - 27	28 - 34	35 - 41
Screening	Screening	X				
B1	Pre-assessment	X				
L1	Lighting intervention setups		X			
	Intervention assessments		X			
L2	Intervention assessments			X		
Washout	Lights removal and return to conventional lighting				X	
A	Post-intervention assessment					X

3.5. Lighting Interventions

In this study, we evaluated the effects of two lighting interventions on sleep, mood, and cognitive functions of participants. Both lighting interventions were whole-day lighting schemes designed according to available research, standards, and circadian lighting metrics to meet the specific lighting needs of older adults.

3.5.1. Luminaires

In order to apply lighting interventions, a tunable white luminaire with high efficiency and lumen output was needed. After comprehensive market research, FloatPlane by Ledalite from Signify Lighting was selected for the study (Figure 5). The FloatePlane is a tunable white LED luminaire that offers a wide range of CCTs from 2700°K to 6500°K with a high lumen output of 4500 lumen/4ft. FloatPlane is available in a variety of mounting options (e.g., suspended, ceiling-mounted, and wall-mounted) and distributions (e.g., direct, direct/indirect). For the purpose of this study, four-foot suspended linear FloatPlane luminaires with a direct/indirect distribution (25% down / 75% up) were specified. The specifications of this luminaire were aligned entirely with the study criteria to apply whole-day lighting interventions.

Figure 6 illustrates the relative combined SPD of the luminaire at 6500°K and 2700°K. Utilizing the online tool developed by Lucas et al. (2014), the luminaire provided the Melanopic Ratio ranging between 0.45 and 0.97 (0.45 at 2700°K and 0.97 at 6500°K).

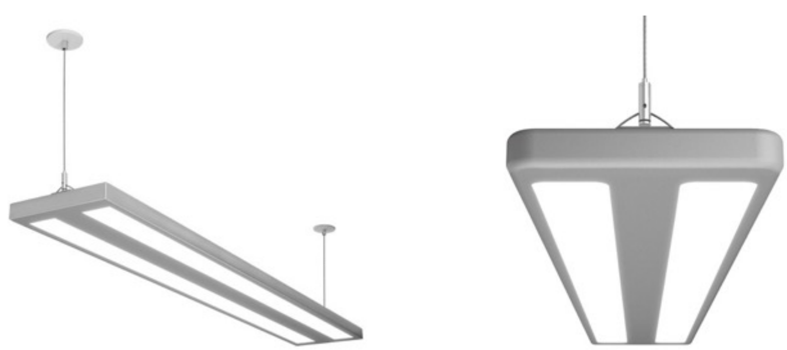


Figure 5. FloatPlane Linear Suspended Tunable White LED Luminaire by Ledalite, Signify

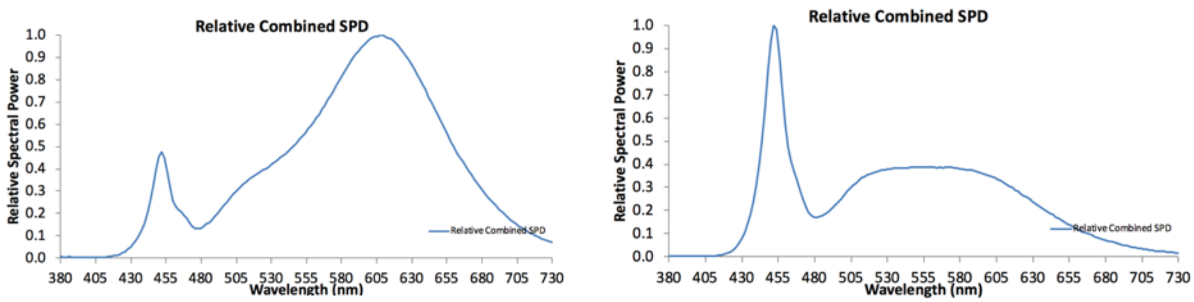


Figure 6. FloatPlane relative combined spectral power at 2700°K (left) and 6500°K (right).

3.5.2. Lighting Intervention 1 (L1)

The L1 was a whole-day lighting intervention which designed to evaluate the effects of varying illumination with constant CCT on the study variables. During this intervention, participants were exposed to a lighting condition with high illuminance levels (500 lux corneal) in the morning (8:00 – 12:00) and then the illuminance level descended gradually towards evening and reached to 100 lux (corneal) after 20:00 as indicated in Table 6. The CCT remained constant throughout the day at 2700°K. This is the common CCT used in residential spaces.. Illuminance levels in the L1 intervention were determined based on current literature and recommended numbers for CS and EML values. This lighting condition provided the CS of 0.38 at 500 lux corneal illuminance level for 4 hours in the morning (8:00 – 12:00) and the CS of 0.12 or less in the evenings (after 20:00). Moreover, considering the Melanopic ratio of 0.45 of the selected luminaires at 2700°K, we could achieve the EML of 225 lux in the morning which is in the range recommended by WELL Building Standard.

Table 6. Illuminance levels, timing, and CCT during L1.

Time	Illuminance (lux)	CCT (°K)	CS / (Cla)	R/EML
6:00 – 7:00	200	2700	0.21 / 170	0.45 / 90
7:00 – 8:00	400	2700	0.34 / 340	0.45 / 180
8:00 – 12:00	500	2700	0.38 / 425	0.45 / 225
12:00 – 16:00	400	2700	0.34 / 340	0.45 / 180
16:00 – 18:00	300	2700	0.29 / 255	0.45 / 135
18:00 – 20:00	200	2700	0.21 / 170	0.45 / 90
20:00 – 22:00	100	2700	0.12 / 85	0.45 / 45
22:00 – 6:00	<33	2700	0.04 / 28	0.45 / 15

As previously mentioned, timing and duration of exposure are other essential factors in designing an effective lighting scheme that meets the circadian needs of occupants. Table 7 shows a summary of the three daily time periods proposed by Andersen, Mardalijevic, & Lockley (2012) to categorize time-varied light exposures according to their expected non-visual effect. We utilized this table to define timing in the lighting interventions. However, as we did not intend to advance or delay the circadian clock in older adults, we adjusted the hours in the proposed lighting schemes based on the daily melatonin levels in healthy older adults (Figure 7) retrieved from 19 studies reviewed by Scholtens, van Munster, van Kempen, & de Rooij (2016). During the L1, older adults received the highest light levels from 8:00 to 16:00, which was the time that their melatonin level was at its lowest rate and the light had both entraining and alerting effects. This timing and duration of exposure were hypothesized to decrease daytime sleepiness and improve alertness, mood, cognitive performance, and nighttime sleep quality.

Table 7. Subdivision of day based on non-visual effect (Mark Andersen et al., 2012).

Daily Time Period	Non-Visual Effect	Description
6:00 – 10:00	Circadian resetting	High levels of bright illuminance can serve to phase advance the clock in the majority of people.
10:00– 18:00	Alerting effects of light	High levels of illuminance may lead to increased levels of subjective alertness without exerting substantial phase shifting effects on the clock
18:00 – 6:00	Bright light avoidance	Hight levels of illumination exposure is to be avoided so as not to disrupt the natural wake-sleep cycle

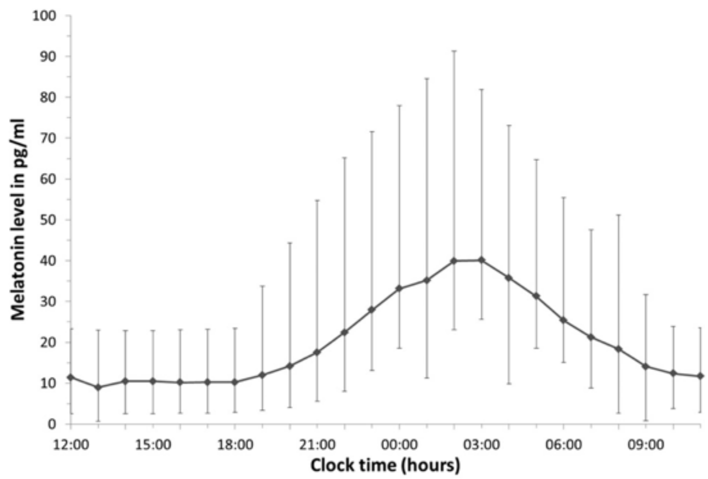


Figure 7. Mean, minimum and maximal melatonin levels in healthy older people. Weighted mean levels are plotted. Vertical bars represent the minimal and maximal levels found at each time point (Scholtens et al., 2016b, 2016a)

3.5.3. Lighting Intervention 2 (L2)

L2 was developed to examine the effectiveness of adding tuning spectrum to the ambient illumination on sleep quality, mood, and cognitive performance in older adults. L2, like L1, was a whole-day lighting scheme that included the same illuminance levels and timing schedule. However, unlike L1 that provided a constant CCT of 2700°K, in L2, the CCT was changing in a range of 2700°K – 6500°K throughout the day. A review of the literature demonstrates that exposure to bright blue light in the morning is beneficial to physical, physiological, and behavioral health in older adults, whereas nighttime exposure to bright light is associated with poorer sleep quality and mood (see Chapter 2 for citations). L2 exposed participants to a lighting condition that provided a high CCT (6500°K) and high illuminance level (500 lux) in the morning (8:00 – 12:00) and then both CCT and illumination decreased gradually every hour throughout the day and reached 2700°K and 100 lux respectively in the evening (after 20:00) as indicated in Table 8. Variable CCTs, in addition to variable illuminations, delivered more effectiveness in terms of circadian lighting. Circadian lighting calculations showed that L2 provided the CS of 0.47 at 500 lux corneal light level for 4 hours in the morning (8:00 – 12:00) and the CS of 0.12 or less in the evenings (after 20:00). Moreover, considering the Melanopic ratio of 0.97 of the selected luminaires at 6500K, the EML of 485 lux in the morning was obtained which was more than twice as large than the EML in L1.

Table 8. Illuminance levels, timing, and CCT during L2.

Time	Illuminance (lux)	CCT (°K)	CS / (Cla)	R/EML
6:00 – 7:00	200	4000	0.19 / 146	0.71 / 143
7:00 – 8:00	400	5000	0.31 / 294	0.82 / 247
8:00 – 12:00	500	6500	0.47 / 688.5	0.97 / 485
12:00 – 16:00	400	4500	0.35 / 353	0.76 / 308
16:00 – 18:00	300	3500	0.23 /183	0.66 / 197
18:00 – 20:00	200	3000	0.16 / 121	0.53 / 105
20:00 – 22:00	100	2700	0.12 / 85	0.45 / 45
22:00 – 6:00	<33	2700	0.04 / 28	0.45 / 14.85

3.5.4. Lighting Setups

Lighting interventions were manipulated by placing 4 to 5 of the selected luminaires in the living rooms of the participants and at the height of 6 feet. All the luminaires were installed on Manfrotto stands and provided a direct/indirect lighting distribution (75%up/25% down). To ensure the conceptual lighting intervention ideas would be transformed into successful installations in the participants' apartments, we employed the use of a lighting mock-up one week before the data collection process started in December 2018.

Figure 8 and Figure 9 illustrate the lighting mock-up that was performed at one of the conference rooms at Meglio & Associates Office. This lighting mock-up took two days during which we worked with the engineers from Meglio & Associates to test the concept and also define default lighting presets for each intervention.

The lighting setup at the participants' living room was done on the day 10^{th} of the study (first day of intervention). It was decided to place the lighting system only in the living room and only around the main sitting spot for two reasons; first, the limited number of luminaires and control systems (21 luminaires and four control sets), and second participants spent most of their active time in their living room. They used their bedrooms only for sleep when they usually kept their lights off.

6:00 – 7:00, 200 Lux, 2700ºK

7:00 – 8:00, 400 Lux, 2700ºK

8:00 – 12:00, 500 Lux, 2700ºK

12:00 – 16:00, 400 Lux, 2700ºK

16:00 – 18:00, 300 Lux, 2700ºK

18:00 – 20:00, 200 Lux, 2700ºK

20:00 – 24:00, 100 Lux, 2700ºK

24:00 – 6:00, 100 Lux, 2700ºK (upon request)

Figure 8. L1 mock-up at Meglio & Associate office

6:00 – 7:00, 200 Lux, 3000ºK

7:00 – 8:00, 400 Lux, 5000ºK

8:00 – 12:00, 500 Lux, 6500ºK

12:00 – 16:00, 400 Lux, 4500ºK

16:00 – 18:00, 300 Lux, 3500ºK

18:00 – 20:00, 200 Lux, 3000ºK

20:00 – 24:00, 100 Lux, 2700ºK

24:00 – 6:00, 100 Lux, 2700ºK (upon participants request)

Figure 9. L2 mock-up at Meglio & Associate office

Before setting up the luminaires, participants were informally interviewed during which they were asked about their main seating position, seating direction, and the type of task that they performed while they were seated. Then the luminaires were set up around that main seating zone to provide the highest corneal illuminance levels in most gazing directions. As participants were older adults who spent most of their time in their residential units and were not very active, they usually had one specific seating spot. The typical tasks performed in the living rooms were watching TV (mostly vertical plane), working with a computer (vertical plane), or reading (could be vertical or horizontal).

The lighting system usually was placed in an L-shape or U-shape geometry. This arrangement of luminaires helped with the uniformity of lighting distribution as the light was transmitted and reflected from various directions to/around the designated spot. However, the layout for placing luminaires was varied depends on the furniture layout, main gazing directions, type of tasks that were performed (e.g., reading, watching TV) and the limitations of floor plans (e.g., size of room and geometry). As the living area of each participant was unique (in terms of material, color, daylight availability, and size), the light intensity and CCT were adjusted accordingly to meet the required numbers defined in the lighting intervention. Hence, lighting setup and programming have always been done based on the specific characteristics of each living space.

3.6. Measures

3.6.1. Independent Variables – Lighting Measurements

The current lighting condition in the living area of the participants as well as the lighting during each intervention were measured. Ambient illuminance levels, Correlated Color Temperatures (CCT), and spectrum were the main independent variables measured in this study, using the Sekonic C-7000 Spectrometer. Measurements of lighting parameters were conducted around the primary sitting zone of the living area, where the luminaires were placed, and in both vertical and horizontal planes. To assure that the measurements were precise enough to indicate the accurate lighting exposure, we measured lighting variables in six points around the main seating zone on both vertical and horizontal planes (three verticals on three gazing directions at the eye level [seated] and three horizontals at the working plane). The measurement heights were also unique for each participant based on their height and the height of the chair they used. We repeated the measurement process for each lighting condition defined in each intervention in all defined gazing directions and working points. Hence, for each participant, we perform 90 measurements in total (6 for current lighting + 42 for L1 + 42 for L2).

In addition to the direct light measurements by a spectrometer, the actiwatches used in the study for the objective evaluation of the sleep also collected multiple light measurements including white and RGB illuminance levels and white light exposure (sum of all valid illuminance data in lux on a logarithmic scale for all epochs from the start time to the end time of a given interval multiplied by the epoch length in minutes). However, as this was a wrist-worn device, it could not measure the corneal illuminations and hence was only suitable for a very rough indication, such as how long people were exposed to the lighting interventions.

To assess the adequacy of the visual lighting levels, measured illuminance levels were compared to values recommended for older adults by the ANSI/IES RP-28-16, Lighting for the Visual Environment for Seniors and the Low Vision Population as well as an Adapted Standard (AS) by De Lepeleire et al. (2007). With regards to the appropriateness of the circadian lighting, circadian lighting metrics were employed to calculate Circadian Stimulus (CS) and EML of the ambient lighting condition.

3.6.2. Dependent Variables – Sleep

Both subjective and objective measures of sleep were obtained. The subjective measures were assessed by reliable and valid sleep questionnaires (which took around 5 - 15 minutes each time). These allowed us to attain information on sleep disturbance, overall quality of sleep, sleep-related impairments, and daytime sleepiness. Objective sleep and wake were assessed by 41-day actigraphy. Study participants were instructed to wear an actigraph on the non-dominant wrist for 24 hours a day for 41 consecutive days except when bathing.

Sleep Questionnaires: The following well-established and validated sleep questionnaires were used to obtain subjective sleep data. Participants completed the Pittsburgh Sleep Quality Index (PSQI), PROMIS Sleep Disturbance, PROMIS Sleep Related Impairments, and the Epworth Sleepiness Scale (ESS). Below is a summary of the key features of each questionnaire.

The Pittsburgh Sleep Quality Index (PSQI): The Pittsburgh Sleep Quality Index (PSQI) is a self-rated 21-item questionnaire that assesses the quality and patterns of sleep in an older adult. It distinguishes "poor" from "good" sleep by measuring subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction over the last month (Nebes et al., 2009). Scoring of the answers is based on a 0 to 3 scale, whereby 3 reflects the negative extreme on the Likert Scale. A global sum of "5" or greater indicates a "poor" sleep quality of an individual (see Appendix B). The PSQI has internal consistency and a reliability coefficient (Cronbach's alpha) of 0.83 for its seven components. Numerous studies using the PSQI in a variety of older adult populations internationally have supported high validity and reliability (Backhaus et al., 2002).

PROMIS Sleep-Related Impairment Item Bank (PROMIS_SRI): This instrument assesses perceptions of alertness, sleepiness, and tiredness during usual waking hours, and the perceived functional impairments during wakefulness associated with sleep problems or impaired alertness within the past seven days. The Sleep-Related Impairment item bank measures the level of waking alertness, sleepiness, and function within the context of overall sleep-wake function, but does not directly evaluate cognitive, affective, or performance impairments (Hanish, Lin-dyken, & Han, 2018; Kooten et al., 2018). It uses a 5-point Likert scale with higher scores indicate greater sleep-related impairments (see Appendix B). In reference to the PSQI, The Sleep-Related Impairment was significantly correlated (r = 0.7) (Cella et al., 2010) and shows internal consistency and a reliability coefficient (Cronbach's alpha) of 0.95 for a sixteen-item form (healthmeasures.net).

PROMIS Sleep Disturbance (PROMIS-SD) Item Bank: This instrument assesses perceptions of sleep quality, sleep depth, and restoration associated with sleep; perceived difficulties and concerns with getting to sleep or staying asleep; and perceptions of the adequacy of and satisfaction with sleep. The PROMIS Sleep Disturbance Scale does not include symptoms of specific sleep disorders, nor does it provide subjective estimates of sleep quantities (e.g., the total amount of sleep, time to fall asleep, or amount of wakefulness during sleep) (Hanish et al., 2018; Kooten et al., 2018). Like PROMIS-SRI, it uses a 5-point Likert scale with higher scores indicate greater sleep disturbance (see Appendix B). In reference to the PSQI, The Sleep Disturbance was significantly correlated (r = 0.85) (Cella et al., 2010) and shows internal consistency and a reliability coefficient (Cronbach's alpha) of 0.90 or above (Yu et al., 2012).

Epworth Sleepiness Scale (ESS): The Epworth Sleepiness Scale is a widely-used questionnaire developed in the field of sleep medicine as a measure of a patient's daytime sleepiness. The test is a list of eight situations in which participants rate their tendency to become sleepy on a scale of 0, no chance of dozing, to 3, high chance of dozing. The total score is based on a scale of 0-24 (see Appendix B). ESS scores of 11-24 represent increasing levels of excessive daytime sleepiness. ESS has a high level of internal consistency and a reliability coefficient of 0.88 as measured by Cronbach's alpha (Johns, 1992). ESS has been used in several studies to evaluate the impacts of lighting on older adults' sleep quality which confirms the validity and reliability of this questionnaire (see Chapter 2).

Actigraphy: Participants were asked to wear a wrist actigraph for 41 consecutive days. Actigraphy is demonstrated as a valid and objective method for evaluating sleep-wake parameters in natural settings (Ancoli-Israel et al., 2002). Actigraphy has been used in numerous studies to measure the objective sleep outcomes among older adults in relation to light (see Chapter 2). We employed the Actiwatch system (Actiwatch, Mini Mitter, Bend, Oregon). It is designed for long-term monitoring of gross motor activity in humans and has an accelerometer capable of sensing motion with a minimal resultant force of 0.01 x g (Actiwatch, 2001).

Actigraphy has been used successfully with a variety of populations (Galland et al., 2018; Meltzer et al., 2019). Actigraphy has been validated against polysomnography and been shown to have high sensitivity (0.965) and accuracy (0.863) but with limitations in specificity (0.329) and is recommended as a valid tool for estimating sleep in the field (Hjetland, Nordhus, Pallesen, & Cummings, 2020).

Study participants were instructed to wear an actigraph on the non-dominant wrist for 24 hours a day for 41 consecutive days except when bathing. Valid data were recorded for a range of 33 to 41 days, with the average participant yielding 37.4 days of actigraphy data meeting inclusion criteria for analysis, as determined by <4 hour off-wrist time per day. Analysis was conducted on Actiware software version 5 (Philips Respironics) with 30-sec sampling epochs. Actigraphy variables analyzed include night time sleep duration (total minutes between the start time and end time of a given interval scored as sleep on nights), daytime sleep duration (total minutes between the start time and end time of a given interval scored as sleep during the active period), night time sleep onset latency (time elapsed between the start time of a given rest interval and the following sleep start time on nights following workdays and free days), night time sleep efficiency (the percentage of scored total sleep time to interval duration minus total invalid time for the given rest period on nights following workdays and free days), and average daytime white light exposure (sum of all valid illuminance data in lux on a logarithmic scale for all epochs from the start time to the end time of a given interval multiplied by the epoch length in minutes from 7:00 – 18:00 (active period)), and average nighttime white light exposure (sum of all valid illuminance data in lux on a logarithmic scale for all epochs from the start time to the end time of a given interval multiplied by the epoch length in minutes from 18:00 – 7:00 (rest period)).

3.6.3. Dependent Variables – Mood

Subjective mood was measured by means of standard questionnaires including Geriatric Depression Scale (GDS) and Positive and The Negative Affect Schedule (PANAS).

Geriatric Depression Scale (GDS): GDS is one of the most common questionnaires that are used by researchers to study the impact of lighting on older adults' mood and depression (see Table 3). GDS is a 30-item self-report assessment used to identify depression in older adults (see Appendix B). GDS is a widely used depression screening device which has high internal consistency (Cronbach's alpha of 0.85), and high test-retest coefficient reliability (0.83) (Kieffer & Reese, 2002). This questionnaire requires a yes/no answer and therefore the scale is particularly easy to administer. The scale focuses mainly on the worries of patients and the way they conceive and interpret their quality of life. In particular, it avoids questions concerning somatic complaints which are common among older adults. Although it does not contain items that assess agitated or psychotic behavior, it is designed to register a cognitive (i.e., thought content) dimension of depression, and is highly correlated with the Beck Depression Inventory (Fountoulakis, Tsolaki, & Kazis, 2000).

The Positive and Negative Affect Schedule (PANAS): PANAS is a 20-item self-report measure of positive and negative effect (see Appendix B). NA and PA reflect dispositional dimensions, with high-NA epitomized by subjective distress and unpleasant engagement, and low NA by absence of these feelings. In contrast, PA represents the extent to which an individual experiences pleasurable engagement with the environment (Antunes, Couto, Vitorino, Monteiro, & Daniel, 2019). The PANAS has strong reported validity with such measures as general distress and dysfunction, depression, and state anxiety. Reliability and Validity reported by (Humboldt, Monteiro, & Leal, 2017) was moderately good. For the Positive Affect Scale, the Cronbach alpha coefficient was 0.86 to 0.90; for the Negative Affect Scale, 0.84 to 0.87.

3.6.4. Dependent Variables–Cognitive Performance

Cognitive performance was measured by means of standard assessment tools such as Montreal Cognitive Assessment (MoCA), Trail-Making Teas A & B (TMT – A & B), and Digit Symbol Substitution Test (DSST).

Montreal Cognitive Assessment (MoCA): The Montreal Cognitive Assessment was used to screen the cognitive function of older adults and evaluate their eligibility to participate in the study. MoCA was developed as a brief cognitive-screening questionnaire to detect patients with mild cognitive impairment (MCI) and mild Alzheimer's (AD). These patients usually score within the normal range on the most commonly used cognitive screening tools such as Mini-Mental State Examination (MMSE) (Nasreddine et al., 2005). The latest version of MoCA is a one-page 30-point test which can be administrated in 10 minutes (see Appendix B). This test includes 7 subscores: visuospatial/executive (5 points), naming (3 points), memory (5 points for delayed recall), attention (6 points), language (3 points), abstraction (2 points), and orientation (6 points). To better adjust the MoCA for individuals with lower levels of education, 2 points is added to the total MoCA score for those with 4-9 years of education and 1 point for 10-12 years of education (Johns et al., 2010). The suggested cutoff point on MoCA is 26 which means that individuals with a score of 26 or more are considered normal. Studies reported that MoCA has a good validity and reliability and detects MCI with 90-96 percent range of sensitivity and specificity of 87 percent with 95 percent coefficient interval (Doerflinger, 2012; Wittich, Phillips, Nasreddine, & Chertkow, 2010).

Trail Making Test A & B (TMT-A & B): TMT is a timed test that provides information on visual search, scanning, speed of processing, mental flexibility, and executive function. TMT consists of two parts. TMT-A requires an individual to draw lines sequentially connecting 25 encircled numbers distributed on a sheet of paper. TMT-B requires participants to continuously scan a page to identify numbers and letters in a particular order while shifting from the number to letter set (see Appendix B). A faster time for completion (in seconds) represents better cognitive functioning. TMT-A purportedly measures attention, visual search and motor function, whereas TMT-B is seen as a measure of executive functioning, speed of attention, visual search and motor function (Dobbs & Shergill, 2013). Moreover, the difference of scores in TMT-A and TMT-B (B – A) indicates cognitive flexibility (Vazzana et al., 2011). Studies show a high validity (Ashendorf et al., 2009; Tombaugh, 2004; Wagner, Helmreich, Dahmen, Lieb, & Tadi, 2011) and reliability of TMT-A and B in testing cognitive function of older adults with test-retest reliability of 0.78 and 0.73 as well as inter-rater reliability coefficients of 0.99 and 0.93, for TMT-A and TMT-B respectively (Cangoz, Karakoc, & Selekler, 2009).

Digit Symbol Substitution Test (DSST): The DSST is a paper-and-pencil test that is used as a tool to evaluate cognitive functioning. The test is presented on a single sheet and requires that the participants fill in a series of symbols that are matched to each number according to a key located on the top of the page (see Appendix B). The number of correct symbols within the allowed time (90 seconds) is measured as the score. DSST measures processing speed, working memory, visuospatial processing, and attention. The DSST is one of the most commonly used tests in all of neuropsychology, owing to several inherent properties including brevity, reliability, and the minimal impact of language, culture, and education on test performance. It has undergone repeated and rigorous psychometric validation such as test-retest reliability and discriminant validity in a range of patient samples (Jaeger, 2018).

3.6.5. Dependent Variables: Health-Related Quality of Life

Health-related quality of life in participants were assessed by means of SF-8 instrument. The SF-8 was developed by QualityMetric and provides a generic measure of physical and mental health status which is not specific to age, disease or treatment groups. This instrument uses single item scales addressing eight domains of general health, physical functioning, role limitations as a result of physical and mental health issues, physical pain, vitality, social functioning, and mental health (see Appendix B). SF-8 showed a very good internal consistency reliability (overall Cronbach's alpha = 0.749) and known-groups validity (Lang et al., 2018).

3.7. Assumptions and Delimitations

The following assumptions were considered:

- Participants provided honest answers when rating their sleep and mood.
- Participants put forth maximum effort during all cognitive tests.

- Participants kept the same daily routines during the study period and no significant change occurred in their lifestyle, such as their medicines, daily tasks, food, etc.
- Participants spent at least seven hours in their apartment during the wake time (8:00 – 22:00) throughout the study period.

Delimitation of the study were the following:

- Participants were delimited to those who were residents of the retirement community.
- Participants were delimited to those who were 65 years of age or older.
- Participants were delimited to those who did not show any evidence of medium to major dementia.
- Participants were delimited to those who resided in their current accommodation for more than 12 months.
- Participants were delimited to those who were retired and spent more than 7 hours of their wake time home.
- The study was delimited to three lighting conditions: Participants Conventional Lighting, Lighting Intervention 1 (L1), and Lighting Intervention 2 (L2)
- The study was delimited to a repeated measures design because it was conducive to the population and the effects of lighting conditions being studies. The design allowed participants to serve as their own controls, eliminating the need for a control group. This study design made the study more efficient and kept the variability low.

3.8. Data Management

A paper file was created for each participant which included demographic data and all the questionnaires and tests filled by participants throughout the four sections of the study. All the information in the paper file was handwritten by the author (myself) and participants. An identification number was assigned to each participant. Data were cleaned up and recorded on Excel sheets before entering that in SPSS for the statistical analysis. Data recorded in the Excel and SPSS did not indicate participants' identifying information and participants were identified only by the assigned ID number. All the data, including paper and digital files, were maintained in a locked file cabinet in the author's home office. Consent forms with identifying information were kept in a separate locked file cabinet. Digital files were all password protected. Data collected will be maintained for a minimum of 36 months after completion of the study and will be marked to destroy after that time period.

3.9. Statistical Analysis

Data were managed and analyzed using IBM SPSS 26.0 statistical software. Descriptive statistics were employed to summarize sample characteristics (age, gender, accommodation type, and education levels), including means and standard deviations for continuous data as well as frequencies for categorical data.

Due to the difference in living conditions, lifestyle, and population type, participants were divided into two groups based on their building of residence (affordable versus high-end). An Independent-Samples t-test was employed to compare baseline mean scores for DVs based on the senior living type. Moreover, baseline mean scores for DVs were compared based on the baseline daylighting condition in the apartments (HQDLR versus LQDLR).

We employed a mixed model analysis of variance (Mixed ANOVA) (4 x 2) to analyze the main effect of group (order of exposure) on DVs. There was no significant effect of group nor any interactions between the group and lighting conditions, suggesting that the effect of lighting conditions on DVs is independent of the order of exposure and so the order can be overlooked.

In the next round of analysis, due to the small sample size, the effect of order was ignored to increase the power of the analysis. Here, the main effect of lighting condition on DVs was analyzed using a one-way general linear model repeated measure analysis of variance (RM ANOVA), a robust method for analyzing repeated measures data. The study included three lighting conditions with four levels of measurements, B1, L1, L2, and B2. Since the lighting conditions at two baselines were the same, mean of B1 and B2 was calculated and considered as one lighting condition, called Baseline. Then, a RM ANOVA with three levels of conditions (Baseline, L1, and L2) was employed to examine the main effect of lighting on DVs. A one-way RM ANOVA was run for the following DVs: Night-Time Sleep Duration (NSD), Daytime Sleep Duration (DSD), Sleep Efficiency (SE), Sleep Onset Latency (SOL), Sleep Disturbance (SDist), Sleep-Related Impairments (SRImp), Daytime Sleepiness (DSle), Sleep Quality (SQ), Depression, Positive Affects (PA), Negative Affects (NA), Health-Related Quality of Life (QL), and three measures of cognitive functions (TMT-A, TMT-B, DSST).

Moreover, in order to further explore changes depending on treatment effects and to better understand stabilization of possible effects within the follow-up period, further post- hoc analyses with paired-samples t-tests were applied for Baseline – L1, Baseline – L2, and L1 – L2. We also examined the relationships between DVs and their possible mediating effect by utilizing the SPSS Macro provided by Preacher & Hayes (2004) which enabled an estimation of the indirect, direct, and total effects in simple mediation models.

Additionally, we ran a RM ANOVA with four levels of measurements (B1, L1, L2, and B2) to investigate the changing pattern of DVs in the course of study as well as any potential carryover effects of lighting observed at B2. However, to avoid redundancy, the results of this analysis along with its related paired samples t-tests were shown in Appendix A.

In the next round of analysis, the effect of senior living types and baseline daylighting conditions, as well as the interaction of them with the lighting conditions, were analyzed using a Mixed ANOVA. For all analyses, statistical significance was set at 95% ($P < 0.05$). Moreover, in all ANOVA analysis, the assumption of sphericity was tested using Mauchly's Test of Sphericity, if significant (means the sphericity assumption was violated), the Greenhouse-Geisser correction was utilized to report the ANOVA's results.

CHAPTER 4: RESULTS

4.1. Descriptive Results

A number of 21 participants met the inclusion/exclusion criteria and signed the informed consent to participate in the study. Table 9 and Table 10 illustrate demographic data of participants in each senior living facility and study group respectively. Out of 21 participants, 76.2% (n = 16) were female and 23.8% (n = 5) were male with a mean age of 78.81 (SD = 8.13). On average, participants had resided in their current dwelling unit for 7.57 years (SD = 4.98). Eighty six percent of participants (n = 18) lived alone. As shown in Table 9, 33.3% (n = 7) had a 12th-grade education, 23.8% (n = 5) had some college or associated degree, 14.3% (n = 3) had a bachelor's degree, 23.8% (n = 5) had master's degree, and 4.8% (n = 1) had a doctorate degree.

Table 9. Demographic data in each senior living facility.

Variables	**Affordable I**	**Affordable II**	**High-End**
Number of Participants	3	11	7
Gender			
Female	3 (100%)	8 (72.7%)	5 (71.4%)
Male	0 (0%)	3 (27.3)	2 (28.6%)
Age			
Mean	76	73.64	82.14
SD	7.55	8.82	4.41
Range	69 - 84	65 - 91	78 - 91
Median	75	70	82
Race			
White	3 (100%)	10 (90.9%)	7 (100%)
African-American	0 (0%)	1 (9.1%)	0 (0%)
Asian	0 (0%)	0 (0%)	0 (0%)
Others	0 (0%)	0 (0%)	0 (0%)
Living Status			
Alone	3 (100%)	11 (100%)	4 (57.15%)
With Someone	0 (0%)	0 (0%)	3 (42.86%)
Education			
12th grade	1 (33.3%)	6 (54.5%)	0 (0%)
Some College/Associated	2 (66.7%)	3 (27.3%)	0 (0%)
Bachelor's	0 (0%)	1 (9.1%)	2 (28.6%)
Master's	0 (0%)	1 (9.1%)	4 (57.1%)
Doctorate	0 (0%)	0 (0%)	1 (14.3%)
Years of Residency			
Mean	4	9.45	6.14
SD	5.2	5.87	0.9
MoCA			
Mean	29.33	27.54	27.85
SD	1.15	1.21	2.04

Table 10. Demographic data in each group.

Variables	Group A	Group B
Number of Participants	11	10
Gender		
Female	9 (81.8%)	7 (70%)
Male	2 (18.2%)	3 (30%)
Age		
Mean	77.27	76.30
SD	8.38	8.26
Range	66 - 91	65 - 91
Median	78	77
Race		
White	11 (100%)	9 (90%)
African-American	0 (0%)	1 (10%)
Asian	0 (0%)	0 (0%)
Others	0 (0%)	0 (0%)
Living Status		
Alone	11 (100%)	7 (70%)
With Someone	0 (0%)	3 (30%)
Education		
12^{th} grade	2 (18.2%)	5 (50%)
Some College/Associated	4 (36.4)	1 (10%)
Bachelor's	3 (27.3%)	0 (0%)
Master's	2 (18.2%)	3 (30%)
Doctorate	0 (0%)	1 (10%)
Years of Residency		
Mean	6.27	9
SD	3.95	5.77
MoCA		
Mean	28.45	27.30
SD	1.63	1.34

One inclusion criterion for this study included a score of 26 or above on the MoCA test. The mean score of the 21 participants on the MoCA test was 27.90 (SD = 1.58) with a range of 26 – 30 (Table 9 and Table 10). Participants were asked about their medical conditions in relation to eye diseases, sleep problems, and psychological issues. Among them, 9.5% (n = 2) reported psychological/psychiatric (mood, anxiety, depression), 14.1% (n = 3) had macular degeneration, and only 19% (n = 4) reported having sleep problems (e.g., insomnia, daytime sleepiness, sleep apnea). No participant took medications for their sleep. However, the 2 participants with psychiatric problems took psychoactive medications and they continued taking them during the period of the study.

4.2. Lighting Measurements and Analysis

4.2.1. Baseline Lighting

Baseline lighting measurements were performed in twenty living rooms and around the main seating area during the daytime between 10:00 – 14:00 h. The first assessment was conducted between December and March 2019 in the two affordable senior livings in Saint Louis, MO. In October and November 2019, the high-end senior living in Chicago, IL, was assessed. No modification was applied to the lighting for the baseline measurements. For instance, if a participant kept the window blinds closed during the daytime, the illumination was measured with closed blinds.

Two references were used to evaluate the illuminance levels and CCT at the baseline and interventions: (1) ANSI/IES RP-28-16, Lighting for the Visual Environment for Seniors and the Low Vision Population and (2) an Adapted Standard (AS) by De Lepeleire et al. (2007). ANSI/IES RP-28-16 recommends a horizontal illuminance level of 200 lux or higher for ambient lighting and 500 - 750 lux for task lighting in the living spaces. De Lepeleire et al. (2007) developed an adapted standard for older adults based on The European Standard for Light and Lighting of Indoor Work Places (ES). Given the fact that an individual's need for light increases inevitably at the rate of 1% per year after the age of 20 years, they increased illuminance levels recommended by ES by 55%. Hence, a horizontal illuminance level of 155 lux or higher for ambient illuminations and 775 lux for task lighting were suggested. The results of lighting measurements were compared to both references. None of these references provides any guidance with regards to vertical illuminance levels and CCTs. The corneal illuminance level along with spectrum plays an important role in the circadian effects of lighting. Two evaluate those variables, CS and EML values were utilized. In the study, we set the critical threshold for CS at the mean value of 0.3 and for EML at the mean value of 220 as recommended by literature and WELL Standard, respectively.

Table 11, Figure 10 and, Figure 11 show the results of baseline lighting measurements. As shown, the mean horizontal illuminance level is 51.32 (SD = 3.50), 13.80 (SD = 99.88), 443.36 (SD = 199.01) lux in Affordable I, Affordable II, and High-end senior livings respectively. Results indicated that 66.7% of measured horizontal illuminances in the living rooms of participants fell below the 200lux threshold defined by ANSI/IES RP-28-16. In fact, among the fourteen living spaces assessed in the affordable senior livings, only one had a mean illuminance level higher than 200 lux. In the High-end senior living, a higher mean horizontal illumination was observed and 5 out of 6 living rooms met the ANSI/IES RP-28-16 threshold. Comparing the results with AS revealed that only 21.4% (n = 3) of the living rooms in the Affordable senior livings had a mean horizontal illuminance level higher than 155 lux. However, in High-end, all the assessed living rooms met the AS threshold. In general, corneal illumination was higher than horizontal in all living spaces as most of the light came through the windows (daylighting) and participants usually did not use electrical lighting during the daytime. Again, the High-end senior living tended to score best in the corneal illuminance level with a mean of 278.47 lux (SD = 146.17).

In terms of CCT, Corneal and Horizontal CCT appeared to be similar. The mean horizontal CCT was varied in a range of 2600°K - 5600°K with the highest mean horizontal CCT of 5230.81°K (SD = 427.23) at the High-end senior living. The range of mean corneal CCT was 2922.67°K – 5713.00°K with the highest mean number obtained at the High-end senior living (Mean CCT = 4887.05°K, SD = 199.01).

The measured spectrum data and vertical illuminance levels were used to calculate CS, R Ratio, and EML in the living rooms. The calculations showed a mean daytime CS of 0.03, 0.13, and 0.28 as well as the EML of 16.86, 103.69, and 250.76 in Affordable I, Affordable II, and the High-end senor living respectively. Around 76% of the living spaces fell below the 0.3 CS and 220 EML threshold during the daytime with more frequency in Affordable I (100%) and Affordable II (81.8%). Lack of sufficient amount of daylighting and, of course, no permanent ceiling or wall electrical lighting system were the main reasons for low levels of CS and EML in these living rooms which were called low quality daylighting living rooms (LQDLR). Out of 20 living rooms, only five provided sufficient daytime circadian lighting based on the CS and EML threshold values. All these living rooms were the ones with quality access to natural light in which participants kept all the window blinds open almost all the time; hence, they were called high quality daylighting living rooms (HQDLR). Although the mean EML in the High-end senior living, is higher than the 220 setpoint, only three out of six living rooms (50%) were actually above this set point. This occurred due to a broad SD and range of calculated EMLs in this senior living (Range: 35.5 – 503.39, SD = 149.54).

Given these results, it could be concluded that the overall lighting condition was better in the High-end senior living compared to the Affordable ones. An independent t-test analysis revealed a significant higher corneal illumination ($t = 2.459$; $P < 0.05$) and higher horizontal illuminance level ($t = 4.69$; $P < 0.05$) in the High-end facility.

Table 11. Results of baseline lighting measurements in each senior living.

Variable	Affordable I	Affordable II	High-end
Number	3	11	6
Corneal Illumination			
Mean Illuminance level	21.24	119.5	278.47
Illuminance level SD	3.50	125.6	146.17
Min - Max	18.87 – 25.27	11.5 – 358.5	41.47 – 513.67
Mean CCT °K	4363.22	4221.7	4887.05
CCT SD	1434.55	945.56	199.01
Min – Max °K	2966.00 – 5713.00	2922.67 – 5552.00	4194.00 – 5629.00
Horizontal Illumination			
Mean Illuminance level	51.32	113.80	443.36
Illuminance level SD	3.50	99.88	199.01
Min - Max	29.53 – 68.67	19.07 – 349.00	177.87 – 658.00
Mean CCT °K	4578.56	4205.58	5230.81
CCT SD	1434.56	1367.30	427.23
Min – Max °K	2966.00 – 5713.00	2676.00 – 6947.00	4543.67 – 5602.33
Comparison with ANSI/IES RP-28-16			
< 200	100% (n = 3)	90.9% (n = 10)	16.6% (n = 1)
≥ 200	0% (n = 0)	0.9% (n = 1)	83.3% (n = 5)
< 750	0% (n = 0)	0% (n = 0)	0% (n = 0)
≥ 750	0% (n = 0)	0% (n = 0)	0% (n = 0)
Comparison with AS			
< 155	100% (n = 3)	72.7% (n = 8)	0% (n = 0)
≥ 155	0% (n = 0)	27.3% (n = 3)	100% (n = 6)
< 775	0% (n = 0)	0% (n = 0)	0% (n = 0)
≥ 775	0% (n = 0)	0% (n = 0)	0% (n = 0)
CS			
Mean CS	0.03	0.13	0.28
SD	0.02	0.14	0.14
Min - Max	0.02 – 0.05	0.01 – 0.4	0.05 – 0.46
< 0.30	100% (n = 3)	81.8% (n = 9)	50% (n = 3)
≥ 0.30	0% (n = 0)	18.2% (n = 2)	50% (n = 3)
EML			
Mean EML	16.86	103.69	250.76
EML SD	9.20	124.77	149.54
EML Min - Max	10.13 – 27.34	9.16 – 369.37	35.30 – 503.39
Mean R Ratio	0.76	0.78	0.88
R Ratio SD	0.29	0.18	0.10
R Ratio Min - Max	0.52 – 1.08	0.48 – 1.00	0.76 – 0.98
< 220	100% (n = 3)	81.8% (n = 9)	50% (n = 3)
≥ 220	0% (n = 0)	18.2% (n = 2)	50% (n = 3)

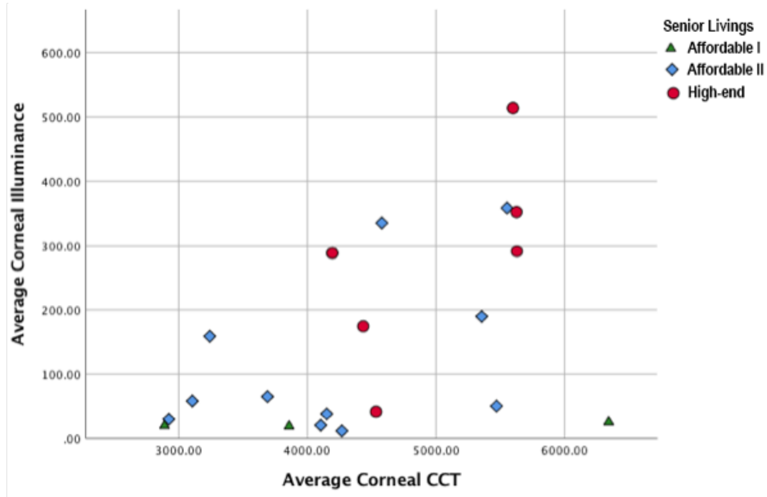


Figure 10. Corneal lighting condition at baseline

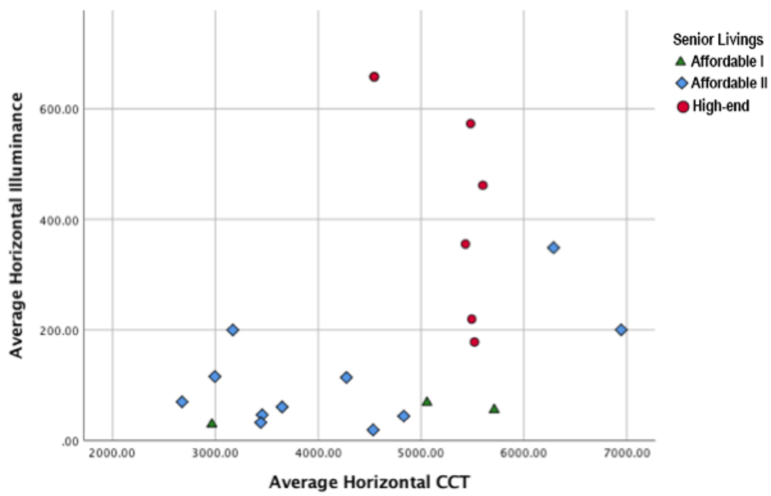
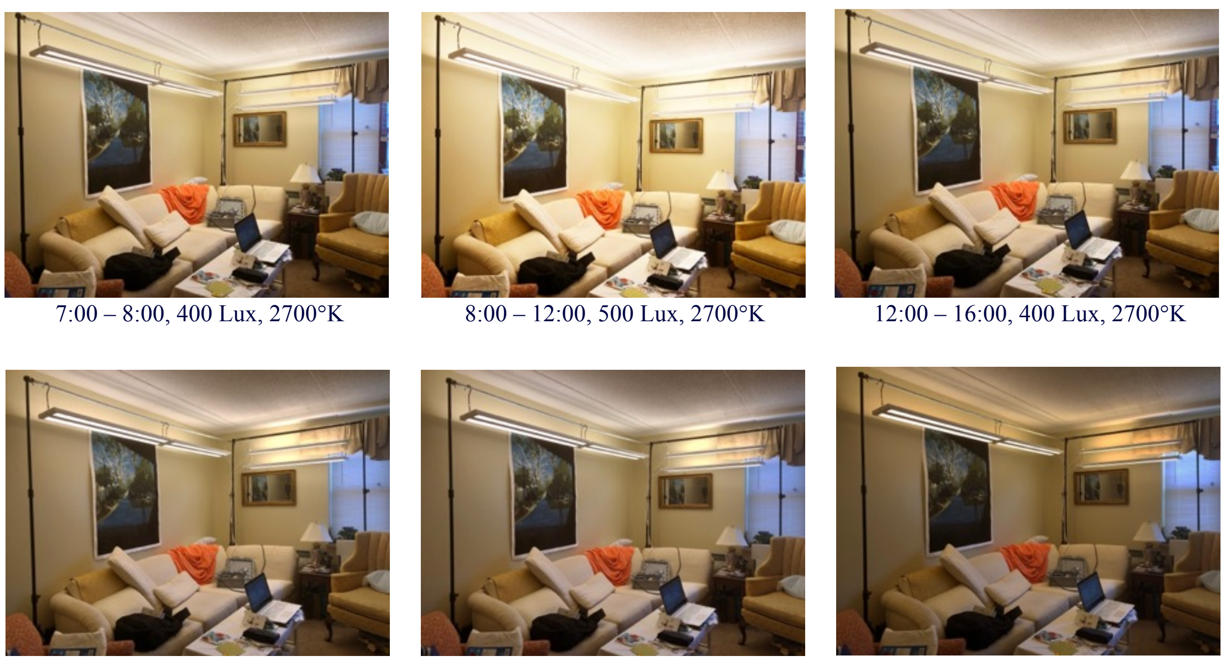


Figure 11. Horizontal lighting condition at baseline

4.2.2. Lighting Intervention 1 (L1)

Figure 12 shows an example of L1 lighting intervention in one living room in the Affordable II facility in Saint Louis. As shown, under this lighting intervention, the color (CCT and spectrum) of the light was consistent throughout the day and only the intensity was changing. In most of the units and due to a negligible amount of daylighting, lighting intervention measurements were conducted during the daytime between 10:00 and 16:00. All the window blinds were closed to minimize the effects of natural light on the outcomes. If the closed window blinds could not reduce natural light effects sufficiently, we performed measurements after 17:00. It should be noted that we covered windows only for the purpose of lighting measurements; to make sure that participants would receive targeted illuminance levels defined in Table 6 and Table 8. During the interventions, participants were allowed to open or close blinds as needed and based on their routine lifestyle. Hence, it was possible that one participant received higher illuminance levels on a sunny day and if they decide to keep blinds open.



7:00 – 8:00, 400 Lux, 2700°K | 8:00 – 12:00, 500 Lux, 2700°K | 12:00 – 16:00, 400 Lux, 2700°K

16:00 – 18:00, 300 Lux, 2700°K | 18:00 – 20:00, 200 Lux, 2700°K | 20:00 – 24:00, 100 Lux, 2700°K

Figure 12. An example of L1 in a living room in the Affordable II Senior Living

Table 12 shows lighting measurement outcomes under L1. As shown, the average obtained corneal illuminance levels were very close to the target numbers defined in Table 6. The average corneal illuminance level at 8:00 was 519.16 lux which was slightly more than 500 lux required for L1 intervention at this time. The evening illuminance level had been determined to be at 100 lux or less and the average measured was at 94.47. No criteria for horizontal illuminance was set in this study. It was hypothesized that by achieving the required illumination for circadian effects, the visual lighting needs defined by ANSI/IES RP-28-16 and De Lepeleire et al. (2007) would be met. The hypothesis appeared to be correct as the average horizontal illuminance levels throughout the day were always higher than the 200 and 155 lux setpoints with the highest average horizontal illumination of 754.83 at 8:00.

Table 12. L1 Lighting measurements.

	Time	Minimum	Maximum	Mean	SD
Corneal Illuminance					
	6:00	185.00	250.33	210.32	13.37
	7:00	393.33	441.33	409.11	10.31
	8:00	491.00	585.00	519.61	26.76
	12:00	393.33	441.33	409.11	10.31
	16:00	279.00	327.00	304.65	11.76
	18:00	158.67	220.33	200.14	15.35
	20:00	74.90	106.00	94.47	9.37
Horizontal Illuminance					
	6:00	335.33	475.00	396.21	35.95
	7:00	594.33	705.33	648.52	31.27
	8:00	704.33	839.00	754.83	44.62
	12:00	594.33	705.33	648.52	31.27
	16:00	354.00	695.67	449.86	77.23
	18:00	277.00	372.33	326.75	24.36
	20:00	201.33	298.00	238.44	28.81
Corneal CCT°K					
	6:00	2499.67	2792.67	2677.83	82.04
	7:00	2517.33	2772.67	2667.43	68.63
	8:00	2527.00	2789.67	2655.11	73.46
	12:00	2517.33	2772.67	2667.43	68.63
	16:00	2523.67	2851.33	2675.54	94.49
	18:00	2474.67	2831.00	2684.62	80.90
	20:00	2479.33	2940.00	2708.46	101.54
Horizontal CCT°K					
	6:00	2636.00	2859.00	2717.95	63.19
	7:00	2627.67	2885.00	2689.63	65.45
	8:00	2626.00	2819.67	2688.41	53.31
	12:00	2627.67	2885.00	2689.63	65.45
	16:00	2626.67	2844.00	2690.54	50.45
	18:00	2519.33	2858.33	2721.60	85.46
	20:00	2525.00	2846.00	2726.65	86.62
CS					
	6:00	0.19	0.24	0.22	0.02
	7:00	0.31	0.36	0.34	0.01
	8:00	0.35	0.40	0.38	0.02
	12:00	0.31	0.36	0.34	0.01
	16:00	0.25	0.31	0.28	0.02
	18:00	0.19	0.24	0.22	0.02
	20:00	0.09	0.13	0.11	0.01
EML					
	6:00	81.89	112.15	93.11	8.00
	7:00	159.68	192.98	179.06	8.77
	8:00	201.96	265.95	226.16	15.99
	12:00	160.07	192.69	179.06	8.50
	16:00	112.46	155.14	133.20	9.67
	18:00	68.23	101.03	88.45	8.80
	20:00	31.86	50.92	42.42	5.57

Although the CCT of the luminaires was fixed at 2700°K, due to the varied color and material characteristics at each living room, a range of corneal CCT (2474°K - 2940°K) and horizontal CCT (2519°K - 2885°K) were obtained. However, the average corneal CCT throughout the day was between 2655°K – 2708°K which was very closed to the target CCT. In addition to the CCT, the spectrum data of the L1 were recorded for the purpose of circadian lighting calculations. Similar to CCT, the spectrum of the light was affected by the dominant wall, floor, ceiling, and furniture color in the living room. Hence, the peak wavelength of the lighting under L1 intervention was varying in the range of 608 – 612 nm all the time during the day, excluding daylighting. Figure 13 shows the absolute corneal SPD of the L1 in the same living room shown in Figure 12.

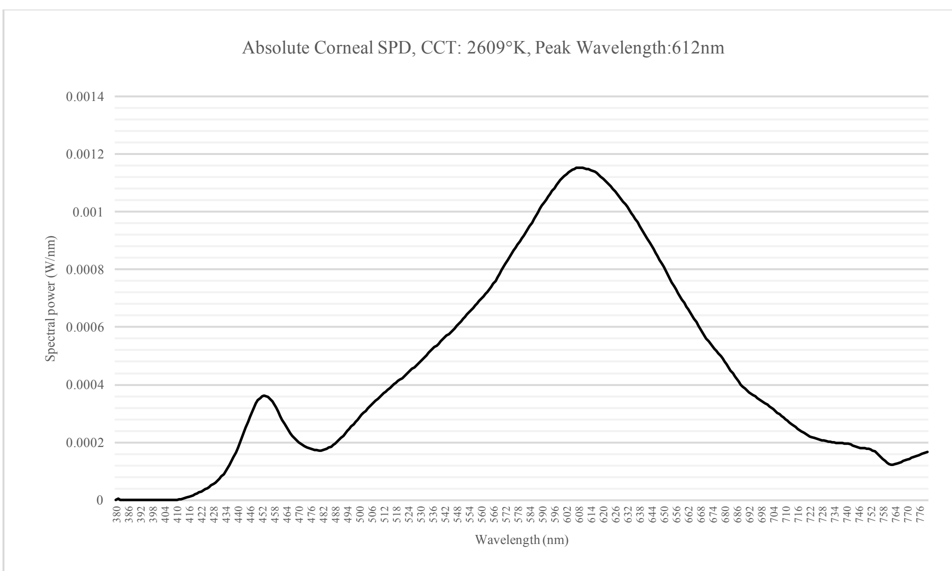


Figure 13. An example of corneal absolute SPD in main gazing direction during the L1 intervention in the living room shown in Figure 12. During the L1, the SPD of the light was programmed to remained constant during the day so as the CCT.

Circadian lighting calculations also showed promising numbers. The average morning (8:00 -12:00) CS value for L1 was 0.38 (SD = 0.02), with all living rooms having the morning CS of more than 0.35 (see Table 12). The average nighttime CS value was as low as 0.11 with a small range of 0.09 – 0.13. Moreover, the L1 intervention provided an EML of 220 or higher in the morning (8:00 – 12:00) in 12 living rooms with a total average of 226.16 (SD = 15.99). The lowest obtained morning EML was 201.96. As illustrated in Table 12, the EML value decreased gradually throughout the day and achieved to an average of 42.42 (SD = 5.57) after 20:00.

L1 intervention significantly increased daytime average corneal illuminance (*df* = 19, *t* = 11.28, $p < 0.001$), average horizontal illuminance (*df* = 19, *t* = 12.5, $p < 0.001$), average EML (*df* = 19, *t* = 2.83, $p < 0.001$), and average CS (*df* = 19, *t* = 6.9, $p < 0.001$) in the all living rooms compared to the baseline (Figure 14).

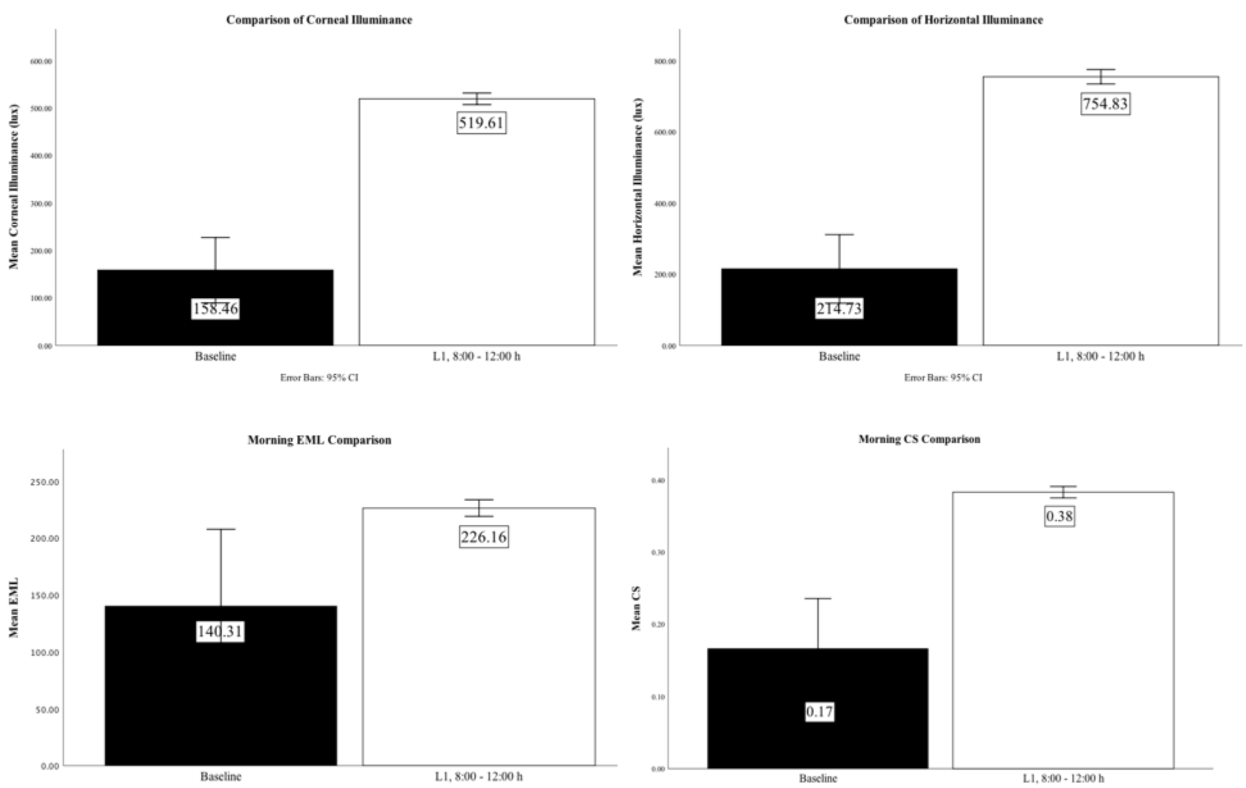


Figure 14. Comparison of the corneal illuminance, horizontal illuminance, EML, and CV value between baseline and morning L1 (8:00 – 12:00).

4.2.3. Lighting Intervention 2 (L2)

L2 lighting intervention was designed to provide varying illuminance levels and CCTs (and so SPD) in the living rooms of participants. Figure 15 shows an example of L2 lighting intervention in one living room in the Affordable II Senior Living. As illustrated, L2 exposed participants to bright cool lighting in the morning (8:00 – 12:00) and then both illuminance levels and CCT decreased gradually throughout the day to create a dimmed warm lighting in the evening time (after 20:00). Similar to L1 intervention, in most apartments, all the measurements of L2 were conducted during the daytime between 10:00 and 16:00 with closed window blinds to remove daylighting effects. If the closed window blinds could not reduce natural light effects sufficiently, we performed measurements after 17:00.

Figure 15. An example of L2 in a living room in the Affordable II senior living

As shown in Table 13, the average obtained corneal illuminance levels were aligned with target numbers defined in Table 8 for L2 interventions. The average corneal illuminance levels from 8:00 – 12:00 was 508.14 lux (SD =16.44) which was slightly higher that the 500 lux aimed for this intervention at this time. The corneal illuminance level of 500 lux or above was achieved in 15 living rooms (75%) with the highest measured number of 547.67 lux. The lowest measured corneal illuminance was 488 lux which was not significantly different from the target number of 500 lux.

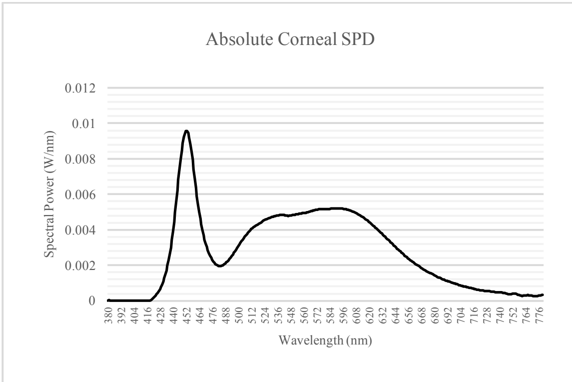
With respect to the horizontal illumination, L2 intervention provided a horizontal illuminance of 200 lux or above in all tested living rooms at all times with the highest average of 743.06 lux (SD = 42.72) in the morning (8:00 – 12:00). This is higher than the setpoints defined by ANSI/IES RP-28-16 and De Lepeleire et al. (2007) and means that the visual lighting criteria were met.

Table 13. L2 Lighting measurements.

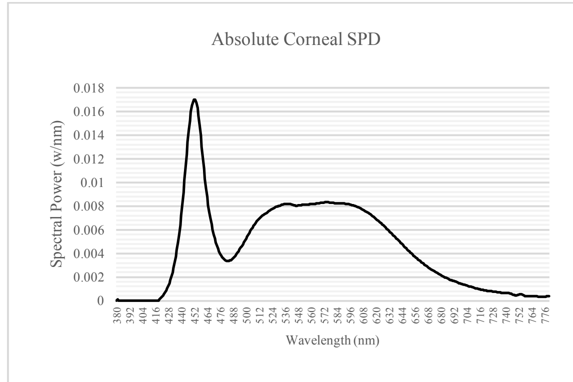
	Time	Minimum	Maximum	Mean	SD
Corneal Illuminance					
	6:00	181.67	229.00	209.02	10.42
	7:00	364.00	485.00	406.70	23.03
	8:00	488.00	547.67	508.14	16.44
	12:00	354.33	457.67	406.40	25.77
	16:00	274.67	326.00	301.22	14.59
	18:00	174.67	223.33	197.08	12.66
	20:00	74.90	106.00	94.47	9.37
Horizontal Illuminance					
	6:00	348.00	477.00	405.98	35.56
	7:00	588.67	679.00	624.56	22.59
	8:00	658.67	829.00	743.06	42.72
	12:00	574.67	678.00	613.02	29.02
	16:00	378.00	525.33	452.33	44.77
	18:00	275.00	344.33	311.73	22.75
	20:00	201.33	298.00	238.44	28.81
Corneal CCT°K					
	6:00	3805.00	4538.00	4162.60	175.72
	7:00	4546.67	5109.67	4925.41	157.15
	8:00	5101.33	5802.33	5522.56	226.83
	12:00	4264.33	4573.00	4475.68	68.74
	16:00	3348.67	3578.67	3473.71	60.01
	18:00	2977.00	3257.00	3098.65	69.16
	20:00	2479.33	2940.00	2708.46	101.54
Horizontal CCT°K					
	6:00	3970.67	4731.33	4336.70	193.71
	7:00	4757.33	5915.67	5119.83	274.72
	8:00	5126.00	6046.67	5693.94	283.06
	12:00	4316.33	4859.67	4489.49	120.29
	16:00	2993.33	3573.00	3343.75	150.87
	18:00	2519.33	3540.33	3181.57	216.29
	20:00	2525.00	2846.00	2726.65	86.62
CS					
	6:00	0.17	0.24	0.21	0.02
	7:00	0.35	0.41	0.37	0.01
	8:00	0.41	0.46	0.44	0.01
	12:00	0.33	0.38	0.35	0.01
	16:00	0.19	0.24	0.21	0.01
	18:00	0.22	0.27	0.24	0.01
	20:00	0.09	0.13	0.11	0.01
EML					
	6:00	123.48	159.63	150.41	7.73
	7:00	301.83	386.53	330.02	18.70
	8:00	409.27	481.07	441.23	16.79
	12:00	269.29	347.83	308.25	19.91
	16:00	167.76	218.39	192.00	11.47
	18:00	94.32	123.57	106.02	6.96
	20:00	31.86	50.92	42.42	5.57

As mentioned previously, as part of the L2 intervention, the CCT was programmed to change gradually from cool light (6500°K) in the morning to warm light (2700°K) in the evening to meet the circadian lighting needs criteria. Hence, all the lights were set on the maximum CCT to provide the CCT of 6500°K between 8:00 – 12:00. However, as indicated in Table 13, the average obtained morning corneal CCT was 5522.26°K (SD = 226.83). In fact, in none of the tested living rooms, the CCT of 6500°K was obtained. The highest measured corneal CCT was 5802.33°K. This occurred due to the effects of surface color and materials on the ambient lighting color. The average horizontal CCT is slightly higher than the corneal one with 5693.94°K (SD = 283.06) and a range of 5101.26 – 6046.67.

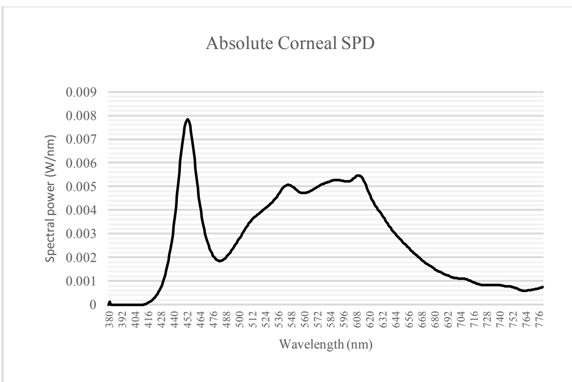
Recorded spectral data showed that L2 delivered lighting with a peak wavelength of 452nm and 608nm in the morning and evening, respectively. Figure 16 illustrates the absolute corneal SPD of lighting in L2 from morning to evening at the living room shown in Figure 15.



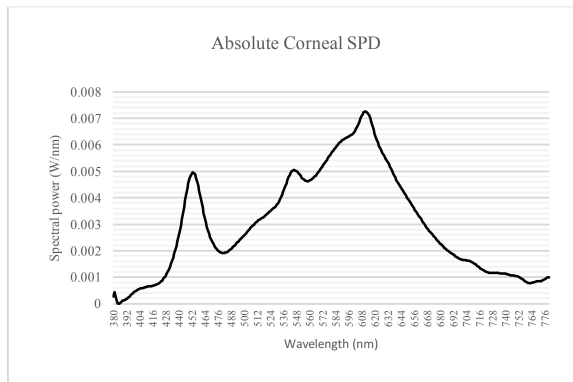
7:00 - 8:00 h, Main Gazing Direction, CCT 5154°K, Peak Wavelength: 453nm



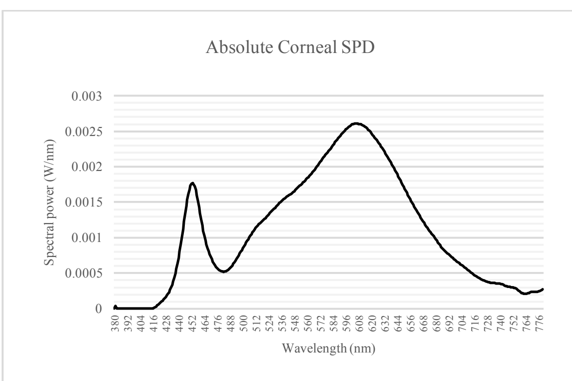
8:00 - 12:00 h, Main Gazing Direction, CCT 5635°K, Peak Wavelength: 452nm



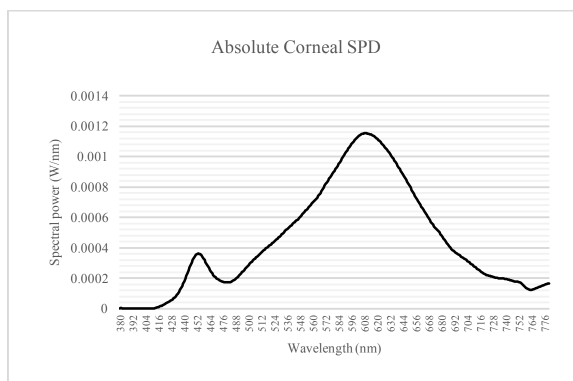
12:00 - 16:00 h, Main Gazing Direction, CCT 4587°K, Peak Wavelength: 453nm



16:00 - 18:00 h, Main Gazing Direction, CCT 4587°K, Peak Wavelength: 609nm



18:00 – 20:00 h, Main Gazing Direction, CCT 3119°K, Peak Wavelength: 605nm



18:00 – 20:00 h, Main Gazing Direction, CCT 2609°K, Peak Wavelength: 612nm

Figure 16. An example of absolute Corneal SPD from 7:00 – 20:00 h in L2 in the living room shown in Figure 15.

Circadian lighting calculations show the significant effects of the spectrum on the CS and EML values. The average morning (8:00 -12:00 h) CS value for L1 was 0.44 (SD = 0.01), with all living rooms having the morning CS of more than 0.41 (see Table 12). The average night time CS value was as low as 0.11, with a small range of 0.09 – 0.13. Moreover, the L1 intervention provided an EML of 409 or higher in the morning (8:00 – 12:00 h) in all living rooms with a total mean of 441.23 (SD = 16.79). This is twice more than the EML setpoint of 220. The highest obtained morning EML was 481.07. As illustrated in Table 12, the EML value decreased gradually throughout the day and achieved to an average of 42.42 (SD = 5.57) after 20:00.

L2 intervention significantly increased daytime mean corneal illuminance ($df = 19$, $t = 10.29$, $P < 0.05$), mean horizontal illuminance (df = 19, t = 11.98, $P < 0.05$) compared to the baseline. However, no significant difference was observed in the mean corneal illuminance levels ($df = 19$, $t = 1.21$, $p > 0.05$) and horizontal illuminance levels ($df = 19$, $t = 1.40$, $p > 0.05$) between L1 and L2 (Figure 17).

Moreover, as illustrated in Figure 18. L2 intervention provided a significant increase in mean morning EML value compared to L1 ($df = 19$, $t = 54.430$, $p < 0.001$) and baseline ($df = 19$, $t = 9.14$, $p < 0.001$). Same significant increase was observed in the average morning CS value of L2 intervention in comparison to L1 ($df = 19$, $t = 14.839$, $p < 0.001$) and baseline ($df = 19$, $t = 8.27$, $p < 0.001$).

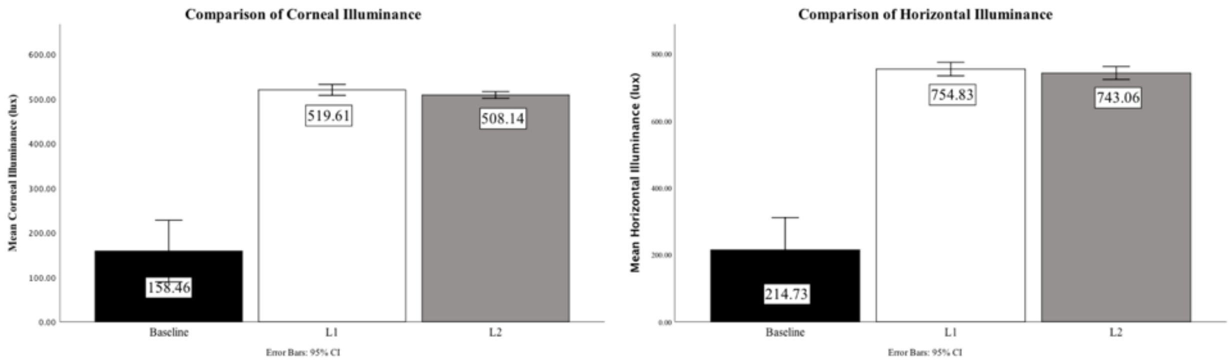


Figure 17. Comparison of corneal and horizontal illuminance levels in Baseline, L1, and L2.

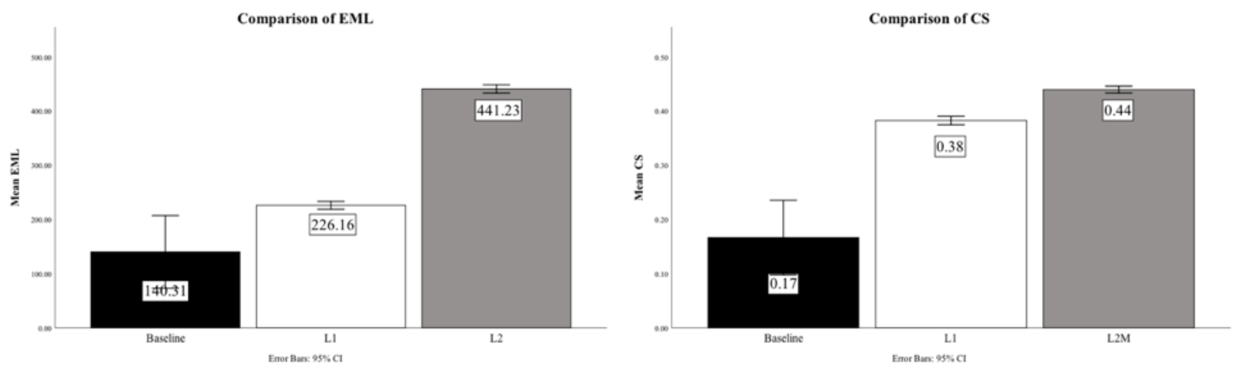


Figure 18. Comparison of EML and CS in Baseline, L1, and L2.

4.2.4. Light exposure as measured by actigraphy

Results from actigraphy confirmed average light exposure difference during the L1 and L2 interventions compared to the both baselines (B1 and B2) with more light exposure during the L2 intervention (Figure 18). As shown, under the L1, actigraphy measured a significantly higher light exposure during the active time (AT) (145,897.49 lux-min versus 85,547.44 lux-min; df = 20, t = - 4.69, P < 0.05) compared to B1. The same results were observed under the L2 intervention with significantly AT higher light exposures (190,256.29 lux-min versus lux-min, df = 20, t = -4.40, P < 0.05). There was no significant difference in AT light exposure between B1 and B2 (85,547.44 lux-min versus 85,707.30 lux-min, df = 20, t = 0.018, P = 0.986) nor between L1 and L2

(145,897.49 lux-min versus 190,256.29 lux-min, df = 20, t = -2.00, P = 0.06). Although it was not significant, the average AT light exposure in L2 was higher than L1 (Figure 19).

Moreover, no significant difference was found in the Rest Time (RT) light exposure between B1 and B2 (3049.25 lux-min versus 2781.06 lux-min, *df* = 20, *t* = 0.491, *p* = 0.629), L1 and B1 (11117.91 lux-min versus 3049.25 lux-min, *df* = 20, *t* = -1.87, *p* = 0.076), L2 and B1 (8261.74 lux-min versus 3049.25 lux-min, *df* = 20, *t* = -1.03, *p* = 0.314), L1 and L2 (11117.91 lux-min versus 8261.74 lux-min, *df* = 20, *t* = -0.654, *p* = 0.629). However, the average RT light exposure was higher under L1 and L2 interventions compared to the baselines.

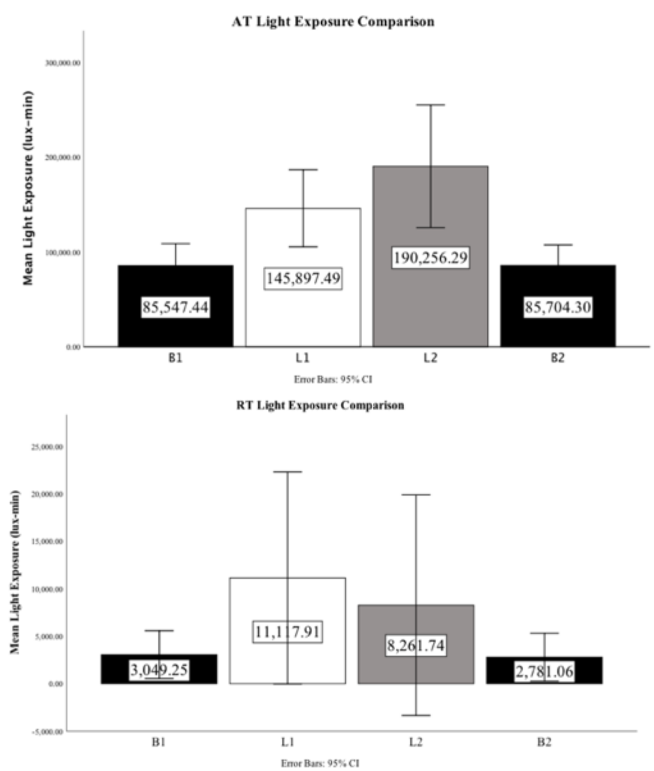


Figure 19. Active Time (AT) and Rest Time (RT) light exposure comparison measured by actigraphy.

Despite the significant difference in daytime illuminance levels between HQDLR and LQDLR apartments, no significant difference was observed in the AT light exposure in older adults residing in these units (df = 19, t = 0.90, p = 0.379). There was also no significant difference in the AT and RT light exposure between participants based on senior living buildings (df = 19, t = 0.345, p = 0.734) or groups (df = 20, t =-1.36, p = 0.141) at B1.

Moreover, actigraphy data were utilized to measure daily direct daylight exposure in participants. In this regard, the duration of time spent in illuminance level of 1000 lux or over was investigated. This threshold was derived from studies by Bellia et al. (2013), Hubalek, Brink, & Schierz (2010) and Nioi et al. (2017). The duration of time spent in 1,000 lux or greater has been defined in previous studies as an indicator of time outdoors (Scheuermaier, Laffan, & Duffy, 2010). Our analysis showed that the mean duration of time above 1000 lux was 19.53 minutes (SD = 13.51), with a range of 4.84 to 50.71 minutes. This shows that participants spent a very short duration of time outdoors under the direct sunlight. The was no significant difference between participants based on senior living types ($df = 19$, $t = 1.186$, $p = 0.250$) or the baseline daylighting condition in their apartment ($df = 19$, $t = 0.479$, $p = 0.638$).

4.3. Effect of Order

As previously mentioned, the study was counterbalanced by assigning participants into two groups where they received a different order of lighting interventions (L1 – l2 and L2 – L1). The effect of order of exposure on DVs as well as the interaction between order and lighting conditions were analyzed using a general linear mixed model of analysis of variances (ANOVA). There was no significant effect of order or interaction between order and lighting conditions on the DVs, suggesting that the effect of lighting on DVs was not dependent on the order of exposure to L1 and L2 interventions. Table 14 shows the results.

Table 14. Results of Mixed ANOVA to test the effect of order on DVs and the interaction between order and lighting.

		F	*MSE*	*p* value	η^2_p
Order					
	NSD	0.69	36480.40	0.42	0.04
	SE	3.91	57.04	0.06	0.17
	SOL	0.80	792.92	0.38	0.04
	DSD	1.73	32448.02	0.20	0.08
	SDist	0.38	840.27	0.55	0.02
	SRImp	0.03	346.47	0.87	0.00
	SQ	4.62	26.07	0.05	0.20
	DSle	0.01	27.60	0.92	0.00
	GDS	0.81	69.61	0.34	0.04
	PA	0.09	131.23	0.77	0.01
	NA	0.09	39.44	0.77	0.01
	QL	0.05	122.20	0.84	0.00
	TMT-A	0.85	1416.64	0.37	0.04
	TMT-B	0.55	3121.57	0.47	0.03
	DSST	2.56	1395.59	0.13	0.12
Lighting * Order					
	NSD	0.23	-	0.87	0.03
	SE	2.92	-	0.06	0.00
	SOL	0.68	-	0.57	0.01
	DSD	1.04	-	0.35	0.04
	SDist	1.11	-	0.35	0.06
	SRImp	1.36	-	0.26	0.07
	SQ	2.90	-	0.07	0.13
	DSle	0.68	-	0.60	0.03
	GDS	2.80	-	0.07	0.13
	PA	0.17	-	0.91	0.01
	NA	0.55	-	0.55	0.03
	QL	2.60	-	0.10	0.12
	TMT-A	0.23	-	0.70	0.01
	TMT-B	0.13	-	0.88	0.01
	DSST	2.89	-	0.06	0.13

4.4. Objective Sleep Quality as Measured by Actigraphy

4.4.1. Baseline Sleep

Actigraphy data indicated no significant difference in Nighttime Sleep Duration (NSD), Daytime (DSD), Sleep Efficiency (SE), and Sleep Onset Latency (SOL) among participants based on senior living types or apartments' daylighting condition (Table 15 and Table 16). In data analysis throughout this dissertation study, Affordable I and Affordable II senior livings in Saint Louis were considered as one senior living type due to their similar architectural and demographic characteristics and called "Affordable". The high-end senior living in Chicago was considered as another type and called "High-end". Hence, to evaluate the effects of senior living type, participants were divided into two groups based on the facility type they resided in.

Table 15. Results of t-tests for actigraphy measures between buildings.

Variable	Affordable	High-end	*p* value
Number	14	7	
NSD (minutes)			
Mean	459.41	407.27	0.11
SD	91.21	34.33	
DSD			
Mean (minutes)	237.17	202.59	0.48
SD	94.83	80.65	
SE			
Mean (%)	82.14	81.36	0.95
SD	4.36	4.76	
OSL			
Mean (minutes)	28.46	32.20	0.66
SD	20.40	17.98	

Table 16. Results of t-tests for actigraphy measures in HQDLR and LQDLR.

Variable	HQDLR	LQDLR	*p* value
Number	5	16	
NSD (minutes)			
Mean	481.71	429.64	0.212
SD	109.29	68.21	
DSD			
Mean (minutes)	204.31	232.31	0.557
SD	98.09	89.46	
SE			
Mean (%)	80.73	82.23	0.519
SD	5.81	4.54	
OSL			
Mean (minutes)	25.94	30.88	0.629
SD	14.05	20.87	

4.4.2. Night time Sleep Duration (NSD)

A one-way RP ANOVA with three levels of repeated measures factors was conducted to compare the effect of lighting conditions on nighttime sleep duration (NSD) before and after L1 and L2 interventions. There was a significant effect of lighting condition on NSD ($F [2, 40] = 11.00$, $p < 0.001$, $MSE = 585.474$, $\eta 2p = 0.36$). The patterns of the average NSD across the study are illustrated in Figure 20 and Figure 21. As shown, the average NSD increased with the L1 intervention from 436.06 (SD = 091.38) in Baseline to 455. 58 (SD = 95.64) and increased even more with the L2 intervention and reached to 741.00 (SD = 107.84).

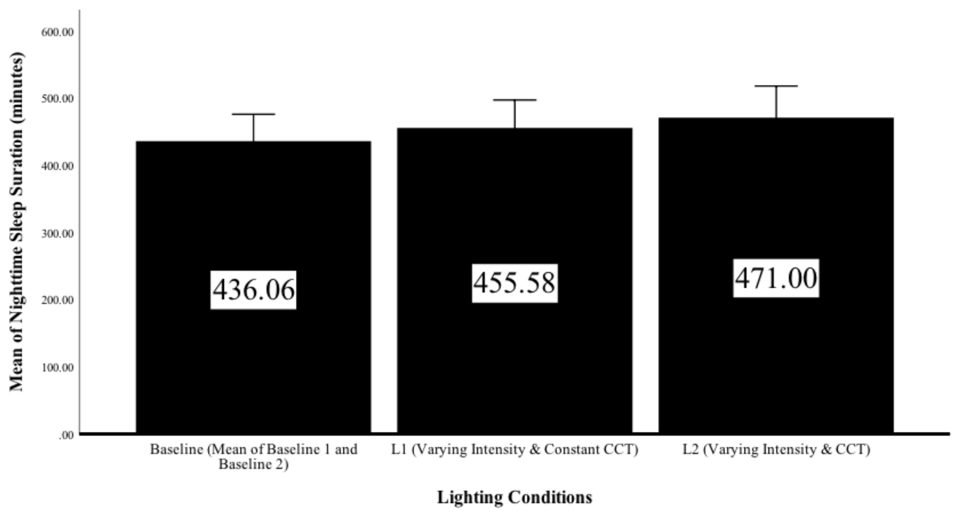


Figure 20. Effect of lighting condition on nighttime sleep duration (NST).

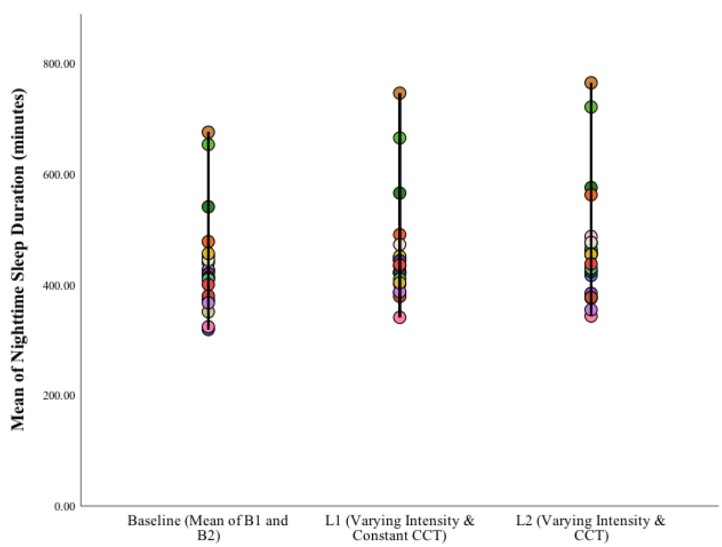


Figure 21. Drop-line mean of nighttime sleep duration (NSD) for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

As the one-way RM ANOVA confirmed the significant effects of lighting, in order to further investigate the effects of interventions on NSD, three paired samples t-tests were employed to make post hoc comparisons between lighting conditions. The pairwise comparison indicated a significant difference between mean NSD at Baseline and L1 (*df* = 20, *t* = -2.87, *p* = 0.009), Baseline and L2 (*df* = 20, *t* = -3.83, *p* = 0.001), L1 and L2 (*df* = 20, *t* = -2.60, *p* = 0.02). Moreover, no significant difference was observed between B1 and B2 (*df* = 20, *t* = 1.25, *p* = 0.26), suggesting no lasting effect of interventions on NSD (see Appendix A for the results of RM ANOVA with four levels repeated measures and related paired-wise analysis). The results are illustrated in Table 17.

Table 17. Results from Paired Sample t-test for nighttime sleep duration (NSD).

	Mean Difference (min)	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (Baseline, L1)	-19.52	31.15	-2.87	0.009
Pair 2 (Baseline, L2)	-34.94	41.82	-3.83	0.001
Pair 3 (L1, L2)	-15.42	28.16	-2.51	0.021
Pair 4 (B1, B2)	11.95	43.71	2.65	0.22

4.4.3. Sleep Efficiency (SE)

A one-way RM ANOVA with three levels of repeated measures factors confirmed the significant effect of lighting condition on sleep efficiency (SE) of participants (F [2, 40] = 9.56, *p* < 0.001, *MSE* = 9.49, $\eta^2_p = 0.32$). As shown in Figure 22 and Figure 23, compared to Baseline, L1 intervention slightly increased the mean ES from 81.64% (SD = 4.76) to 82.78 (SD = 5.61), while, L2 intervention increased that more and reached to 85.68 (SD = 4.66).

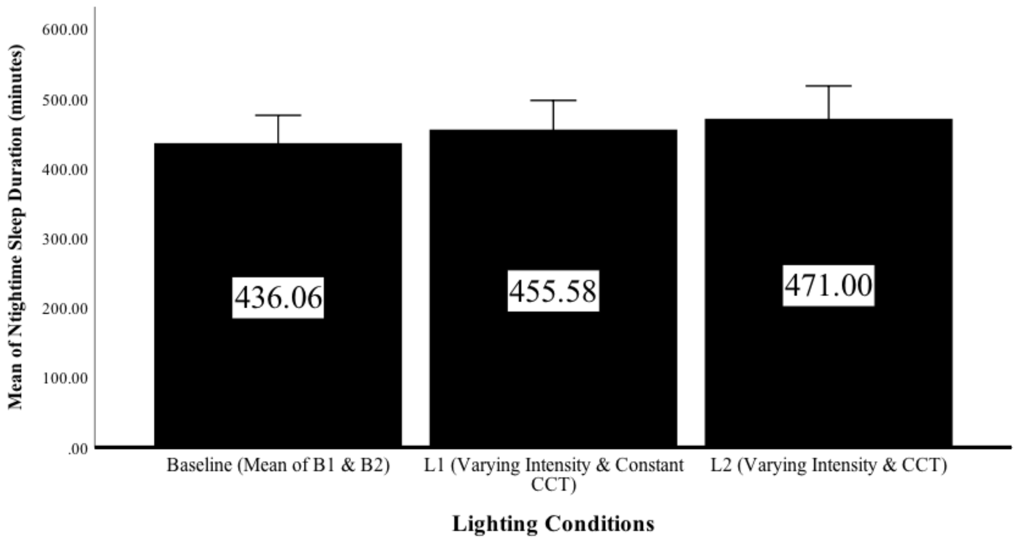


Figure 22. Effect of lighting conditions on sleep efficiency (SE).

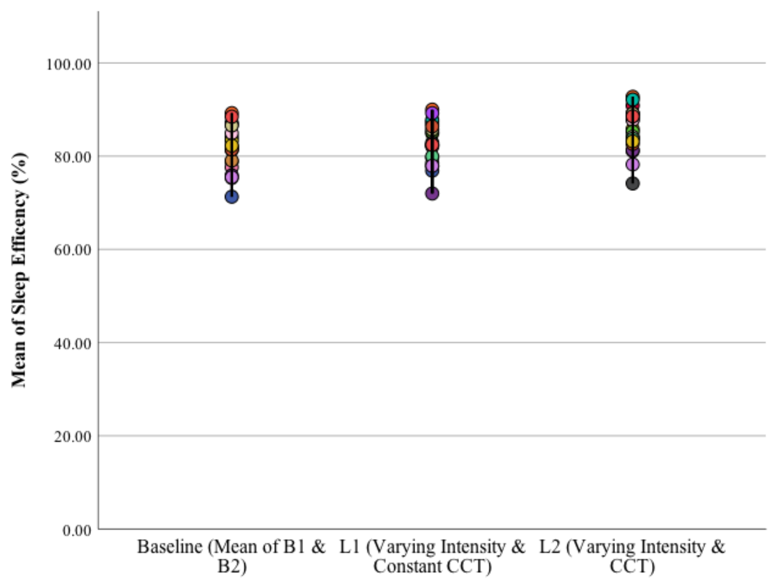


Figure 23. Drop-line mean of sleep efficiency (SE) for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

In order to further investigate the effects of interventions on ES, three paired samples t-tests were employed to make post hoc comparisons between lighting conditions. Table 18 shows the t-test results obtained for SE. The t-test analysis revealed a significant difference between

Baseline and L2 (*df* = 20, *t* = -3.97, *p* = 0.001) as well as L1 and L2 (*df* = 20, *t* = -2.82, *p* = 0.010). There was no significant difference between Baseline and L1 (*df* = 20, *t* = -1.43, *p* = 0.168), suggesting that whole-day lighting with varying lighting intensity did not significantly improve SE in older adults. Moreover, we did not observe any significant difference between B1 and B2 (*df* = 20, *t* = 0.59, *p* = 0.560). This confirms that interventions did not have any carryover effect on SE in participants (see Appendix A for the results of RM ANOVA with four levels of repeated measures and related paired-wise analysis).

Table 18. Results from Paired Sample t-test for sleep efficiency (SE) across the study.

	Mean Difference (min)	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (B1, L1)	-1.14	3.64	-1.43	0.168
Pair 2 (B1, L2)	-4.03	4.65	-3.97	0.001
Pair 3 (L1, L2)	-2.89	4.70	-2.82	0.010
Pair 4 (B1, B2)	0.46	3.56	0.59	0.560

4.4.4. Daytime Sleep Duration (DSD)

For the daytime sleep duration, the one-way repeated measures ANOVA indicates no significant effects of lighting conditions (F [2, 40] = 1.37, *p* = 0.265, *MSE* = 1819.80, $\eta^2_p = 0.06$), suggesting that the tested lighting interventions did not have any significant effects on DSD. Figure 24 and Figure 25 show the patterns of the mean of DSD across the study. Although insignificant, this pattern reveals a reducing trend in the mean DSD after L2 intervention. In fact, L2 intervention reduced the mean DSD in participants by 19.30 minutes compared to Baseline. L1 intervention decreased DSD slightly by 0.86 minutes.

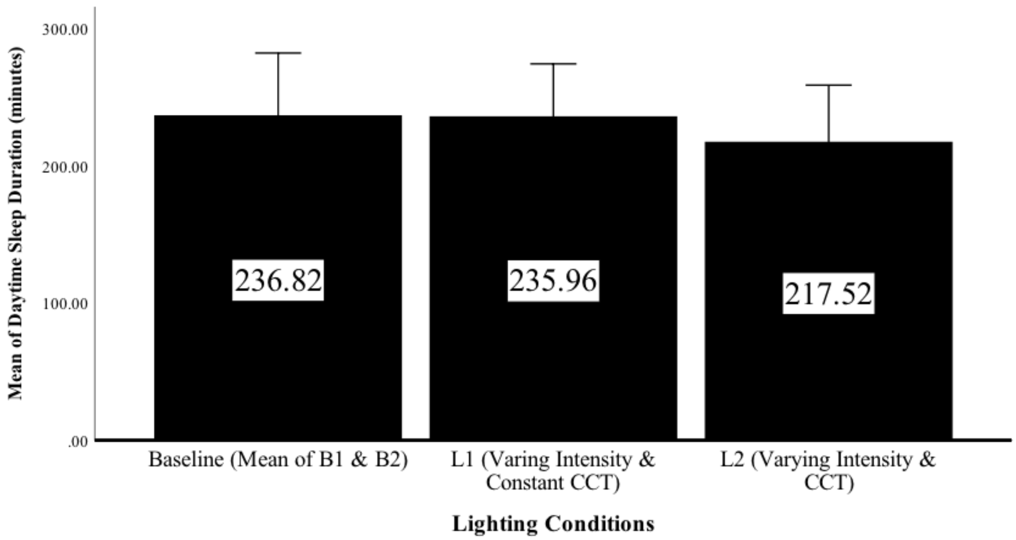


Figure 24. Effect of lighting conditions on daytime sleep duration (DSD).

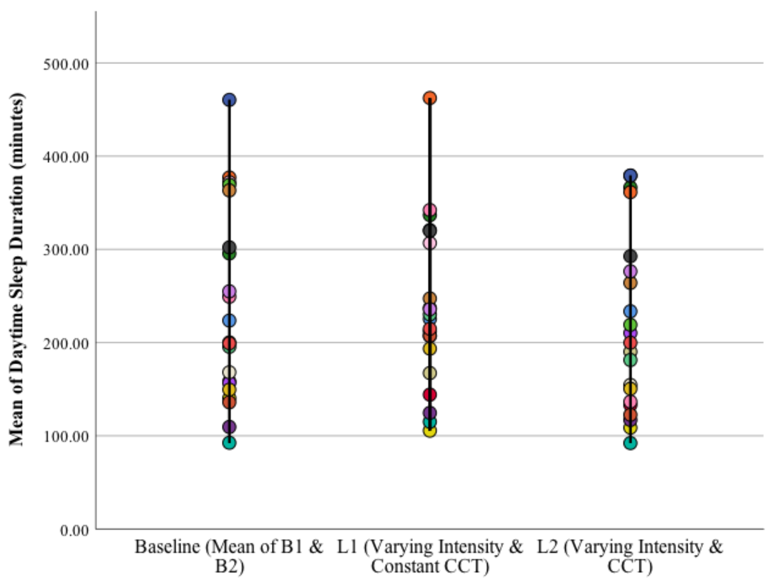


Figure 25. Drop-line mean of daytime sleep duration (DSD) for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

4.4.5. Sleep Onset Latency (SOL)

Actigraphy data for sleep onset latency (SOL) exhibited a significant main effect of lighting (F [2, 40] = 6.15, $p = 0.005$, $MSE = 161.194$, $\eta^2_p = 0.235$). The pattern of SOL in the course of the study is illustrated in Figure 26 and Figure 27. Whereas L1 increased the mean SOL from 29.83 minutes (SD = 16.01) in the Baseline to 34.96 minutes (SD = 21.68), L2 intervention significantly decreased the mean SOL to 21.35 minutes (SD = 13.14). This pattern suggests that varying intensity alone is not sufficient to reduce SOL in older adults. However, adding tuning color quality to varying intensity could be an effective lighting solution. Table 19 shows the results of the t-test analysis. We found a significant difference between Baseline and L2 ($df = 20$, $t = 2.60$, $p = 0.017$) and between L1 and L2 ($df = 20$, $t = 2.93$, $p = 0.008$). However, there was no significant difference between the mean SOL in Baseline and L1 ($df = 20$, $t = -1.38$, $p = 0.18$). We also observed no significant difference between B1 and B2, suggesting that the lighting interventions had no lasting impact of SOL in participants (see Appendix A for the results of RM ANOVA with four levels repeated measures and related paired-wise analysis).

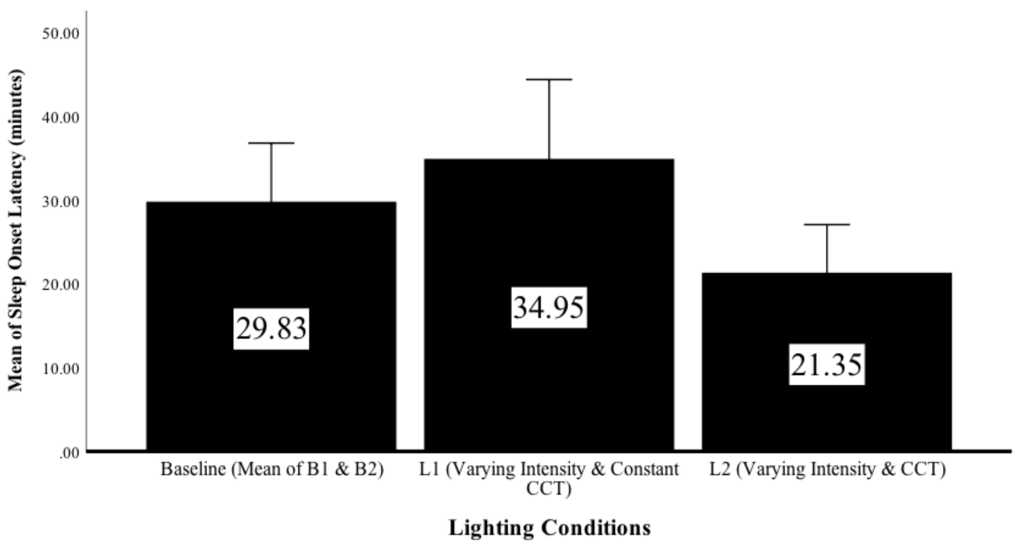


Figure 26. Effect of lighting conditions on sleep onset latency (SOL).

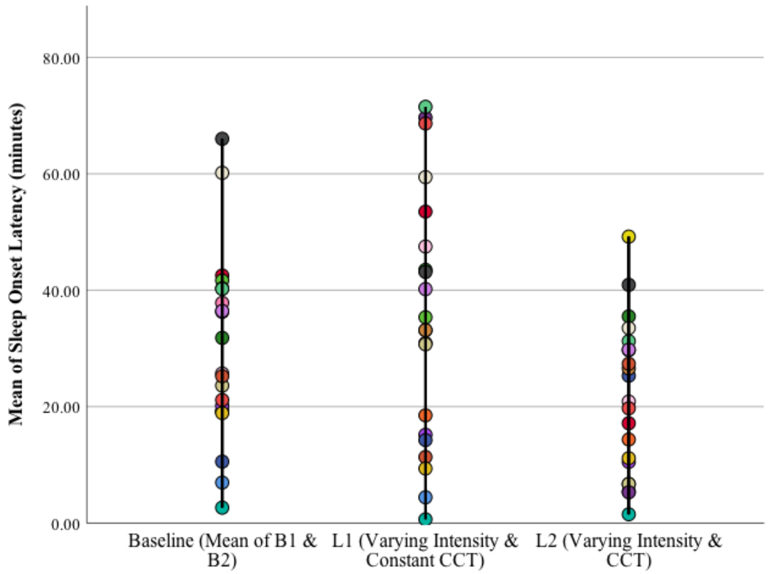


Figure 27. Drop-line mean of sleep onset latency (SOL) for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

Table 19. Results from Paired Sample t-test for sleep onset latency (SOL) across the study.

	Mean Difference (min)	**SD**	**t (df = 20)**	***p* Value**
Pair 1 (B1, L1)	-5.25	17.47	-1.38	0.18
Pair 2 (B1, L2)	8.35	20.55	1.86	0.08
Pair 3 (L1, L2)	-13.60	21.30	2.93	0.01
Pair 4 (B1, B2)	-0.26	17.07	-0.07	0.945

4.5. Subjective Sleep as Measured by Questionnaires

4.5.1. Baseline Subjective Sleep

Self-rating questionnaires were employed to assess the effectiveness of lighting interventions on subjective sleep quality. Sleep disturbance (SDist), sleep-related impairment (SRImp), sleep quality (SQ), and daytime sleepiness (DSle) were measured using PROMIS SD, PROMIS SRI, PSQI, and ESS respectively. There was no significant difference between average scores obtained in baseline (B1) based on the senior living type or the daylighting conditions in the living rooms. Table 20 and Table 21 show the results.

Table 20. Results of t-tests for self-rating measures between buildings.

Variable	Affordable	High-end	*p* value
Number	14	7	
SDist			
Mean	58.86	54.71	0.61
SD	14.80	21.01	
SRImp			
Mean	38.43	28.29	0.57
SD	12.13	7.30	
SQ			
Mean	7.71	5.86	0.33
SD	4.16	3.76	
DSle			
Mean	7.21	5.29	0.18
SD	2.86	3.15	

Table 21. Results of t-tests for self-rating measures in HQDLR and LQDLR.

Variable	HQDLR	LQDLR	*p* value
Number	5	16	
SDist			
Mean	64.80	55.19	0.272
SD	20.92	15.22	
SRImp			
Mean	33.20	35.63	0.695
SD	6.30	12.99	
SQ			
Mean	8.60	6.63	0.353
SD	2.97	4.29	
DSle			
Mean	6.00	6.75	0.641
SD	3.74	2.89	

4.5.2. Sleep Disturbance (SDist)

A one-way RM ANOVA revealed a significant effects of lighting conditions on the SDist scores of participants measured by PROMIS-SD ($F [2, 40] = 17.04$, $p < 0.001$, $MSE = 34.30$, $\eta^2_p = 0.46$). The mean score for SDist significantly decreased from 54.83 (SD = 14.35) in Baseline to 52.52 (SD =17.00) after L1 and decreased even more to 44.76 (SD = 13.98) after L2 intervention. The difference between the mean score for SDist in Baseline and L2 ($df = 20$, $t = 6.00$, $p < 0.001$) as well as L1 and L2 ($df = 20$, $t = 3.91$, $p = 0.001$) were significant. Figure 28, Figure 29, and Table 22 show the results. We found no significant difference between Baseline and L1 ($df = 20$, $t = 1.32$, $p = 0.20$). This confirms that a whole-day varying intensity alone is not sufficient to improve

SDist in older adults. There was no significant difference between mean scores for SDist in B1 and B2 ($df = 20$, $t = 1.59$, $p = 0.13$), suggesting that the lighting interventions did not have any lasting impact on SDist (see Appendix A for the results of RM ANOVA with four levels of repeated measures and related paired-wise analysis).

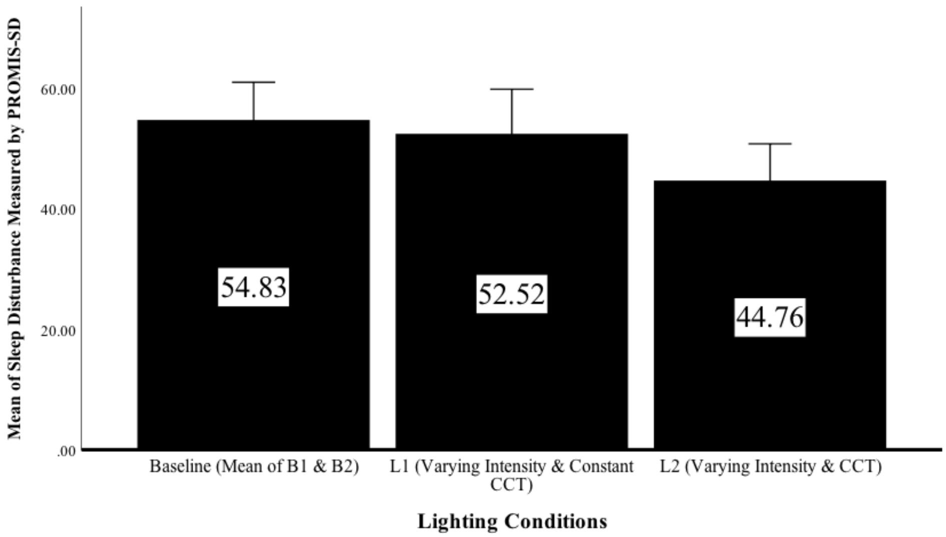


Figure 28. Effect of lighting conditions on sleep disturbance (SDist) in participants measured by PROMIS-SD.

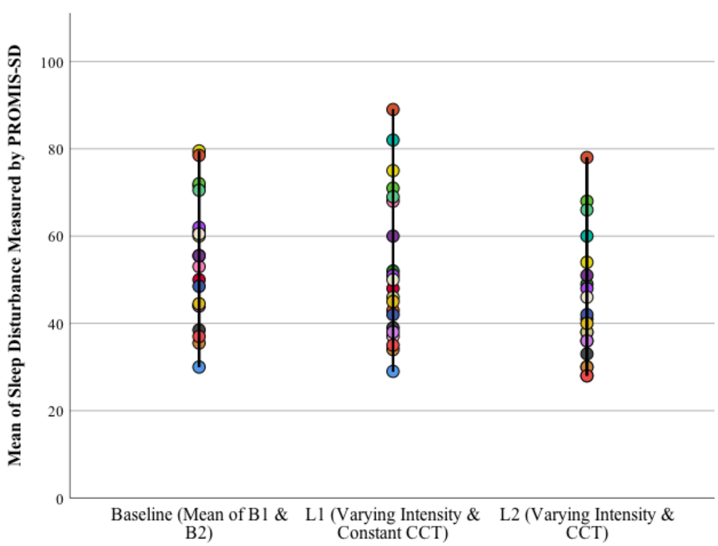


Figure 29. Drop-line mean of sleep disturbance measured by PROMIS-SD for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

Table 22. Results from Paired Sample t-test for sleep disturbance measured by PROMIS-SD scores across the study.

	Mean Difference	SD	*t* (df = 20)	*p* Value
Pair 1 (B1, L1)	2.31	8.00	1.32	0.201
Pair 2 (B1, L2)	10.07	7.70	6.00	< 0.001
Pair 3 (L1, L2)	7.76	9.09	3.91	0.00
Pair 4 (B1, B2)	5.29	15.26	1.59	0.13

4.5.3. Sleep-Related Impairments (SRImp)

Results from the PROMIS-SRI exhibited a significant effect of lighting conditions on the SRImp scores in participants (F [2, 40] = 13.60, $p < 0.001$, $MSE = 16.87$, $\eta^2_p = 0.41$). The mean score for SRImp decreased from 33.00 (SD = 10.59) in Baseline to 30.67 (SD = 8.67) after L1 intervention, the difference was nonsignificant, though. L2 intervention decreased the mean score for SRImp more to 26.48 (SD = 8.65) which was significantly different from Baseline ($df = 20$, $t = 4.83$, $p < 0.001$) and L1 ($df = 20$, $t = 3.88$, $p = 0.001$). Figure 30, Figure 31, and Table 23 show the results.

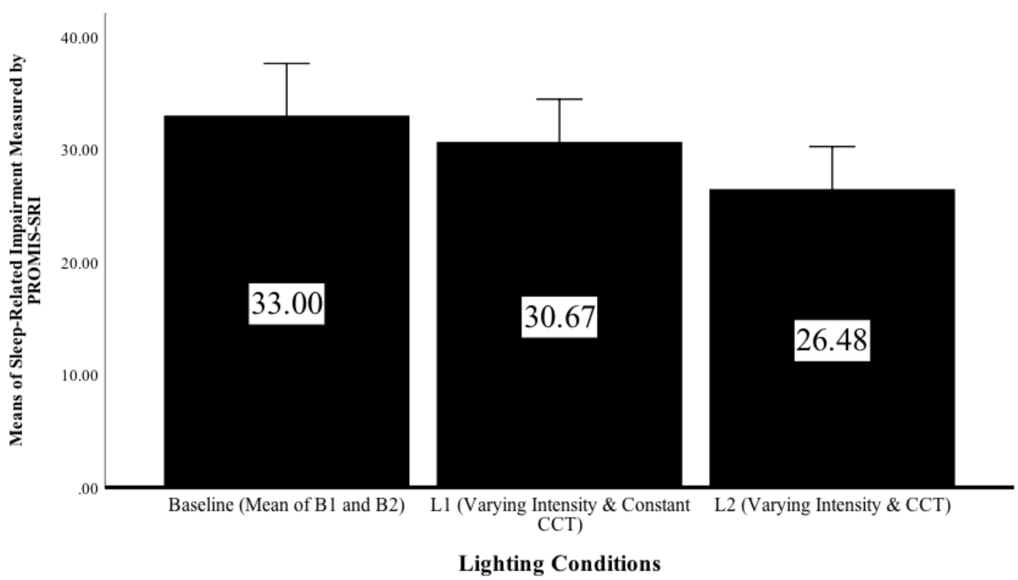


Figure 30.Effect of lighting conditions on sleep-related impairment (SRImp) measured by PROMIS-SRI.

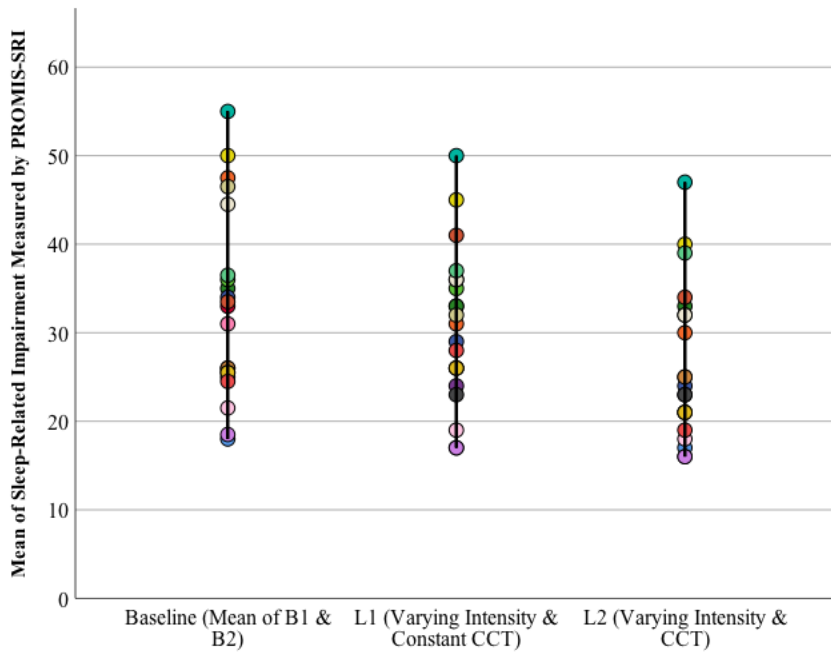


Figure 31. Drop-line mean of sleep-related impairment (SRImp) measured by PROMIS-SRI for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

Moreover, a paired-wise comparison revealed a significant difference between B1 and B2 ($df = 20$, $t = 3.10$, $p = 0.01$) which might indicate the carryover effect of lighting interventions on SRImp (see Appendix A for the results of RM ANOVA with four levels of repeated measures and related paired-wise analysis).

Table 23. Results from Paired Sample t-test for sleep-related impairment measured by PROMIS-SRI scores across the study.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (B1, L1)	2.33	5.61	1.91	0.07
Pair 2 (B1, L2)	6.52	6.73	4.45	< 0.001
Pair 3 (L1, L2)	4.19	4.95	3.88	0.001
Pair 4 (B1, B2)	4.10	6.06	3.10	0.01

4.5.4. Sleep Quality (SQ)

Seventeen participants (81%) had baseline assessment scores of five or greater for SQ measured by PSQI, suggesting they suffered from poor sleep quality. The frequency of participants with poor sleep quality reduced to 62% (n = 13) after L1 and L2 interventions. This frequency started to increase after the intervention was discontinued and reached 71% (n = 15) at B2.

A one-way RM ANOVA confirmed the significant effects of lighting conditions on the subjective sleep quality (SQ) measured by PSQI (F [2, 40] = 4.83, p = 0.013, MSE = 1.99, η^2_p = 0.20). Figure 32 and Figure 33 show the pattern of SQ throughout the course of the study with a lower mean score indicating a higher SQ in participants. As illustrated, the mean score for SQ improved from 6.48 (SD = 2.95) in Baseline to 6.33 (SD = 3.34) after L1 and improved even more after L2 and reached to 5.24 (SD = 2.70).

The paired-wise comparisons for the main effect of lighting on SQ revealed a significant difference between Baseline and L2 (df = 20, t = 2.58, p = 0.018) as well as between L1 and L2 (df = 20, t = 2.61, p = 0.017). There was no significant difference between Baseline and L1 (df = 20, t = 0.354, p = 0.727) (Table 24).

In fact, after the intervention had been removed, the mean score for SQ score started increasing (mean of SQ at B2 = 5.86, SD = 2.60); however, after two weeks, the mean score for SQ was still lower than the L1 intervention. This might reflect a carryover effect of lighting interventions on subjective sleep quality in participants (see Appendix A for the results of RM ANOVA with four levels of repeated measures and related paired-wise analysis).

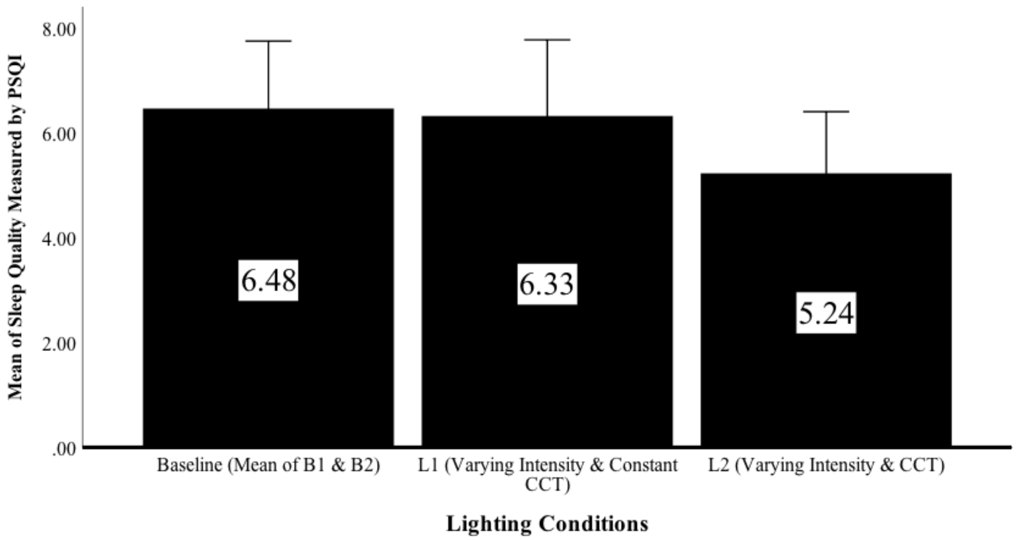


Figure 32. Effect of lighting conditions on sleep quality (SQ) measured by PSQI.

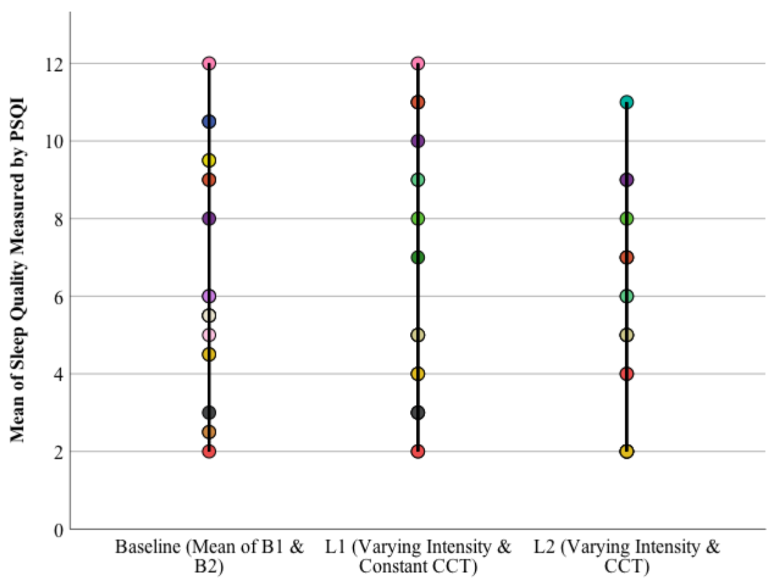


Figure 33. Drop-line mean of sleep quality measured by PSQI for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

Table 24. Results from Paired Sample t-test for sleep quality (SQ) measured by PSQI scores across the study.

	Mean Difference	**SD**	***t*** **(*df* = 20)**	***p*** **Value**
Pair 1 (Baseline, L1)	0.14	1.85	0.35	0.727
Pair 2 (Baseline, L2)	1.24	2.20	2.58	0.018
Pair 3 (L1, L2)	1.10	1.92	2.61	0.018
Pair 4 (B1, B2)	1.24	3.35	1.70	0.112

4.5.5. Daytime Sleepiness (DSle)

Mean scores for DSle measured by ESS exhibited no significant effect of lighting condition (F [2, 60] = 2.270, p = 0.116, MSE = 3.72, η^2_p = 0.10). The mean scores for DSle was dropped from 6.76 (SD = 2.63) in Baseline to 5.90 (SD = 3.21) in L1 and dropped even more after L2 and reached to 5.52 (SD = 3.27), suggesting a reducing trend in the DSle after exposure to the lighting interventions. Figure 34 and Figure 35 show the results.

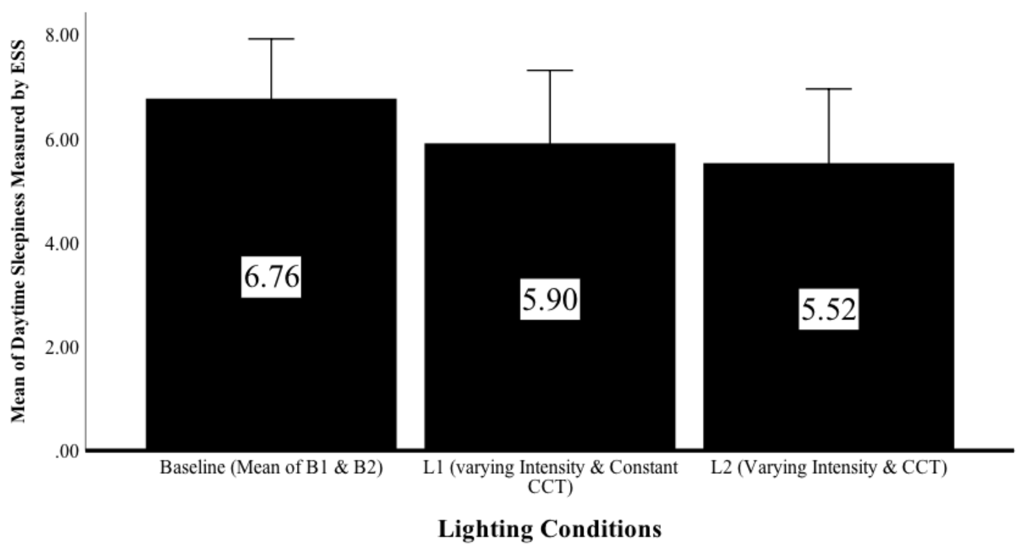


Figure 34. Effect of lighting conditions on daytime sleepiness (chance of dozing) in participants measured by ESS.

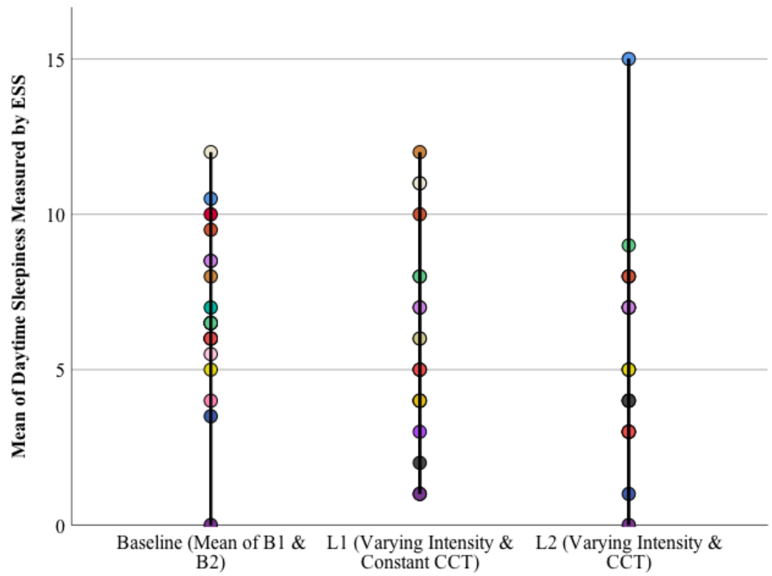


Figure 35. Drop-line mean of daytime sleepiness (chance of dozing) measured by ESS for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

4.6. Depression

GDS were employed to evaluate depression in participants through the course of study. Eight participants (39%) had the initial score of nine or greater, suggesting they were depressed. Only one out of eight was the resident of the high-end senior living. In fact, an independent t-test analysis revealed a significant difference between the baseline mean score for depression in participants based on senior living types (t = 2.66, p = 0.02). No significant difference was found in the baseline mean score for depression based on the daylighting conditions (t = 0.646, p = 0.526). Table 25 and Table 26 show the results.

Table 25. Results of t-tests for Depression between buildings.

Variable	**Affordable**	**High-end**	***p* value**
Number	14	7	
Depression			
Mean	9.50	3.71	0.021
SD	4.69	4.72	
Frequency (≥ 9)	7 (50%)	1 (14.3%)	

Table 26. Results of t-tests for Depression in HQDLR and LQDLR.

Variable	**HQDLR**	**LQDLR**	***p* value**
Number	5	16	
Depression			
Mean	6.20	8.00	0.526
SD	5.50	5.43	
Frequency (≥ 9)	1 (20%)	7 (43.8%)	

A one-way RM ANOVA was run to investigate the effects of lighting on depression scores in older adults. The mean scores for depression exhibited a significant effect of lighting on depression (F [1.54, 30.76] = 13.69, $p < 0.001$, $MSE = 3.18$, $\eta^2_p = 0.41$). As the assumption of Sphericity was violated (Mauchly's Test of Sphericity: $p = 0.01$), the GreenHouse-Geisser correction was used to report the RM ANOVA results. The patterns of the depression scores across the study are illustrated in Figure 36 and Figure 37. As shown, the mean score for depression slightly decreased with L1 intervention from 6.95 (SD = 4.67) in Baseline to 6.10 (SD = 4.49), decreased more with L2 and reached 4.14 (SD = 3.62).

Table 27 shows the results of t-test analysis. There was a significant difference between the mean score for depression between Baseline and L1 ($df = 20$, $t = 2.18$, $p = 0.042$), Baseline and L2 ($df = 20$, $t = 4.23$, $p < 0.001$), as well as L1 and L2 ($df = 20$, $t = 3.50$, $p = 0.002$).

We found no significant difference in mean scores for depression between B1 and B2 ($df = 20$, $t = 1.62$, $p = 0.12$), suggesting that the lighting interventions did not have any significant carryover effect on depression (see Appendix A for the results of RM ANOVA with four levels repeated measures and related paired-wise analysis).

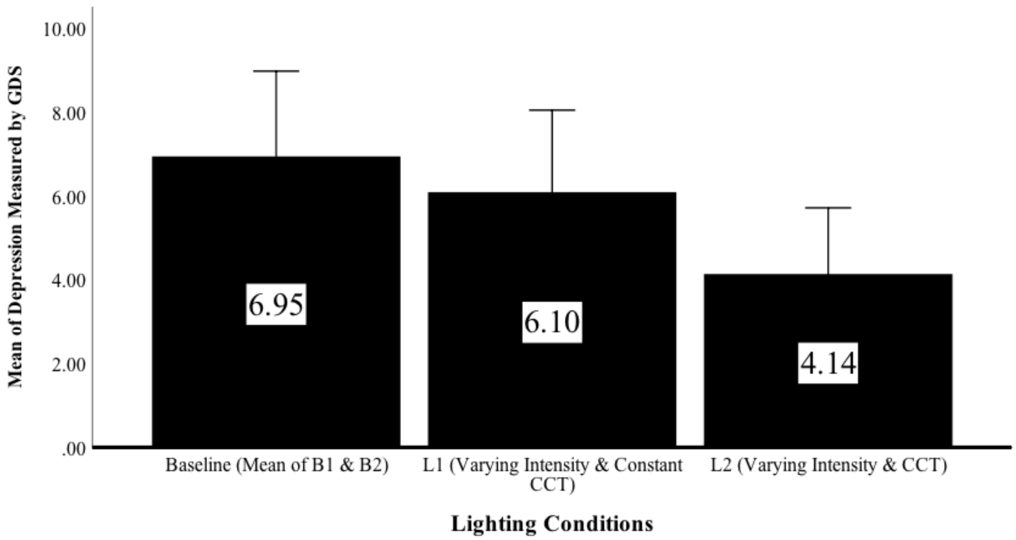


Figure 36. Effect of lighting conditions on depression measured by GDS.

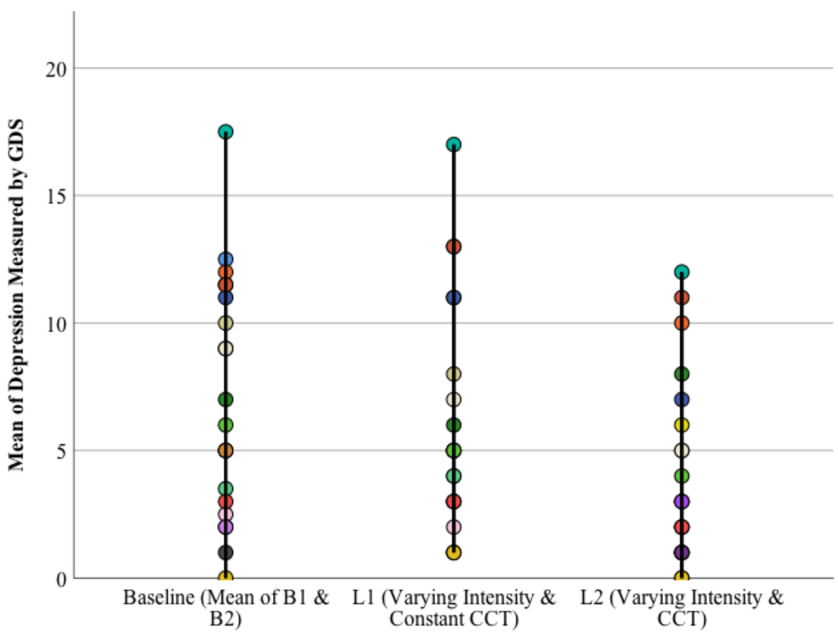


Figure 37. Drop-line mean of depression measured by GDS for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

Table 27. Results from Paired Sample t-test for depression measured by GDS.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (Baseline, L1)	0.86	1.80	2.18	0.042
Pair 2 (Baseline, L2)	2.81	3.05	4.23	< 0.001
Pair 3 (L1, L2)	1.95	2.56	3.50	< 0.001
Pair 4 (B1, B2)	1.24	3.51	1.62	0.12

The interaction between lighting and depression was also tested. In this regard, participants were divided into two groups based on their GSD scores in B1: Depressed (GSD score of 9 or greater) and not depressed (GDS score of 8 or lower). Then, a mixed ANOVA was run to compare the mean score for depression in these two groups as well as the interactions between lighting and baseline depression. There was a significant main effect of lighting (F [1.54, 29.24] = 9.76, p = 0.001, MSE = 3.55, η^2_p = 0.34), baseline depression (F [1, 19] = 5.00, p = 0.037, MSE = 40.60, η^2_p = 0.208), and interaction between lighting and baseline depression (F [1.54, 29.24] = 4.29, p = 0.032, η^2_p = 0.18). This suggested that the effects of lighting on depression is dependent on the baseline depression level, with more effects on depressed participants. Figure 38 shows the results.

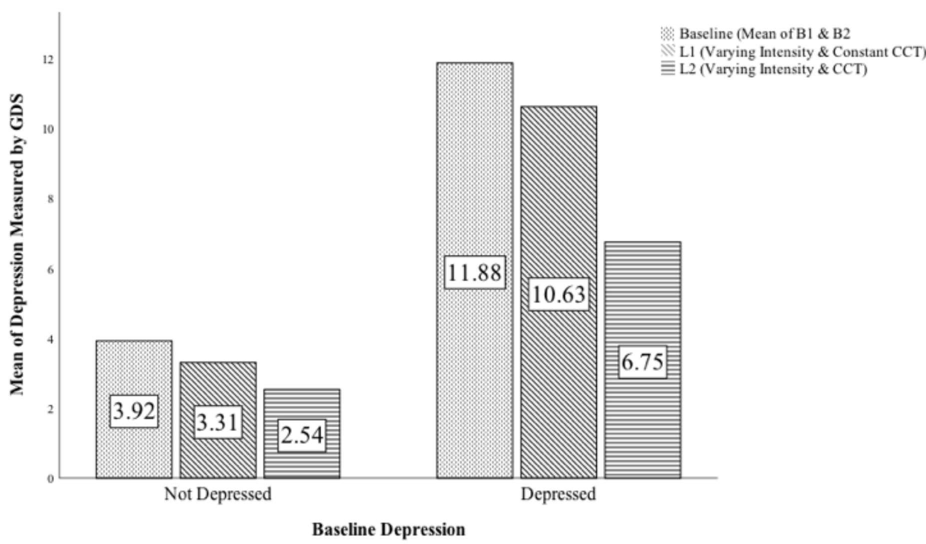


Figure 38. Comparison of the main effect of lighting on depression for depressed versus not depressed participants.

4.7. Mood: Positive and Negative Affects

PANAS was employed to assess mood in the course of the study. The analysis of the baseline mean scores for Positive Affects (PA) exhibited a significant difference between senior living types (Affordable versus High-end) (df = 19, t = -3.62, p < 0.001). No significant difference was found in the mean score for Negative Affects (NA) between senior living types (df = 19, t = 1.23, p = 0.15). Moreover, there was no significant difference in the mean score for PA and NA based on the daylighting conditions. The results are illustrated in Table 28 and Table 29. In general, participants in the High-end senior living showed a higher mean score for PA and a lower mean score for NA compared to the affordable ones.

Table 28. Results of t-tests for Positive and Negative Affects measured by PANAS between buildings.

Variable	**Affordable**	**High-end**	***p* value**
Number	14	7	
PA			
Mean	26.64	36.71	< 0.001
SD	6.31	5.31	
NA			
Mean	15.21	12.86	0.24
SD	4.74	2.41	

Table 29. Results of t-tests for Positive and Negative Affects measured by PANAS between participants in HQDLR and LQDLR.

Variable	**HQDLR**	**LQDLR**	***p* value**
Number	5	16	
PA			
Mean	34.20	28.69	0.163
SD	7.16	7.48	
NA			
Mean	15.20	14.19	0.650
SD	2.78	4.61	

A one-way RM ANOVA indicated a significant effect of lighting conditions on PA in participants (F [2, 40] = 12.76, $p < 0.001$, $MSE = 8.56$, $\eta^2_p = 0.39$). The mean score for PA increased with L1 from 31.50 (SD = 6.51) in Baseline to 33.48 (SD = 6.48). L2 increased the mean score for PA even more to 36.05 (SD = 4.50) (Figure 39 and Figure 40).

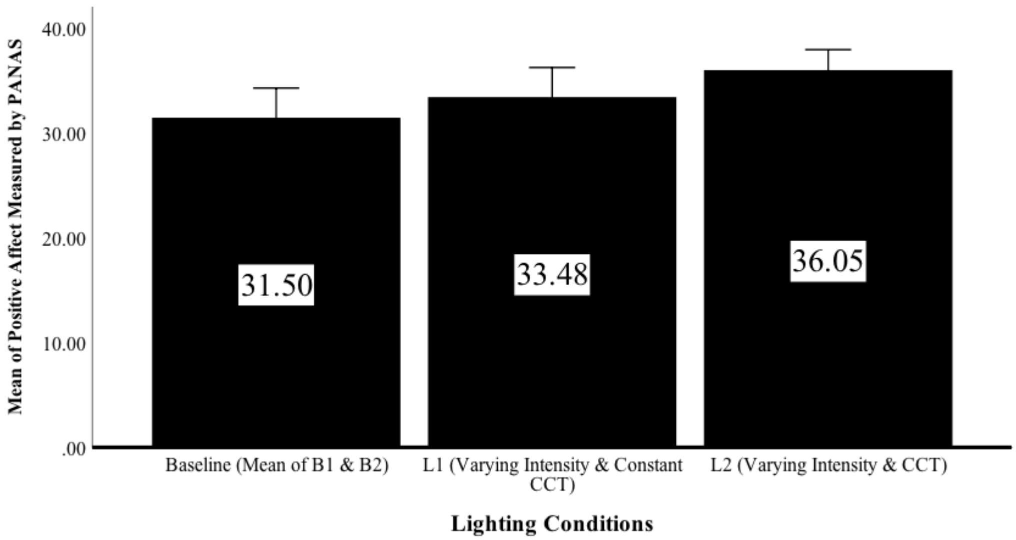


Figure 39. Effect of lighting conditions on positive affect (PA) measured by PANAS.

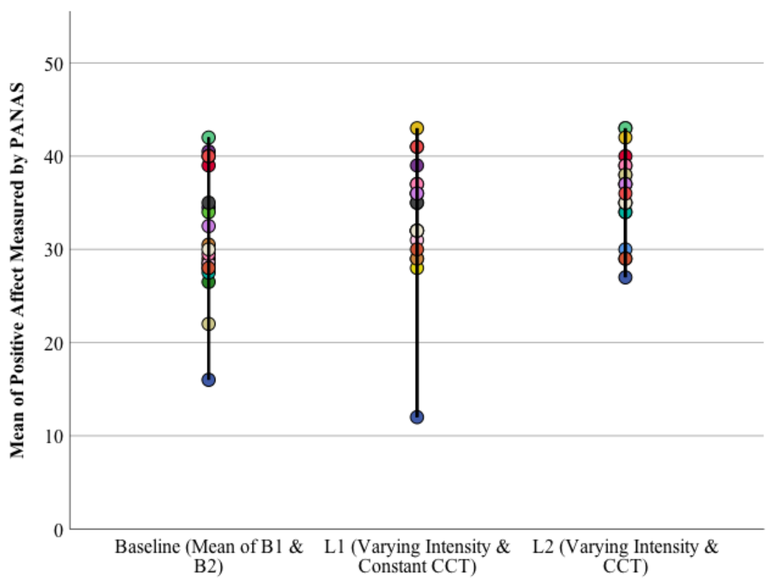


Figure 40. Drop-line mean of positive affect (PA) measured by PANAS for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

The pairwise comparison for the main effect of lighting on PA reflected a significant difference between Baseline and L1 ($df = 20$, $t = -2.51$, $p = 0.021$), B1 and L2 ($df = 20$, $t = -4.35$, $p < 0.001$), L1 and L2 ($df = 20$, $t = -3.01$, $p = 0.007$). Table 30 shows the results. We also found a significant difference between mean score of PA in B1 and B2 *(df* = 20, *t* = -2.29, *p* = 0.033), suggesting the lighting intervention may have lasting effects on the PA (see Appendix A for the results of RM ANOVA with four levels of repeated measures and related paired-wise analysis).

Table 30. Results from Paired Sample t-test for positive affect (PA) measured by PANAS in across the study.

	Mean Difference	SD	*t* (*df* = 20)	*p* Value
Pair 1 (Baseline, L1)	-1.98	3.61	-2.51	0.021
Pair 2 (Baseline, L2)	-4.55	4.80	-4.35	< 0.001
Pair 3 (L1, L2)	-2.57	3.92	-4.35	0.007
Pair 4 (B1, B2)	-3.00	6.02	-2.29	0.033

A one-way RM ANOVA indicated no significant effect of lighting conditions on NA in participants (F [2, 40] = 2.54, p = 0.09, MSE = 3.01, η^2_p = 0.11). However, a reducing trend was observed after the interventions (Figure 41 and Figure 42). In fact, the mean score for NA decreased from 13.88 (SD = 3.36) in Baseline to 13.71 (SD = 3.38) in L1 and decreased more to 12.76 (SD = 3.38) after L2.

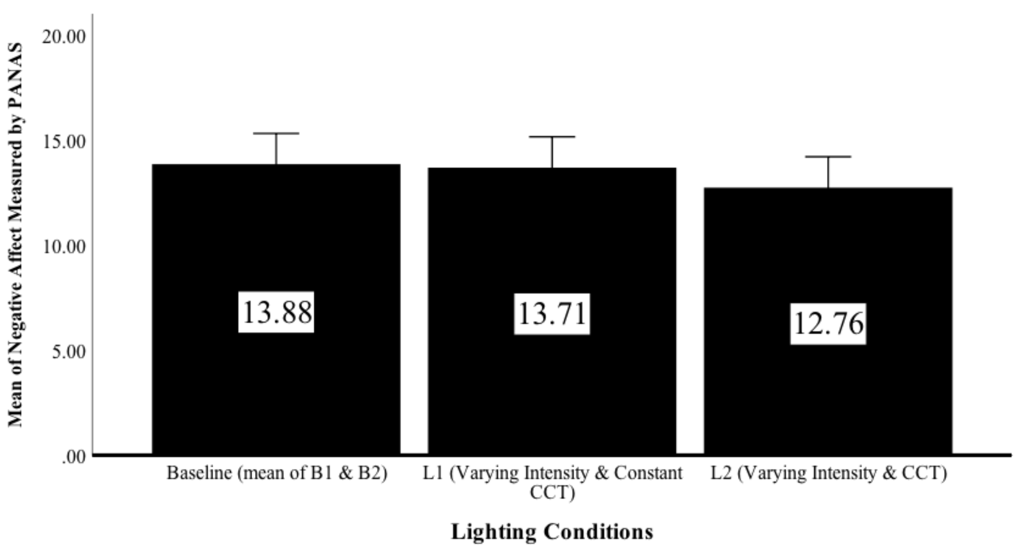


Figure 41. Effect of lighting conditions on negative affect (NA) measured by PANAS.

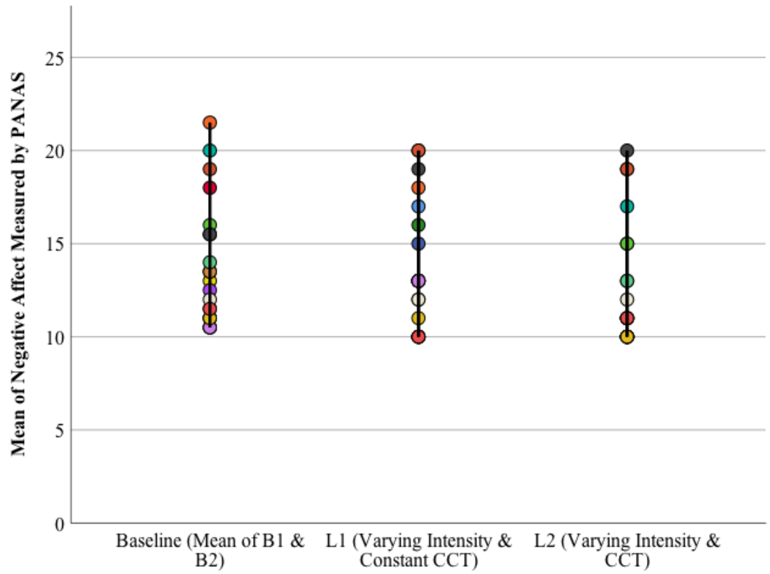


Figure 42. Drop-line mean of negative affect (NA) measured by PANAS for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

4.8. Health-Related Quality of Life (QL)

SF-8 was employed to assess health-related quality of life (QL) in participants, with lower scores indicating a higher QL. Analysis of the initial assessment of QL in B1 confirmed a significant difference between senior living types with a lower mean score (higher QL) for participants in the High-end senior living (df = 19, t = 3.56, p < 0.001). There was no significant difference in the mean score for QL based on the daylighting conditions ($df = 19$, $t = 0.955$, $p = 0.352$). Table 31 and Table 32 show the results.

Table 31. Results of t-tests for health-related quality of life (QL) measured by SF-8 between buildings.

Variable	**Affordable**	**High-end**	***p* value**
Number	14	7	
QL			
Mean	23.71	12.86	< 0.001
SD	12.86	3.13	

Table 32. Results of t-tests for health-related quality of life (QL) measured by SF-8 in HQDLR and LQDLR.

Variable	HQDLR	LQDLR	*p* value
Number	5	16	
PA			
Mean	17.00	21.06	0.352
SD	5.05	8.98	

A one-way RM ANOVA confirmed the significant main effect of lighting on QL (F [2, 40] = 5.22, p = 0.010, MSE = 6.54, η^2_p = 0.21). Figure 43 and Figure 44 show the pattern of QL in the course of the study. L1 intervention improved mean score for QL from 28.12 (SD = 6.13) in Baseline to 16.76 (SD = 5.38) and then L2 improved that even more to 15.57 (SD = 5.44).

The pairwise comparison for the main effect of lighting on QL reflected a significant difference between Baseline and L2 (df = 20, t = 3.06, p = 0.006). There was no significant difference in the mean score for QL between Baseline and L1 (df = 20, t = 1.59, p = 0.128), and L1 and L2 (df = 20, t = 1.78, p = 0.09). Table 33 shows the results.

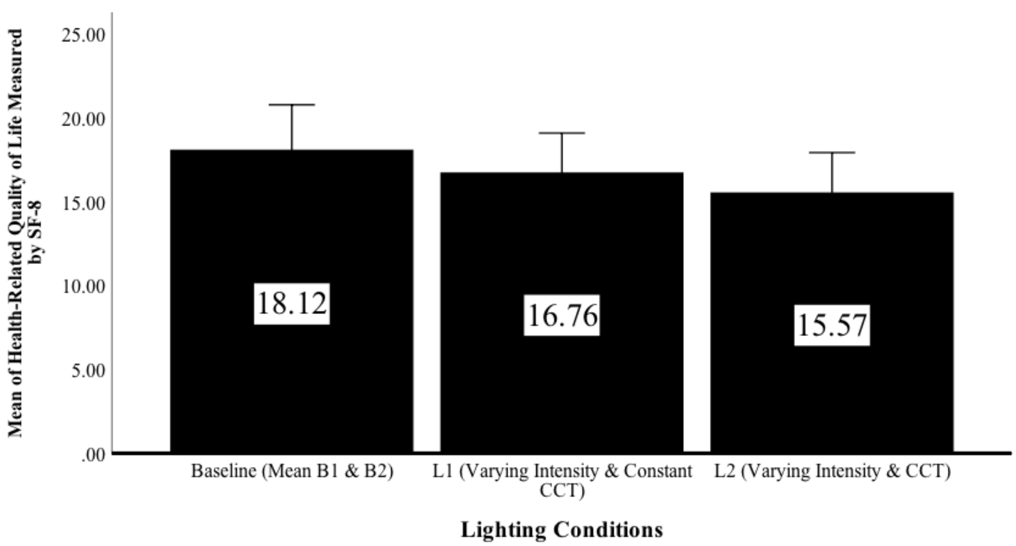


Figure 43. Effect of lighting conditions on health-related quality of life measured by SF-8.

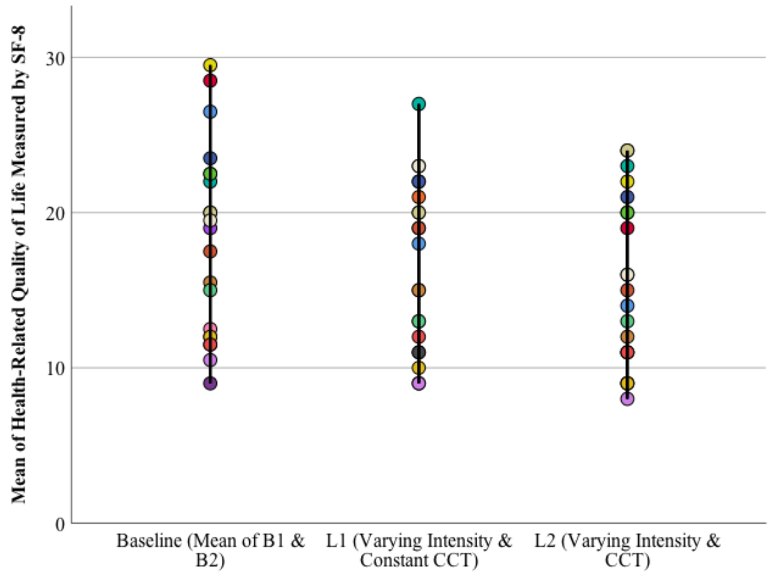


Figure 44. Drop-line mean of health-related quality of life measured by SF-8 for each lighting condition in the course of study for each participant. Each color represents the score of one participant.

Table 33. Results from Paired Sample t-test for health-related quality of life.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (Baseline, L1)	1.36	3.92	1.59	0.128
Pair 2 (Baseline, L2)	2.55	3.81	3.06	0.006
Pair 3 (L1, L2)	1.19	3.06	1.78	0.09
Pair 4 (B1, B2)	3.95	6.41	2.83	0.010

Moreover, a significant difference was found between the mean score for QL in B1 and B2 ($df = 20$, $t = 2.83$, $p = 0.010$) which might be as a result of carryover impacts of interventions on the QL (see Appendix A for the results of RM ANOVA with four levels of repeated measures and related paired-wise analysis).

4.9. Cognitive Performance

Three tests were employed to evaluate cognitive performance in participants throughout the study course: TMT-A, TMT-B, and DSST. There was no significant difference between mean scores for TMT-A, TMT-B, and DSST based on senior living types or the daylighting conditions. The results are shown in Table 34 and Table 35.

Table 34. Results of t-tests for Cognitive Performance tests between buildings.

Variable	Affordable	High-end	*p* value
Number	14	7	
TMT-A			
Mean (Sec)	59.61	41.97	0.20
SD	32.53	17.49	
TMT-B			
Mean (Sec)	131.83	94.16	0.12
SD	49.50	50.15	
DSST			
Mean	38.43	46.57	0.15
SD	9.82	14.91	

Table 35. Results of t-tests for Cognitive Performance tests in HQDLR and LQDLR.

Variable	HQDLR	LQDLR	*p* value
Number	5	16	
TMT-A			
Mean (Sec)	45.37	56.34	0.478
SD	17.92	31.94	
TMT-B			
Mean (Sec)	105.13	123.67	0.498
SD	58.47	50.71	
DSST			
Mean	44.60	40.06	0.476
SD	18.50	9.83	

4.9.1. TMT-A Test

TMT-A measures cognitive performance in relation with attention, visual search ability, and motor functions. The score of the TMT-A test is reported based on the time (seconds) took for each participant to complete the task, with less time indicating greater cognitive performance. A one-way RM ANOVA confirmed the significant effect of lighting conditions on the mean score for TMT-A in participants (F [1.41, 28.22] = 41.05, $p < 0.001$, MSE = 44.54, $\eta^2_p = 0.67$). As the assumption of sphericity was violated (p = 0.006), the Green-Geisser correction was used to report RM ANOVA results. Both lighting interventions appeared to reduce the time needed to complete TMT-A task in participants, suggesting an improvement in attention, visual search, and motor function of cognition. As shown in Figure 45 and Figure 46, L1 intervention improved the mean score for TMT-A from 48.18 sec (SD = 23.11) in Baseline to 40.94 sec (SD = 20.58), the mean score improved even more with L2 and reached 32.52 sec (SD = 15.57).

Paired sample t-test confirmed a significant difference for the mean score for TMT-A between Baseline and L1 ($df = 20$, $t = 6.03$, $p < 0.001$), Baseline and L2 ($df = 20$, $t = 7.17$, $p < 0.001$), and L1 and L2 ($df = 20$, $t = 5.06$, $p < 0.001$). Table 36 shows the results. There was also a significant difference between the mean score for TMT-A in B1 and B2 ($df = 19$, $t = 3.55$, $p < 0.001$), probably occurred as a result of practicing the test or carryover effects of interventions on cognitive functions (see Appendix A for the results of RM ANOVA with four levels repeated measures and related paired-wise analysis).

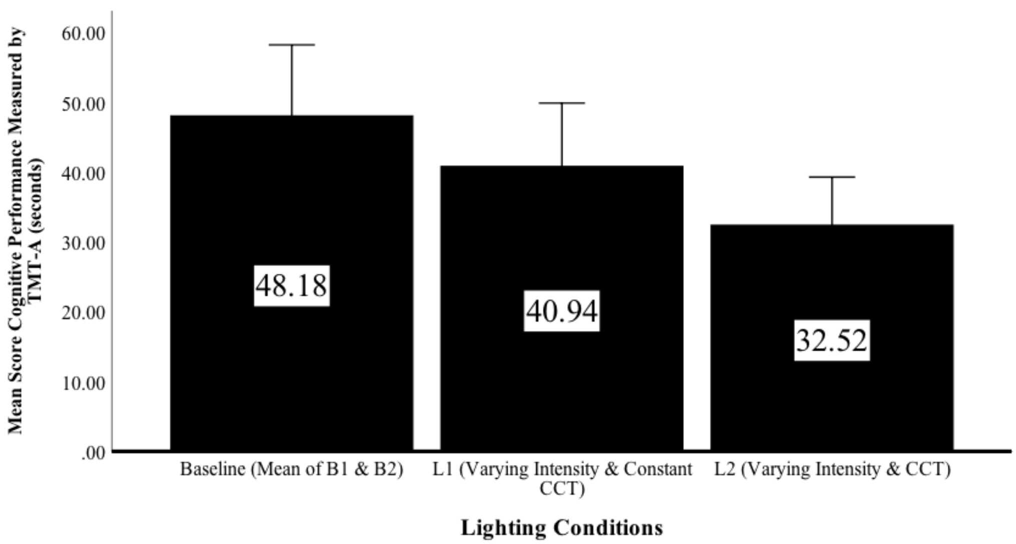


Figure 45. Effectiveness of the L1 and L2 Interventions on cognitive performance measured by TMT-A test. Less time to complete the task indicates a higher level of cognition in relation to attention, visual search ability, and motor function.

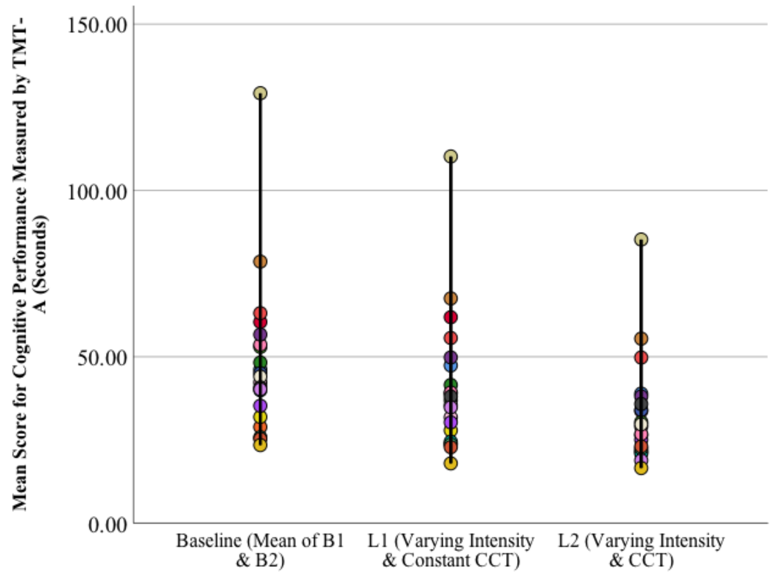


Figure 46. Drop-line mean score for cognitive performance measured by TMT-A under each lighting condition in the course of the study for each participant. Each color represents the score of one participant.

Table 36. Results from Paired Sample t-test for cognitive performance measured by TMT-A.

	Mean Difference	**SD**	***t*** **(*df* = 20)**	***p*** **value**
Pair 1 (Baseline, L1)	7.24	5.50	6.03	< 0.001
Pair 2 (Baseline, L2)	15.66	10.01	7.17	< 0.001
Pair 3 (L1, L2)	8.42	7.62	5.06	< 0.001
Pair 4 (B1, B2)	14.33	14.33	3.55	< 0.001

4.9.2. TMT-B Test

TMT-B measures cognitive performance through examining cognitive alternation, executive functioning, and speed of attention. Similar to TMT-A, the score of the cognitive performance obtained from TMT-B is reported based on the time (seconds) took for each participant to complete the task, with less time indicating greater cognitive performance. There was a significant effect of lighting conditions on TMT-B scores (F [1.54, 30.78] = 30.15, $p < 0.001$, MSE = 398.82, $\eta^2_p = 0.60$). The mean score for TMT-B at Baseline was 108.68 sec (SD = 46.01), it was improved after L1 (mean = 93.06, SD = 37.66), and improved even more after L2 (mean = 67.13, SD = 27.21) (Figure 47 and Figure 48).

The pairwise comparison for the main effect of lighting reflected a significant difference between Baseline and L1 ($df = 20$, $t = 3.40$, $p = 0.003$), Baseline and L2 ($df = 20$, $t = 6.18$, $p < 0.001$), and L1 and L2 ($df = 20$, $t = 5.61$, $p < 0.001$). Table 37 shows the results. We also observed a significant difference between B1 and B2 ($df = 20$, $t = 3.48$, $p < 0.001$), probably occurred as a result of practicing the test or carryover effects of interventions on cognitive functions (see Appendix A for the results of RM ANOVA with four levels repeated measures and related paired-wise analysis).

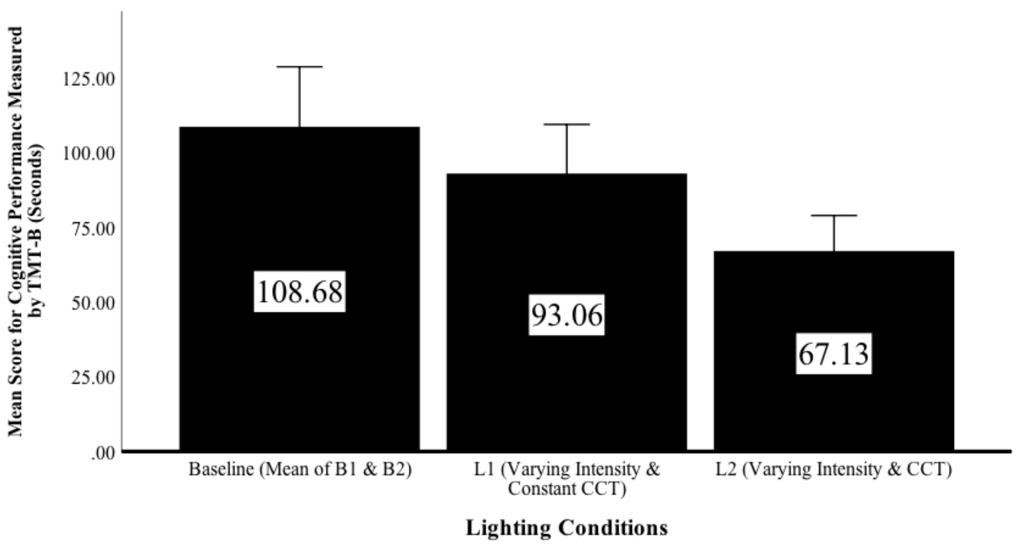


Figure 47. Effectiveness of the L1 and L2 Interventions on cognitive performance measured by TMT-B test. Less time to complete the task indicates a higher level of cognition in relation to cognitive alternation, executive functioning, and speed of attention.

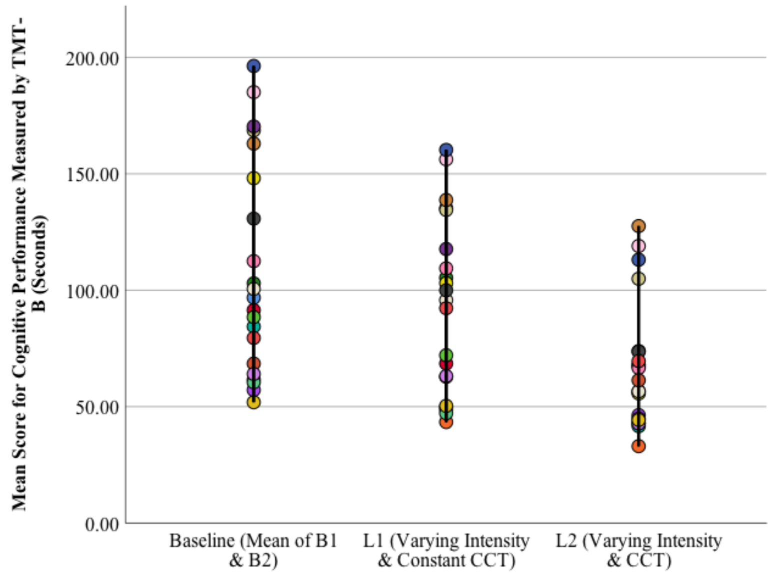


Figure 48. Drop-line mean score for cognitive performance measured by TMT-B under each lighting condition in the course of the study for each participant. Each color represents the score of one participant.

Table 37. Results from Paired Sample t-test for cognitive performance measured by TMT-B.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* value**
Pair 1 (Baseline, L1)	15.63	21.04	3.40	0.003
Pair 2 (Baseline, L2)	41.56	30.82	6.18	< 0.001
Pair 3 (L1, L2)	25.93	21.19	5.61	< 0.001
Pair 4 (B1, B2)	21.19	27.89	3.48	< 0.001

4.9.3. The Difference Between TMT-A and TMT-B (B – A)

The difference between scores (time required to complete the task) of TMT-A and TMT-B is considered as a measure of cognitive flexibility that is relatively independent of manual skills. A one-way RM ANOVA reflected the significant effect of lighting conditions on difference of the two scores (B – A) (F [1.53, 30.56] = 4800.475, $p < 0.001$, MSE = 387.450, $\eta^2_p = 0.38$). Both lighting interventions decreased the difference of the TMT-A and TMT-B scores compared to the Baseline; however, only the difference between L2 and Baseline reached statistical significance ($df = 20$, $t = 3.91$, $p = 0.001$), suggesting that L2 significantly improved cognitive flexibility in participants. Figure 49 - Figure 50 and Table 38 show the results (see Appendix A for the results of RM ANOVA with four levels repeated measures and related paired-wise analysis).

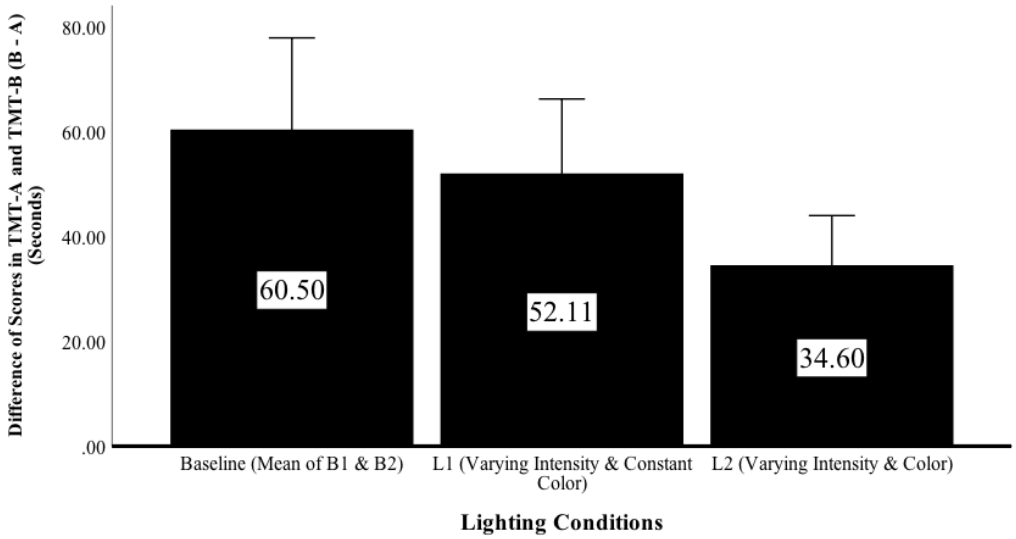


Figure 49. Effects of lighting condition on cognitive flexibility measured by the difference between scores of TMT-A and TMT-B (B – A).

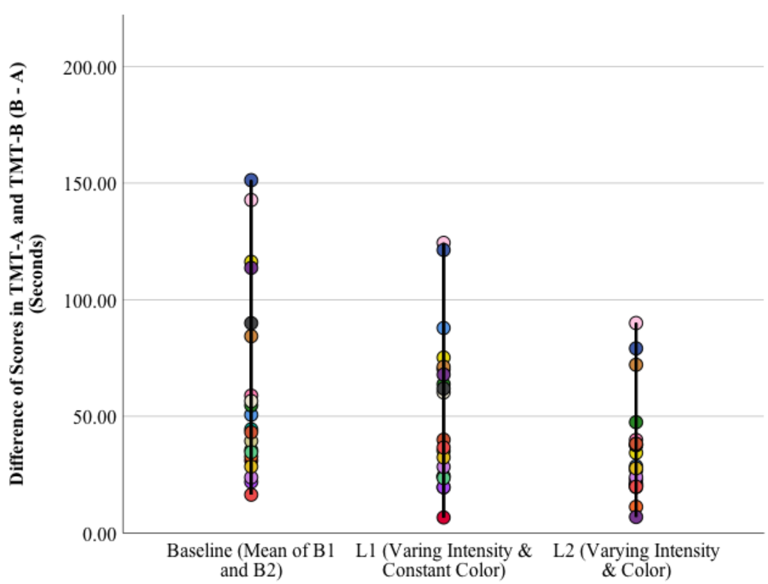


Figure 50. Drop-line mean score for score difference of TMT-A and TMT-B (B – A) under each lighting condition in the course of the study for each participant. Each color represents one participant.

Table 38. Results from Paired Sample t-test for difference of TMT-A and TMT-B Scores.

	Mean Difference	**SD**	***t*** **(*df* = 20)**	***p*** **value**
Pair 1 (Baseline, L1)	8.39	20.11	1.91	0.071
Pair 2 (Baseline, L2)	25.90	30.33	3.91	0.001
Pair 3 (L1, L2)	17.51	21.24	3.78	0.001
Pair 4 (B1, B2)	10.09	24.92	1.86	0.078

4.9.4. DSS Test

DSST measures cognitive performance in relation to processing speed, working memory, visuospatial processing, and attention. A one-way RM ANOVA confirmed the significant effect of lighting conditions on DSST score (F [2, 40] = 22.98, $p < 0.001$, $MSE = 6.92$, $\eta^2_p = 0.54$). The lighting interventions increased the mean score for DSST from 43.10 (SD = 12.15) in Baseline to 46.29 (SD = 11.47) in L1 and 48.90 (SD = 13.32) in L2. Figure 51 and Figure 52 show the pattern of mean scores for DSST in the course of study. The mean score for DSST started worsening after the intervention had been discontinued and reached to 45.67 in B2 which was significantly higher than the B1 (mean = 41.14, SD = 12.03) (see Appendix A for the results of RM ANOVA with four levels repeated measures and related paired-wise analysis).

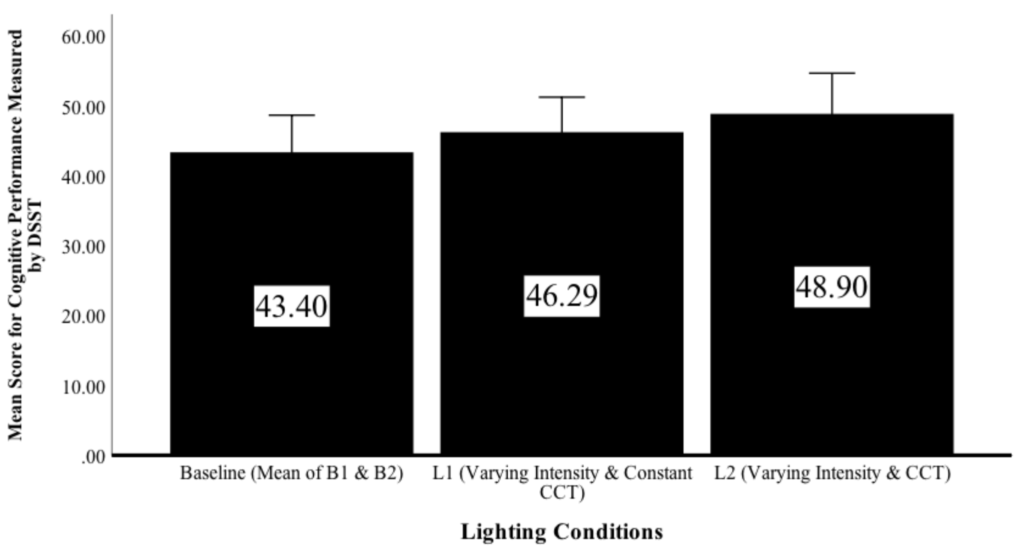


Figure 51. Effectiveness of the L1 and L2 Interventions on cognitive performance in participants measured by DSST.

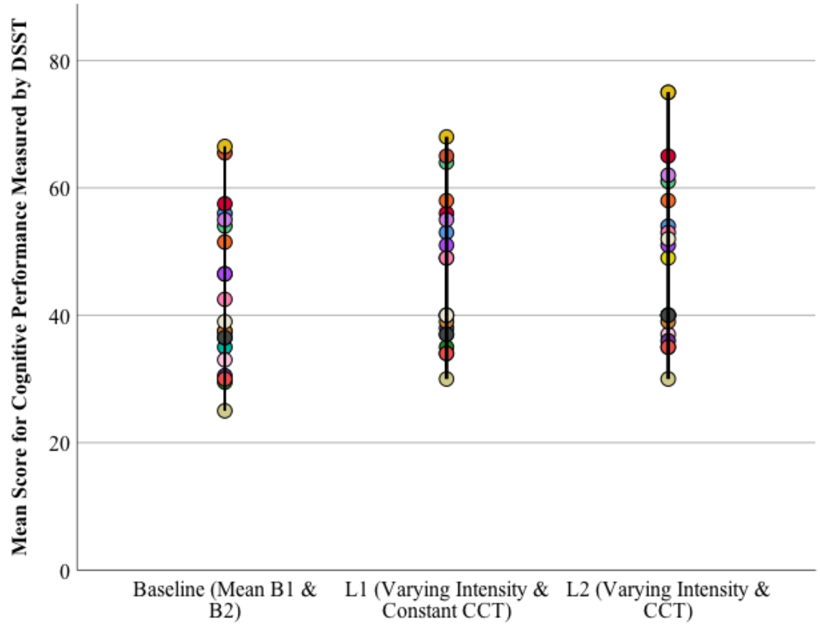


Figure 52. Drop-line mean score for DSST under each lighting condition in the course of the study for each participant. Each color represents one participant.

A pairwise comparison on the main effect of lighting conditions on the DSST scores exhibited a significant difference between Baseline and L1 ($df = 20$, $t = -3.80$, $p = 0.001$), Baseline and L2 ($df = 20$, $t = -3.12$, $p = 0.005$), and L1 and L2 ($df = 20$, $t = 5.61$, $p < 0.001$). The difference between B1 and B2 was also significant (df = 20, t = -4.62, p < 0.001). Table 39 shows the results.

Table 39. Results from Paired Sample t-test for cognitive performance measured by DSST.

	Mean Difference	SD	*t* (*df* = 20)	*p* value
Pair 1 (Baseline, L1)	-2.88	3.47	-3.80	0.001
Pair 2 (Baseline, L2)	-23.72	34.83	-3.12	0.005
Pair 3 (L1, L2)	-2.62	4.31	-2.79	< 0.001
Pair 4 (B1, B2)	-4.52	4.49	-4.62	< 0.001

4.10. Mediating Effects of Dependent Variables

To examined the relationships between DVs and their possible mediating effect, we utilized the SPSS Macro provided by Preacher & Hayes (2004) which enabled an estimation of the indirect, direct, and total effects in simple mediation models. For this purpose, mediation analyses, according to Baron & Kenny (1986), were employed by testing the categorical independent variable "Lighting Condition" with two levels (Baseline and L2) and the DVs and mediators as explained in the following sections. We only chose to compare the L2 condition as this lighting condition showed more significant and promising effects on the DVs compared to L1.

4.10.1. The Mediating Effect of Sleep on Cognitive Performance

To examine the mediating effects of sleep on cognitive performance, we deployed a mediation analysis by testing the scores on TMT-A, TMT-B, DSST as DVs and NSD, SE, SDist, SRImp, and SQ as mediators.

TMT-A: Our analysis showed that SDist (B = -0.72, $p = 0.018$) and SRImp (B = 0.070, $p = 0.016$) tended to have a significant direct effect on the TMT-A scores. Lower SRImp was associated with less time required to complete the TMT-A task, suggesting a higher visual search ability and motor functions. However, contrary to our expectation, the relationship between SDist and TMT-A scores was negative, meaning a higher SDist resulted in improved TMT-A scores.

Using the bootstrap method to detect mediation effects, we measured a significant indirect effect of lighting condition on TMT-A scores through SDist. The 95% bootstrap confidence interval for the indirect effects did not include zero (95% CI: [0.58, 16.00]). This result indicated that SDist mediated the relationship between light exposure and cognitive performance in relation to visual search ability and motor functions. There was no significant indirect effect of lighting condition on TMT-A scores through SRImp (95% CI: [-13.72, 0.93]).

There was no significant effect of NSD (B = 0.01, $p = 0.738$), SE (B = -0.13, $p = 0.818$), and SQ (B = 0.01, $p = 0.991$), on TMT-A scores; Hence, according to Baron and Kenny (1986), the mediating role of these DVs on scores for TMT-A could be ruled out.

TMT-B: The statistical analysis reflected that SDist (B = -1.45, *p* = 0.008) and SE (B = -2.20, *p* = 0.036) had a significant direct effect on the scores for TMT-B. The negative correlation revealed that a higher SE is associated with improved scores in TMT-B, suggesting an enhancement in cognitive alternation. However, contrary to our expectations, it appeared that a higher SDist resulted in less time required to complete the TMT-B task.

The 95% bootstrap confidence intervals indicated a significant indirect effect of light exposure on TMT-B scores through SDist (95% CI: [1.21, 29.22]). This result indicated that SDist mediated the relationship between light exposure and cognitive alternation. There was no significant indirect effect of lighting condition on TMT-B scores through SE (95% CI: [-19.64, 0.15]).

Our analysis indicated no significant effect of NSD (B = 0.05, *p* = 0.346), SRImp (ß = 0.84, *p* = 0.284), and SQ (ß = 3.06, *p* = 0.157), on TMT-B scores; Hence, according to Baron and Kenny (1986), the mediating role of these DVs on scores for TMT-B could be ruled out.

DSST: We measured a significant direct effect of SDist (B = 0.57, *p* = 0.001) and SQ (ß = -1.62, *p* = 0.0.022) on DSST scores. The standard regression coefficient indicated that improved SQ (lower SQ scores) were significantly associated with higher scores in DSST, suggesting an increase in cognitive functions. Nonetheless, similar to the TMT-A and TMT-B, more SDist appeared to improve DSST scores.

The 95% bootstrap confidence intervals showed a mediation effect of SDist in the relationship between light exposure and DSST scores (95% CI: [-0.85, -0.05]). However, no mediation effect of SQ was measured (95% CI: [-0.04, 0.41]).

There was no significant effect of NSD (B = -0.029, p = 0.061), SRImp (B = -0.49, p = 0.057), and SE (B = 0.034, p = 0.92), on DSST scores, suggesting no mediating role of these DVs on cognitive performance.

4.10.2. The Mediating Effect of Mood and Depression on Cognitive Performance

To examine the mediating effect of depression and mood on cognitive performance, we deployed a mediation analysis by testing the scores on TMT-A, TMT-B, DSST as DVs and depression (GDS scores) and PA as mediators.

TMT-A: No significant direct effect of depression (B = -0.69, p = 0.33) and PA (ß = -0.88, p = 0.084) on TMT-A scores was found. Thus, these DVs did not have any mediation effects in the relationship between light exposure and cognitive performance measured by TMT-A.

TMT-B: Both depression (B = -3.71, p = 0.001) and PA (B = -4.82, p < 0.001) were significantly related with TMT-B scores. A more positive mood (PA) resulted in a better cognitive alternation measured by TMT-B. However, contrary to our expectation, a lower level of depression was associated with more time required to complete the TMT-B task and hence, a drop in cognitive functions. These results indicated that depressed people might have better cognitive alternation ability. The 95% bootstrap confidence intervals revealed a significant mediation effect of depression (95% CI: [0.81, 18.84]) and PA (95% CI: [-33.08, -4.04]) on the relationship between lighting and cognitive functions measured by TMT-B.

DSST: We found a significant direct effect of PA on cognitive function measured by DSST (B = 0.72, p = 0.020). A more positive mood (PA) resulted in higher DSST scores and, so cognitive performance. The mediation analysis also revealed that PA significantly mediated the relationship between light exposure and DSST scores (95% CI: [0.30, 5.60]). No significant correlation was found between depression and DSST scores (ß = 0.46, p = 0.270); thus, there was no significant indirect effect of lighting condition on cognitive performance measured by DSST through depression.

4.10.3. The Mediating Effect of Sleep on Depression

To examine the mediating effects of sleep on depression, we ran a mediation analysis by testing the depression (GDS scores) as DV and NSD, SE, SDist, SRImp, and SQ as mediators. A significant direct effect of SRImp (B = 0.27, $p < 0.001$), SQ (B = 0.42, $p = 0.039$), and SE (B = 0.26 $p = 0.01$) on depression was measured. While a more SRImp was associated with more depression in our participants, improved SQ (lower scores) resulted in lower depression. Nevertheless, the correlation between SE and depression was positive, suggesting that higher SE predicted higher depression in older adults. This was in contrast to our expectations.

The 95% bootstrap confidence intervals exhibited a mediation effect of SRImp (95% CI: [-3.34, -0.11]) and SE (95% CI: [0.18, 2.01]) on the relationship between light exposure and depression. However, we found no mediating effect of SQ (95% CI: [-1.41, 0.16]). Moreover, there was no significant direct association between NSD (B = -0.002 $p = 0.63$) and SDist (B = -0.08, $p = 0.095$) with depression and hence no mediating effect of these DVs.

4.10.4. The Mediating Effect of Cognitive Performance on Depression

To examine the mediating effect of cognitive performance on depression, a mediation analysis was utilized by testing depression (GDS scores) as DVs and scores for TMT-A, TMT-B, and DSST as mediators. No significant direct effect of cognitive performance on depression was measured, TMT-A (B = -0.003, $p = 0.931$), TMT-B (B = -0. 001, $p = 0.732$), and DSST (B = -0.02, $p = 0.741$). Hence, the mediating role of cognitive performance measured by these three tests on depression could be ruled out.

4.10.5. The Mediating Effect of Positive Mood (PA) on Depression

Our analysis exhibited a significant direct relationship between PA and depression (B = -0.37, $p < 0.001$). The negative correlation coefficient indicated that a more positive mood resulted in lower depression levels in older adults. Moreover, a significant mediating role of PA on the relationship between lighting and depression was measured (95% CI: [-2.42, -0.32]).

4.10.6. The Mediating Effect of Sleep on Positive Mood (PA)

To examine the mediating effects of sleep on depression, we ran a mediation analysis by testing the PA as DV and NSD, SE, SDist, SRImp, and SQ as mediators. A significant direct effect of SDist (B = 0.22, $p = 0.009$), SRImp (B = -0.28, $p = 0.026$), and SQ (B = -0.80, $p = 0.020$) on PA was found. While a more SRImp was associated with a drop in PA, improved SQ (lower scores) resulted in higher levels of positive mood in participants. Nevertheless, the correlation between SDist and PA was positive, suggesting that a higher SDist predicted a decreased PA in older adults. This is in contrast to our expectations. Moreover, the 95% bootstrap confidence intervals exhibited a mediation effect of SRImp (95% CI: [0.001, 4.076]) on the relationship between light exposure and PA. No mediation effect of SDist (95% CI: [-5.34, 0.09]) and SQ (95% CI: [-0.34, 3.12]) was found.

There was no significant direct association between NSD (B = -0.003 $p = 0.66$) and SE (B = -0.11, $p = 0.489$) with PA and hence no mediating effect of these DVs.

4.10.7. The Mediating Effect of Cognitive Performance on Positive Mood (PA)

To examine the mediating effect of cognitive performance on PA, a mediation analysis was utilized by testing PA as DVs and scores for TMT-A, TMT-B, and DSST as mediators. A significant direct effect of cognitive performance measured by TMT-B was exhibited (B = -0.10,

$p < 0.001$). TMT-B measured cognitive alternation ability. These results suggested that a higher ability in cognitive alternation resulted in improved PA in older adults. We also found the mediation effect of cognitive alternation ability on the relationship between lighting and PA (95% CI: [0.94, 6.08]).

There was no significant association between cognitive performance measured by TMT-A (B = 0.04, $p = 0.361$) and DSST (B = -0.01, $p = 0.872$) with PA, and consequently no mediating role.

4.10.8. The Mediating Effect of Depression on Positive Mood (PA)

Our analysis exhibited a significant direct relationship between depression and PA (B = -0.71, $p < 0.001$). The negative correlation coefficient indicated that more depression predicted lower levels of PA in older adults. Moreover, a significant mediating role of depression on the relationship between lighting and PA was measured (95% CI: [0.21, 3.44]).

4.10.9. The Mediating Effect of Cognitive Performance on Sleep

To examine the mediating effect of cognitive performance on sleep, a mediation analysis was employed by testing NSD, SDist, SRImp, SE, and SQ as DVs and scores on TMT-A, TMT-B, and DSST as mediators. The mediation analysis exhibited no direct effect of cognitive performance measured by the three tests on NSD, SDist, and SRImp. Therefore, the mediating effect of cognitive performance on the relationship between light exposure and NSD, SDist, and SRImp did not exist. Table 40 illustrates the results.

The regression analysis showed that scores in TMT-A and TMT-B significantly predicted SQ (B = -0.05, $p = 0.037$) and SE (B = -0.58, $p = 0.004$) respectively. More precisely, an improved score in TMT-B resulted in a better SE in older adults which showed the positive effect of higher cognitive alternation on SE. However, contrary to our expectation, better scores in TMT-A (less time to complete the task) was associated with a lower SQ (higher scores in PSQI). We also found a mediating effect of cognitive performance measured by TMT-A (95% CI: [0.21, 3.44]) and TMT-B (95% CI: [0.21, 3.44]) on the relationship of lighting with SQ and SE respectively. There was no significant direct effect of cognition measured by TMT-B (B = -0.002, p = 0.907) and DSST (B = -0.07., p = 0.097) on SQ; hence no significant mediating role in relation between lighting and SQ. Likewise, we found that the scores in TMT-A (B = 0.03, p = 0.339) and DSST (B = -0.07, p = 0.282) did not significantly predict SE and therefore the mediating effect also did not exist.

Table 40. Results of mediation analysis for cognitive performance and sleep

Variables	**NSD**		**SDist**		**SRImp**		**SQ**		**SE**	
	B	*p* Value	B	*p* Value	B	*p* Value	B	*p* Value	B	*p* Value
TMT-A	-0.21	0.790	-0.17	0.145	-0.04	0.555	-0.05	0.037	0.03	0.339
TMT-B	-0.05	0.913	-0.87	0.173	-0.06	0.113	-0.002	0.907	-0.06	0.004
DSST	-2.04	0.132	-0.11	0.595	-0.20	0.119	-0.07	0.097	-0.07	0.281

4.10.10. The Mediating Effect of Depression on Sleep

To examine the mediating effect of depression on sleep, a mediation analysis was employed by testing NSD, SDist, SRImp, SE, and SQ as DVs and depression (GDS scores) as a mediator. There was a significant direct effect of depression on SDist, SRImp, SQ, and SE. Table 41 indicates the results. Lower depression resulted in improved SDist, SRImp, and SQ in participants. However, it appeared that a lower GDS score was associated with a decrease in SE which was not expected. Depression was also shown as a significant mediator in relationship between lighting and SDist (95% CI: [-9.09, -0.43]), SRImp (95% CI: [-6.82, -0.34]), SQ (95% CI: [-1.38, -0.003]), and SE (95% CI: [-2.93, -0.13]).

No significant direct effect of depression on NSD was measured; thus, depression did not mediate the impact of light exposure on NSD.

4.10.11. The Mediating Effect of Mood on Sleep

We examined the mediating effect of mood on sleep by utilizing a mediation analysis that tested NSD, SDist, SRImp, SE, and SQ as DVs and PA (positive mood) as a mediator. PA significantly predicted SE (B = 0.28, p = 0.011); more precisely, a more positive mood was associated with an improved SE. However, PA did not mediate the relationship between light exposure and SE (95% CI: [-0.01, 2.51]). There was no significant direct effect of PA on NSD, SDist, SRImp, and SE, and therefore the mediating role of PA on the relationship between lighting and these sleep metrics can be ruled out (see Table 41).

Table 41. Results of mediation analysis for depression, mood, and sleep

Variables	**NSD**		**SDist**		**SRImp**		**SQ**		**SE**	
	B	*p* Value	B	*p* Value	B	*p* Value	B	*p* Value	B	*p* Value
Depression	-1.84	0.598	1.77	0.001	1.44	< 0.001	0.25	0.012	0.60	<0.001
PA	-1.27	0.614	0.58	0.099	0.20	0.29	-0.04	0.612	0.28	0.011

4.11. Effect of Senior Livings Buildings

Participants were recruited from three different buildings: two affordable senior livings (Affordable I and Affordable II) and one high-end senior living (High-end). The effect of senior living type on DVs as well as the interaction between the senior living type and the lighting condition were analyzed using a general linear mixed model ANOVA. There was a significant effect of senior living type on depression (F [1, 19] = 5.00, p = 0.04, MSE = 40.60, η^2_p = 0.19), PA (F [1, 19] = 7.38, p = 0.01, MSE = 66.40, η^2_p = 0.28), and QL (F [1, 19] = 18.58, p < 0.001, MSE = 29.53, η^2_p = 0.49). Moreover, there was a significant interaction between senior living types and lighting conditions on Depression (F [2, 38] = 4.29, p = 0.02, η^2_p = 0.18), PA (F [1, 19]

= 3.94, $p = 0.03$, $\eta^2_p = 0.17$), SE (F [2, 38] = 2.57, $p = 0.04$, $\eta^2_p = 0.11$), and SRImp (F [2, 38] = 3.92, $p = 0.03$, $\eta^2_p = 0.17$), suggesting that the effect of lighting conditions on these DVs depends on the senior living types. In fact, the lighting condition is more influential in affordable senior livings compared to the high-end one. Table 42 and Figure 53, Figure 54, Figure 55, and Figure 56 indicate the results.

Table 42. Results of Mixed ANOVA to test the effect of senior living type on DVs and the interaction between senior living type and lighting.

		F	***MSE***	***p* value**	η^2_p
Senior Living Type					
	NSD	2.10	26499.63	0.16	0.10
	SE	4.05	40.45	0.06	0.18
	SOL	1.88	552.20	0.19	0.09
	DSD	1.17	23543.62	0.29	0.06
	SDist	0.01	654.11	0.91	0.00
	SRImp	1.63	221.35	0.22	0.08
	SQ	0.50	23.75	0.49	0.03
	DSle	0.66	20.78	0.43	0.03
	GDS	5.00	40.60	0.04	0.21
	PA	7.38	66.40	0.01	0.28
	NA	0.00	29.53	0.98	0.00
	QL	18.58	44.16	< 0.01	0.49
	TMT-A	1.05	1134.47	0.32	0.05
	TMT-B	2.48	3409.42	0.13	0.12
	DSST	2.26	416.44	0.15	0.11
Senior Living Type * Lighting					
	NSD	2.57	-	0.09	0.12
	SE	3.54	-	0.04	0.16
	SOL	0.96	-	0.38	0.05
	DSD	1.07	-	0.35	0.05
	SDist	1.96	-	0.16	0.09
	SRImp	3.92	-	0.03	0.17
	SQ	0.82	-	0.45	0.04
	DSle	0.00	-	0.97	0.00
	GDS	4.29	-	0.02	0.18
	PA	3.94	-	0.03	0.17
	NA	1.10	-	0.34	0.06
	QL	0.42	-	0.66	0.02
	TMT-A	2.81	-	0.07	0.13
	TMT-B	0.35	-	0.71	0.02
	DSST	0.44	-	0.65	0.02

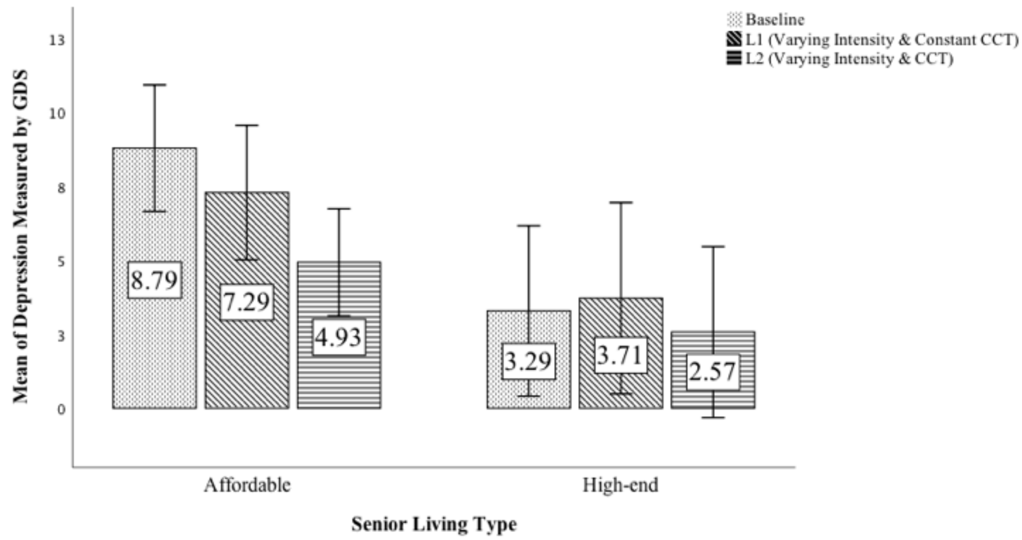


Figure 53. Effect of Senior living types on the Depression measured by GDS.

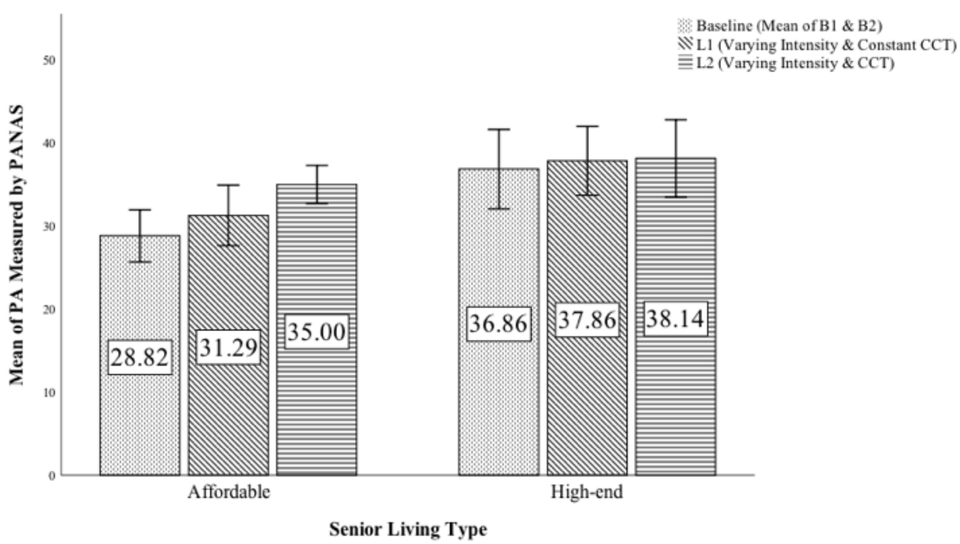


Figure 54. Effect of Senior living types on the PA.

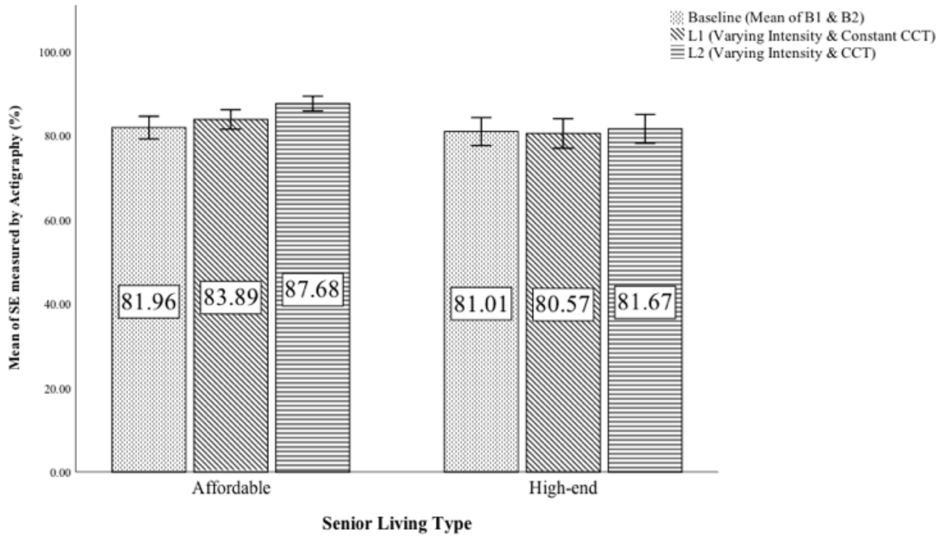


Figure 55. Effect of Senior living types on the SE.

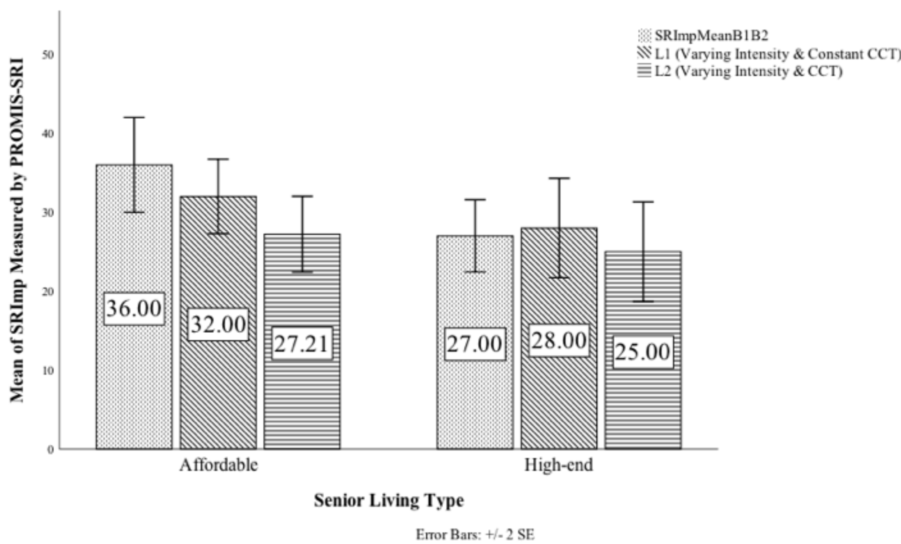


Figure 56. Effect of Senior living types on the SRImp.

4.12. Effect of Daylighting

As previously mentioned, five out of twenty apartments met the setpoints for CS (≥ 0.3) and EML (≥ 220) and were categorized as the ones with high quality daylighting conditions. In this section, the effect of daylighting condition in the apartments on DVs and the interaction of that with the tested lighting conditions were analyzed. In this regard, HQDLRs were compared with LQDLRs through running a general linear mixed model ANOVA. There was no significant effect of daylighting on DVs or the interaction of daylighting and lighting conditions, suggesting that the effect of lighting on the DVs was not impacted by the daylighting condition in the apartments. Table 43 shows the results.

Table 43. Results of Mixed ANOVA to test the effect of daylighting on DVs and the interaction between daylighting and lighting.

		F	***MSE***	***p* value**	**η^2_p**
Daylighting					
	NSD	1.46	27333.05	0.24	0.07
	SE	0.58	47.63	0.46	0.03
	SOL	0.00	606.79	0.99	0.00
	DSD	0.36	24523.13	0.56	0.02
	SDist	3.48	553.11	0.08	0.16
	SRImp	0.02	240.09	0.90	0.00
	SQ	1.69	22.38	0.21	0.08
	DSle	0.05	21.45	0.83	0.00
	GDS	0.10	51.04	0.76	0.01
	PA	0.71	88.87	0.41	0.04
	NA	0.31	29.05	0.58	0.02
	QL	0.03	50.00	0.87	0.00
	TMT-A	0.73	1152.63	0.40	0.04
	TMT-B	0.61	3733.80	0.44	0.03
	DSST	0.40	456.47	0.54	0.02
Lighting * Daylighting					
	NSD	0.95	-	0.40	0.05
	SE	0.48	-	0.62	0.03
	SOL	0.04	-	0.96	0.00
	DSD	0.07	-	0.93	0.00
	SDist	1.20	-	0.15	0.10
	SRImp	1.78	-	0.18	0.09
	SQ	0.44	-	0.65	0.02
	DSle	1.77	-	0.18	0.09
	GDS	3.03	-	0.06	0.14
	PA	0.61	-	0.55	0.03
	NA	0.30	-	0.73	0.02
	QL	0.82	-	0.45	0.04
	TMT-A	0.13	-	0.88	0.01
	TMT-B	0.07	-	0.93	0.00
	DSST	0.20	-	0.82	0.01

CHAPTER 5: DISCUSSION

There are six sections in this chapter. Section 5.1 and 5.2 discuss the current lighting conditions in the living spaces of older adults and its association with their sleep, mood, and cognitive performance. Sections 5.3 explains lighting conditions under lighting interventions. Sections 5.4 and 5.5 discuss the effects of applying a whole-day lighting scheme on sleep, mood, and cognitive performance in older adults respectively. Section 5.6 and 5.7 address the impact of living conditions on DVs as well as the carryover effects of lighting interventions on them.

5.1. Current Lighting in the Living Spaces of Older Adults

Corneal and horizontal illuminations were measured in the living spaces of participants and around their main seating spot. Measurements included illuminance levels, CCT, and spectrum. Results demonstrated poor lighting conditions in 80% of the assessed living spaces. The lighting conditions in the living spaces for older adults were poor due to low illuminance, inappropriate CCT, and hence low delivered morning EML and CS.

The measurements showed that illuminance levels in 60% of the living rooms were far below ANSI/IES RP-28-16's recommendations, such that residents of these spaces were almost living in darkness. Though, there was a broad range of interior ambient illumination, from sun-filled to very dark living rooms. Earlier studies confirmed poor lighting conditions in the dwelling units of older adults (Eilertsen et al., 2016; Hegde & Rhodes, 2010). Overall, the lighting condition was poorer in Affordable senior livings compared to the High-end living arrangements. In fact, only one out of fourteen measured living spaces in affordable senior livings met the illuminance threshold of 200 lux recommended by ANSI/IES RP-28-16. In High-end senior living, five out of six measured living spaces met the illuminance threshold. These results are aligned with those stated in a previous study (Eilertsen et al., 2016) which confirms that older adults with higher income have higher average illuminance levels than those living in affordable senior living facilities. One explanation for lower illuminance levels in affordable senior livings could be characteristics of the building's facade, which result in poor daylighting. Daylight systems in these buildings were limited to one window in the living room which was sometimes covered by window blinds. In contrast, the high-end senior living facility evaluated in this study was a relatively new high-rise residential building with floor-to-ceiling curtain walls that provided good quality daylighting in most apartments, particularly for those located in higher floors. However, the electrical lighting system in all twenty living rooms was limited to a few floor lamps placed by the residents; no permanent ceiling or wall lighting system was utilized. Our observations and informal conversations with the participants revealed that daylighting was the only daytime lighting source in all these apartments: floor lamps were only used in the evening. As the measurements were conducted in the daytime, the results, in fact, indicated the daylighting condition in these living spaces. Consequently, apartments with more access to daylight had a higher average illumination. Measured living rooms in the high-end senior living facility were in levels 24 – 47, which were expected to have higher daylight access. The only apartment in affordable senior living that met the ANSI/IES RP-28-16' recommendations was located on 8th floor, which was the top floor.

Low illuminance levels have been associated with reduced visual performance (Bakker et al., 2004) and increased risk of fall (Brawley, 2001). Moreover, as corneal illuminance plays a significant role in circadian lighting, low illumination results in lower EML and CS values. Our lighting measurements data showed that the daytime CS value and EML fell below the recommended setpoints in 60% of the apartments; 94% of them were the ones with the average horizontal illuminance levels lower than 200 lux. Poor circadian lighting is associated with sleep problems (Akie Ichimori et al., 2013, 2015; Obayashi, Saeki, Iwamoto, et al., 2014a) and depression (Akie Ichimori et al., 2015; van Hoof, Aarts, et al., 2009).

5.2. Ambient Lighting in Living Rooms and Sleep, Mood, and Cognitive Functions

Tested living rooms in this study were divided into two groups: HQDLR and LQDLR. HQDLR category included the living rooms that had an EML of 220 or greater or CS of 0.3 or greater as recommended by WELL Building Standards and literature. Five out of twenty apartments were categorized as HQDLR and the rest were placed in the LQDLR group. Results showed no significant difference between HQDLR and LQDLR in terms of sleep, depression, mood, health-related quality of life, and cognitive performance. However, participants residing in HQDLR apartments exhibited longer NSD, shorter DSD, and better mean scores for PA, QL, TMT-A, TMT-B, and DSST as well as shorter SOL and lower mean scores for depression, DSle, and SRImp. These results indicated some associations between the lighting conditions in the living rooms and sleep, mood, and cognitive performance in older adults. Previous studies demonstrated a significant relationship between the daily light exposure and sleep in older adults. In a study by Münch et al. (2017) on 66 institutionalized older adults, a significant effect of daily light exposure on night-time sleep quality was proven. These results were aligned with those from other previous studies (Figueiroa et al., 2011; Shochat et al., 2000). Moreover, a significant negative correlation between daytime illuminance levels in the dwelling units of older adults and depression scores has been demonstrated (e.g., Ichimori et al., 2015). No previous study examined the association between daily light exposure or illuminations in the living environments with cognitive functions in older adults. However, research on other age groups revealed a significant positive correlation between illuminance levels and cognitive functions (Chellappa, Gordijn, & Cajochen, 2011) with daily higher illuminance level exposure resulting in higher cognitive performance. Moreover, studies that exposed participants to bright light indicated significant improvements in the cognitive performance of participants in all age groups, including older adults (e.g., Graf et al., 2001; Keis, Helbig, Streb, & Hille, 2014; Sun, Lian, & Lan, 2019).

Therefore, results from our study along with previous studies suggest that environments without proper illumination that delivers light/dark cycles could decrease depression and promote sleep quality and cognitive performance in healthy older adults. One unexpected outcome was the lower SE and higher mean score for SDist and SQ in HQDLRs compared to the LQDLRs. This result was in contrary to former research that indicated bright light exposure during the daytime decreased sleep disturbance and increase subjective sleep quality in older adults (Friedman et al., 2009; Kohsaka et al., 2000; Lieverse et al., 2011).

Moreover, our analysis showed that participants spent a very short duration of time outdoors under the direct sunlight (19.53 minutes on average); no significant difference was found between HQDLRs and LQDLRs. Previous studies reported similar findings. Nioi et al., (2017) reported that older adults (72 – 99 years) spent only 3 minutes exposed to the illuminance level of 1000 or greater during winter; duration of exposure was higher in summer up to 46 minutes. Shochat et al. (2000) reported a median of 10.5 minutes of exposure to the illuminance level of more than 1000. There are two limitations associated with the results here. First, the data collection was performed in winter when, naturally, older adults spend less time outside due to cold weather. Second, lighting data collected by actigraphy might be inaccurate as it is possible that participants covered the actiwatch by their sleeves while they were outdoor.

Non-significant results found in this part of our study might be as a result of small sample size. Moreover, our data collection about the number of hours participants spent outside of their dwelling units might be inaccurate. It is possible that participants with lower illuminance levels in their apartments spent more time outside and thus received more sunlight exposure. Additionally, we did not measure evening illuminations in the living rooms. There are some studies that found a significant positive correlation between nighttime illuminance levels and poor sleep quality and depression (Obayashi, Saeki, Iwamoto, Ikada, & Kurumatani, 2013; Obayashi, Saeki, Iwamoto, et al., 2014b; Obayashi, Saeki, Iwamoto, Okamoto, et al., 2013; Obayashi, Saeki, & Kurumatani, 2014; Yannielli & Harrington, 2001). When it comes to the non-visual effects of light, whole-day lighting conditions matter; thus, future studies should consider measuring illumination from morning to evening to obtain a more comprehensive understanding of daily light exposure and its associations with sleep, mood, and cognitive function.

5.3. Lighting Conditions in the Living Rooms Under Interventions

Corneal and horizontal illuminance levels significantly increased by both lighting interventions. Under L1 and L2, all the tested living rooms met the recommended numbers by ANSI/IES RP-28-16 and AS throughout the day; even the mean for evening horizontal illumination (after 20:00) was 238.5 lux with the minimum of 201 lux which was higher than the 200 lux setpoint. In the morning, the mean horizontal illumination increased up to 754 lux. This was even sufficient as task lighting for older adults.

Moreover, the actigraphy data confirmed a significant increase in the AT and RT light exposure during the lighting interventions. Despite the close mean corneal and horizontal illuminance levels in L1 and L2, actigraphy data showed a significantly higher AT light exposure in L2. One explanation could be through the way that the actiwatch measures white light exposure. L2 intervention provided a cool daytime lighting with high CCT (6500ºK – 4500ºK), as opposed to the L1 with a constant warm lighting with a low CCT of 2700ºK. The actiwatch detected more white light from cool lighting with CCT compared to the warm lighting with low CCT; that is why it showed a higher white light exposure in L2 than L1. In addition, anecdotally, we realized that almost all participants preferred L2 intervention over L1, as they felt L2 is more similar to natural lighting. Therefore, it was possible that participants spent more time in their living rooms under L2 than L1. Moreover, actigraphy data revealed a significant increase in the RT light exposure. Although we did not measure the baseline evening lighting in the tested living rooms, the increase in the RT light exposure proved that the evening lighting in these apartments did not meet ANSI/IES RP-28-16, hence, it was insufficient for the aged vision of their residents. However, it is not clear why the RT light exposure in L1 is higher than L2 because both interventions set illuminance levels and CCT exactly the same after 20:00.

With respect to the circadian lighting, both lighting interventions provided high EML and CS values in the morning for circadian stimulation, hence increased morning EML and CS values significantly compared to the baseline with significantly more increase with L2. Under the interventions, all apartments met the WELL Building Standards and LRC recommendations for circadian lighting. As opposed to morning lighting, the EML and CS were very low after 20:00 to prevent any unwanted disruption of the circadian rhythms. The evening lighting interventions were designed to provide visual lighting needs without causing any significant circadian effects. We achieved that by providing the minimum ambient horizontal illuminance level of 200 lux and the lowest possible CCT of 2700ºK (this was the lowest CCT that could be obtained from the luminaires used in this study). We do not have any data about the evening EML and CS in the baseline. This is one of the limitations of this study that should be considered in the future research. However, the increase in the RT light exposure measured by the actiwatches could indicate an increase in the evening EML and CS during the interventions. This increase was inevitable, as we had to meet the minimum recommendations for the visual needs of older adults in the evening.

However, as it was shown in the results sections and will be explained later, this higher evening EML and CS value during the interventions did not cause any damage to participants' sleep, mood, or cognitive performance.

There are some other explanations that should be mentioned here. First of all, lighting measurements of the interventions were performed without daylighting contributions. However, in some apartments and based on the participants' habits, the contribution of daylighting on the ambient illumination was significant. In those apartments, regardless of the sky condition, daylighting increased the corneal and horizontal illuminance levels and influenced the CCT in the living rooms. The increase in illuminance levels varied in each living room based on the window to wall ratio, blinds status, window orientation, and apartment location. Higher illuminance levels during the daytime did not provide any negative impact on our intervention as it would have resulted in higher EML and CS values and potentially improved visual and circadian system performance.

On the other hand, daylighting might increase the CCT of the lighting interventions, which would also be in favor of our lighting interventions by increasing the circadian effects. However, this should be considered in the interpretation of the results, especially for the L1 intervention. Daylighting, in fact, could increase CCT and hence influence spectrum of lighting in the L1 intervention which was designed to deliver a low CCT of 2700ºK with the peak wavelength of 612 - 614nm. The within-subject comparison performed in this study eliminated several issues associated with various daylighting conditions in the apartments, as the effect of daylighting on DVs was measured in the baseline and if any observed improvement could be considered as a result of the interventions.

5.4. Effects of a Whole-Day Ambient Lighting with Varying Illuminance Levels and Constant CCT on Sleep, Mood, and Cognitive Performance

Among other factors, the magnitude of non-visual effects of lighting drastically depends on the light intensity (Rea & Figuero, 2011). This study hypothesized that exposure to a whole-day lighting scheme with high intensity morning and dimmed evening illumination would result in improved sleep, mood, and cognitive performance in older adults, regardless of CCT and spectrum. To test this hypothesis, participants were exposed to the L1 intervention for nine days during which they received a morning illuminance level of 500 lux or higher (8:00 – 12:00). Then, the illuminance level was decreased gradually throughout the day, reaching 100 lux in the evening (after 20:00). The CCT of the lighting was kept constant at 2700ºK. Positive effects of a whole-day lighting scheme with varying intensity and constant CCT were found on sleep, mood, and cognitive function.

Nine days of exposure to the L1 intervention significantly increased NSD by 19.52 minutes on average compared to Baseline. Improvements were also observed in SE, SDist, and SRImp after exposure to L1; nonetheless, they did not reach statistical significance. The positive effect of daytime bright light exposure on sleep quality has been confirmed in previous studies. Sloane et al. (2007) found that 2.5 hours of morning bright light and 8 hours of whole-day bright light with the illuminance levels of 2500 lux significantly improved nighttime sleep duration by 16 minutes. In a long-term study by Riemersma-van der Lek et al. (2008), a whole-day bright light exposure with an illuminance level of 1000 lux increased sleep duration by 27 minutes in community-dwelling older adults.

Moreover, no significant effect of the L1 intervention was exhibited on DSD, DSle, self-rated SQ, and SOL. This finding was not aligned with results from previous research. Bright light exposure during the daytime had been shown to decrease DSD and DSle (Alessi et al., 2005;

Martin et al., 2006) and improve SQ (Leggett et al., 2017). Additionally, it was shown that exposure to bright light in early morning decreased SOL (Sloane et al., 2007). However, in our study, SOL increased by 5.12 minutes after exposure to L1. One explanation for this result could be the applied illuminance levels in the morning. In fact, in this study, the morning illuminance level provided by L1 was 500 lux which was dramatically lower than that tested by Sloane et al. (2007). It is possible that 500 lux of illumination with 2700ºK CCT was not sufficient to influence SOL in older adults. The same explanation could be applied for the lack of significant differences found in DSD, DSle, and self-rated SQ.

Exposure to L1 also decreased depression in older adults with more decrease in older adults with depressive symptoms. The mean depression score was significantly dropped from 6.95 in the Baseline to 6.10 after the L1 intervention ($P < 0.05$). Moreover, a significant improvement was found in PA with a 1.98-point increase after nine days of exposure to L1. Similar findings were exhibited in previous studies, (Lieverse et al., 2011; R. T. Loving, Kripke, Elliott, et al., 2005; Riemersma-van der Lek et al., 2008; Royer et al., 2012b) which demonstrated the positive effect of bright light exposure on mood and depressive symptoms. Lieverse et al. (2011) reported that three weeks of one-hour exposure to bright light (750 lux) in the morning improves depressive symptoms by 43% in older adults. Nonetheless, there were a good number of studies that did not find any significant effect of lighting exposure on depression and mood in older adults. Most of these studies are those that tested BLT, which forced participants to sit in front of a lightbox for a certain period.

The L1 intervention did not influence NA and QL in our participants. The number of studies evaluating the effect of lighting intensity on NA and QL is limited. In fact, to our knowledge, this was the first study to investigate the effect of varying lighting intensity on NA and

QL. Nonetheless, a significant association between daily light exposure and QL has been demonstrated (Grandner, Michael A., Kripke, Daniel F., Langer, 2005; Akie Ichimori et al., 2013).

With respect to cognitive performance, exposure to the L1 intervention significantly improved mean scores for all three cognitive tests. The L1 intervention significantly improved mean scores for TMT-A by 15.00%, TMT-B by 14.37%, and DSST by 6.00%. There are a limited number of clinical trials that investigate the direct impacts of bright light exposure on cognitive functions. In general, results from these trials showed a positive association between exposure to bright light and cognitive performance. Graf et al. (2001) reported that bright light significantly improved MMSE scores versus dim light placebo. In a more comprehensive study that included cognitive functions as an outcome measure, Reimersma-van der Lek et al. (2008) found a significant improvement in cognitive scores and the intervention prevented a decline over the long duration of the study. In a more recent study, Kretschmer and colleagues (2013) proved that bright light had a strong direct effect on cognitive performance which was independent from sleepiness and mood.

These results suggest that a whole-day lighting scheme with varying intensity and a constant CCT of 2700ºK with delivery of a high illuminance level in the morning and dimmed lighting in the evening could be an effective solution to improve sleep, mood, and cognitive performance in older adults. In this study, we only tested the CCT of 2700ºK. The results might be different for other CCTs. For instance, exposure to blue-enriched lighting has been recommended in the morning, but not in the evening. Hence, applying a dimmed illumination with high CCT in the evening might cause unwanted circadian disruptions which might result in poor sleep, mood, and cognitive function. Future studies should aim to extend these findings by testing varying intensity aligned with other constant CCTs.

Furthermore, the morning illuminance level provided by L1 in this study was at 500 lux (corneal) which was relatively lower than most previous studies. Nevertheless, we found significant improvements in some sleep metrics, mood, and cognitive function. In fact, one main advantage of this study was that the morning bright light was provided through ambient illumination instead of a light box. Therefore, participants received light for longer hours while they were performing their life routines. Other studies with no significant findings usually applied lighting interventions through light boxes. This shows the importance of providing bright light through ambient illumination.

5.5. Effects of a Whole-Day Ambient Lighting with Varying Illuminance Levels and CCTs on Sleep, Mood, and Cognitive Performance

The magnitude of the impact of spectrum and CCT on sleep, mood, and cognitive function has been debated among lighting researchers. This debate has continued due to the mixed results obtained from research. Some studies did not find any significant difference between blue-enriched illumination and red- or yellow-enriched illumination (e.g., Royer et al., 2012; Wu, Sung, Lee, & Smith, 2015), whereas others reported a strong effect of spectrum on sleep, mood, and cognitive function (e.g., Figueiro & Rea, 2012; Sloane, Md, Figueiro, & Cohen, 2008; van Hoof, Schoutens, & Aarts, 2009). These findings are why some researchers have argued that varying CCT is not necessary to stimulate circadian rhythms. As a result, technologies like tunable white luminaires were labeled as not worth the extra cost.

To investigate if adding tuning spectrum to the ambient illumination with varying intensity would provide any additional benefits to sleep, mood, and cognitive functionality, the L2 intervention was designed. L2 delivered a high illuminance level and high CCT in the morning (500 lux and 6500ºK). Then, both intensity and CCT were decreased gradually throughout the day to provide dimmed lighting with low CCT in the evenings (> 100lux and 2700ºK). The intensity of the light in L2 was the same as what was provided by L1 and the only difference was in the CCT. Participants were exposed to L2 for another nine days. Positive effects of the L2 intervention were found on sleep, mood, and cognitive performance as compared to Baseline and L1.

Actigraphy data confirmed a significant improvement in NSD, SE, and SOL after exposure to L2. Nine days of exposure to L2 significantly increased NSD by 34.94 minutes from Baseline and by 15.42 minutes compared to L1. L2 also significantly improved SE by 4.03% from Baseline. Moreover, as opposed to L1 that had no significant effect on SOL and DSD, we observed a significant drop in SOL and a reducing trend in DSD after exposure to L2.

From self-rating sleep questionnaires, an improvement was found in subjective sleep under L2 with significantly higher scores for SQ and a statistically meaningful drop in SDist, SRImp, and DSle as compared to Baseline and L1. Participants exhibited an 18.37% decreased in SDist, 19.76% decrease in SRImp, 19.14% increase in SQ, and 18.43% decline in DSle. These results suggested a meaningful improvement in subjective and objective sleep quality in older adults.

Results from the only other study with a whole-day dynamic lighting intervention with varying intensity and CCT support our findings. Van Lieshout-van Dal and colleagues (2019) reported that three weeks of exposure to a dynamic ambient lighting with an intensity of 600 – 1100 lux and CCT of 6500ºK in the daytime (8:00 – 17:00 hr) and 600 lux with 1800ºK in the evenings (after 17:00 hr) significantly improved NSD from 408 to 495 minutes on average and decreased nighttime awakening and DSD (Van Lieshout-van Dal et al., 2019). These results are also consistent with the conclusion of a review study by White et al. (2013), including 18 cited studies that a lighting interventions with varying intensity and CCT might mitigate symptoms of circadian disruption in community-dwelling older adults.

It should be further noted that most previous studies did not specifically examine the impact of a whole-day lighting intervention with varying intensity and CCT, and to our knowledge, none implemented the intervention in the real dwelling units of older adults. Instead, these studies were conducted either in a lab environment or in the common rooms of senior living facilities. However, previous studies demonstrated the positive effects of exposure to bright light with high CCT in the morning on sleep quality in older adults (Figueiro et al., 2014; Lieverse et al., 2011; van Hoof, Aarts, et al., 2009). In most of these studies, researchers used 3 – 4 weeks of interventions to influence circadian clock and hence sleep quality. Nevertheless, we were able to find significant results after only nine days of exposure.

Along with sleep, depression and mood have also been examined as DVs in previous studies like the one by Figueiro et al. (2014), but none of those studies were a whole-day lighting scheme. Except for the study by Figuerro et al. (2014), the intervention in most studies included vertical bright blue light applied by a light box for a certain period of time (30 – 120 minutes). A significant effect of lighting with high intensity and high CCT on depressive symptoms and mood were demonstrated (Leggett et al., 2017; Loving, Kripke, Knickerbocker, & Grandner, 2005). These results are consistent with our findings. In fact, L2 significantly decreased the mean score for depression by 40% from Baseline and 32% as compared to L1; more reduction was observed in depressed older adults. We also observed a significant increase in PA and a dropping trend in NA after L2 which showed an improvement in mood.

Furthermore, L2 provided more improvement in cognitive function than L1. Participants' mean score in all three cognitive tests increased significantly by 20.57%, 27.86%, and 5.63% in TMT-A, TMT-B, and DSST respectively as compared to L1. None of the previous studies examined the effect of a whole-day lighting scheme with varying intensity and CCT on cognitive function in older adults. However, a previous study demonstrated a strong association between bright blue lighting exposure and cognitive functionality in older adults (Royer et al., 2012b). Research on young individuals recognized blue light as a potent mean for cognitive stimulation. We previously reported the effect of light intensity on cognition. However, it is evident that the positive effect of light is greater using blue wavelength light, suggesting an involvement of ipRGC cells and circadian system (Cajochen et al., 2005; Vandewalle et al., 2011). Motamedzadeh et al. (2017) found a significant impact of blue-enriched lighting (17,000ºK) on the reduction of working memory errors (Motamedzadeh, Golmohammadi, Kazemi, & Heidarimoghadam, 2017). However, the lighting effects on cognitive performance changes with aging. Daneault et al. (2014) reported that older brains remained capable of showing sustained responses to light in several brain areas, but the effect of blue light on brain responses declined with aging in areas typically involved in visual functions and alertness (V Daneault et al., 2013). In this study, we were able to obtain meaningful improvement in cognitive functions of older adults by exposing them to a whole-day lighting scheme with higher intensity and CCT (blue wavelength) in the morning. This shows by adjusting the illuminance levels and spectrum, it is possible to compensate for age-related changes in visual, circadian, and cognitive systems; hence, lighting could be used as an additional means of helping cognitive performance in older healthy individuals.

Our findings from this section suggest that the addition of color tuning quality to an ambient illumination with varying intensity could provide additional benefits to sleep, mood, and cognitive performance in older adults. The L2 intervention delivered a 500lux illumination with CCT of 6500ºK in the morning. The higher morning CCT significantly increased the circadian stimulating effect of lighting when compared to L1. Many previous studies examined higher intensities (1000 lux – 2500 lux) and CCTs (9000ºK – 17000ºK). However, the main advantage of our intervention was to provide a whole-day lighting scheme which increased duration of exposure and included a significant difference between daytime and nighttime lighting. This is essential to meet circadian lighting needs.

Although significant improvements in sleep, mood, and cognitive function were observed under L2, a more efficient whole-day lighting scheme for older adults might be available by optimizing the spectrum. The luminaire used in this study produced 6500ºK illumination with the peak wavelength of 454 nm. The human circadian system is more sensitive to light with a peak wavelength of 480 nm. Hence, lower lighting intensity would be required for a lighting with the peak wavelength of 480 nm to achieve the same circadian effect. Unfortunately, most tunable white light sources available in the market do not provide the optimized spectrum. To compensate, we need to increase the intensity, which consumes more energy. Future lighting technology should consider that. On the other hand, in designing lighting for older adults, we should always consider their visual performance. This means that the illuminance level should not fall below a certain point. ANSI/IES RP-28-16 recommended a horizontal ambient illuminance level of 200 lux. Whether it is sufficient or not for older adults requires more investigation. What is important to consider are the visual and circadian effects of light in designing healthy, comfortable lighting for this population.

5.6. Effects of Living Conditions on Sleep, Mood, and Cognitive performance

In this study, the effect of living condition on the sleep, mood, and cognitive function was evaluated in two ways: Daylighting Condition and Senior Living Types.

In sections 5.1 and 5.2, we described current lighting conditions in the living spaces of our participants. We concluded that as there was no lighting system in the living rooms used during the daytime, lighting measurement in baseline could represent daylighting conditions. We also explained how we categorized living rooms into two categories: HQDLR and LQDLR. As explained, there was no significant difference in sleep, mood, and cognitive performance between participants in HQDLR and LQDLR.

Interestingly, we also could not find any significant differences in DVs under L1 and L2 between these two groups. Moreover, no interaction was found between daylighting condition and interventions (lighting condition). These results suggest that the effects of L1 and L2 interventions on sleep, mood, and cognitive function in older adults were independent from the daylighting conditions in their living room. In other words, even in living rooms with high quality daylighting, residents could benefit from the lighting interventions. This is new information that has not been discussed in previous studies. It should be noted that data collection for this study was conducted during the Fall and Winter seasons when less daylight is available due to the sun position and there are more cloudy days. This factor is especially prevailing in climates like those in Chicago and Saint Louis where the study was conducted. Future studies should repeat similar protocols in Spring and Summers as well as other climates to investigate the interaction of daylighting condition and lighting interventions in more depth.

In addition to the conventional daylighting condition, we analyzed the effect of senior living types on sleep, mood, and cognitive function to find any significant difference at the baseline or after the interventions. Two senior living types were included in this study: one high-end and two affordable ones. These two types were varied in term of architecture (apartment size, finishes, amenities, and architectural styles [high-rise versus low-rise]) as well as population. The high-end senior living facility was a high-rise building located in downtown Chicago with larger units, large windows, city or lake views for units in upper floors, and extra amenities such as a dining area, breakfast area, chapel, training rooms, large-sized well-equipped gym, and a swimming pool. The affordable senior living facilities were low-rise buildings with smaller units, small windows, and no especial outside view. Amenities included a common room and a mid-sized gym. In terms of population demographics, residents in the high-end senior living had an overall higher education and income.

We found significant differences in mood (depression and PA) and QL between residents of high-end versus affordable senior living facilities. Participants from the high-end senior living facility exhibited significantly lower levels of depression along with significantly higher PA and QL. One explanation for that could be the higher income of the residents in the high-end senior living facility. There is a well-established inverse association between socioeconomic status and depression as well as quality of life among older adults (Ma & Mcghee, 2013; Murata, Kondo, Hirai, Ichida, & Ojima, 2008).

In addition to socioeconomic status, architectural and environmental elements could play a significant role in older adults' quality of life. In fact, built environments have been recognized as a dimension of quality of life, impacting individuals' performance by supporting their abilities (World Health Organization Quality of Life Assessment (WHOQOL), Group, 1998). As people age, they become more dependent on their environment to compensate for increasing cognitive, physical, and sensory limitations (Brawley, 2001). Moreover, several interrelated factors such as functional and cognitive impairments, chronic diseases, diminished social networks, low levels of physical activity, and sleep quality all affect dependency and quality of life in older adults (Lupi et al., 2012; Ribeiro Do Valle et al., 2013). These factors are significantly influenced by the design and quality of the physical environment (Anderiesen, Scherder, Goossens, & Sonneveld, 2014; Cohen-Mansfield et al., 2012; Maximov, 2000).

In this study, we only focused on lighting as one of the main environmental elements affecting quality of life in older adults. However, there are other environmental factors such as neighborhood characteristics, ambient quality of the space (e.g., indoor air quality, noise and acoustics, thermal comfort), spatial organization, as well as building size and location. Besides lighting, we did not systematically analyze other environmental features in participants' dwelling units, as it was not our focus. Hence, our data is not sufficient to evaluate their impacts on depression and mood.

There was no significant difference in cognitive performance and sleep quality between participants in high-end and affordable senior living facilities, indicating no significant effect of senior living type on these variables. However, we found a significant interaction between senior living type and lighting condition for depression, PA, SE, and SRImp, suggesting the effect of lighting condition (which mean lighting interventions) on these DVs is dependent on the senior living type. Our results showed that applying lighting interventions in affordable senior living facilities offered more improvements in depression, PA, SRImp, and SE to residents than those residing in high-end senior living facility. One explanation for that could be the fact that participants in the affordable senior living showed a higher level of depression and SRImp as well as lower levels of PA at the Baseline. Another reason might be related to the overall lower illuminance levels in the affordable senior living facilities. In the high-end senior living facility, the mean for baseline corneal illuminance level was approximately twice more. That caused a more dramatic change in the lighting condition by the interventions in the affordable senior living facilities compared to the high-end one.

Our analysis showed no significant interactions between senior living type and lighting conditions with respect to NSD, DSD, SOL, SDist, DSle, NA, QL, as well as the results for TMT-

A, TMT-B, and DSST, suggesting that the effect of lighting conditions on these variables were independent from the senior living type and perhaps income and educational levels.

5.7. Carryover Effects of Lighting

To examine the potential carryover effects of 18-day lighting intervention, we had all participants wear the actiwatch for another two weeks (including one week of washout) after the conclusion of the intervention phase. The final study visit was performed after a 2-week follow-up period when participants completed self-rating sleep and mood questionnaires as well as cognitive tests. Then, in our analysis, we compared scores from B1 and B2 to assess any possible carryover effect of light.

Mean Scores for SRImp, PA, QL, TMT-A, TMT-B, and DSST remained significantly improved in B2 compared to Baseline 1. We also observed lower scores for depression, SDist, and SQ in B2, although the difference between B1 and B2 did not reach statistical significance. These results showed that lighting interventions had a long-lasting effect on sleep, mood, and cognitive performance. The carryover effect of light on subjective ratings of sleep and depression as well as cognition tests after the intervention was removed is consistent with other studies (Figueiro et al., 2015, 2016; Riemersma-van der Lek, Swaab, Twisk, Hol, Hoogendijk, & Van Someren, 2008; Sun et al., 2019; E. J. van Someren et al., 1996). From a practical perspective, this suggests that the daytime exposure to bright blue light might not have to be delivered every day, enabling older adults to vary their daily routines as needed without fear of sudden relapse.

Although the lasting effect of light is well-evident in research, in our study, there might be other factors that played a role in improved scores in B2, especially in terms of mood and cognition. For instance, we cannot overlook the effect of practice on better outcomes in cognitive TMT-A, TMT-B, and DSST cognitive tests. When participants were taking these tests in B2, they had practiced taking the tests three times before. Even a two-week break could not totally remove the effect of this previous practice. That might be one main reason for better outcomes for cognitive performance. Moreover, in the last study meeting, participants expressed their excitements about completing the study as well as receiving compensation for their participation. This occurred primarily for those in the affordable senior living facilities. That excitement could have an impact on their mood, which resulted in improved outcomes for PA, depression and QL. It is essential to consider these factors in assessing the carryover effects of light.

5.8. Relationship Between Sleep, Mood, Depression, and Cognitive Performance

In this study, we examined whether any of the tested DVs played a mediating role in the relationship between lighting and other DVs. According to our analysis, there was a significant direct effect of sleep, positive mood, and depression on cognitive performance. More precisely, while lower levels of SRImp resulted in an improved visual search ability and motor functions measured by TMT-A, better SE and SQ predicted higher levels of cognitive performance measured by TMT-B (cognitive alternation) and DSST (attention, working memory, and processing speed) respectively. In contrary to the assumption that the high levels of SDist might decrease cognitive performance, in the present study, we observed that higher levels of SDist tended to enhance various metrics of cognitive performance. One explanation could be that sleep disturbance is associated with increased stress levels which result in improved arousal levels and thus cognitive performance (Vgontzas et al., 2007). The deployed mediation analysis also revealed a mediation effect of SDist in the relationship between light exposure and cognitive performance. Nevertheless, as the effect of SDist on cognitive performance was positive (more SDist led to better cognitive function), according to Mackinnon, Krull, & Lockwood (2000), an inconsistent mediation or suppression effect could be indicated. This special case of mediation is called negative confounding because sleep disturbance resulted in an underestimation of the L2 intervention effect on cognitive performance (Kretschmer et al., 2013; Mackinnon et al., 2000). In other words, SDist, decreased the magnitude of the relationship between lighting and cognitive performance. According to our statistical analysis, L2 intervention resulted in a significant increase in cognitive performance and a significant decrease in SDist in older adults. On the other hand, lower levels of SDist was associated with improved cognitive functions. Given the fact that cognitive performance significantly improved after L2 exposure, it is evident that lighting has a direct effect of cognitive performance measured in the present study that is independent of SDist.

We found no significant mediation effect of SRImp, SE, and SQ on the relationship between lighting and cognitive performance. Moreover, there was no significant direct or mediating effect of NSD on cognitive performance.

Furthermore, both PA and depression indicated a significant direct effect on cognitive performance measured by DSST and TMT-B, respectively. More PA was associated with higher scores in DSST and TMT-B, suggesting a better cognitive alternation, attention, working memory, and processing speed. These results are in line with previous research which demonstrated that psychological well-being is related to cognitive performance (Ziegler, Mood, Characteristics, Ex-, & Ziegler, 2010). PA also indicated a significant mediating effect on the relationship between lighting and cognitive performance, suggesting that a positive mood may improve the effect of lighting on cognition.

In contrast to the assumption that lower depression levels might cause enhance cognitive functions (Donovan et al., 2017), in this study, we observed that a lower depression level is associated with lower levels of cognitive alternation measured by TMT-B test. Additionally, depression significantly mediated the effect of lighting on cognitive performance. However, similar to SDist, there was a negative confounding effect, as depression led to an underestimation of the L2 intervention effect of on cognitive performance. Hence, we may conclude that lighting has a direct effect on cognitive performance which is independent of depression levels in older adults.

Depression also showed a significant direct effect on SDist, SRImp, SQ, and SE. Lower depression resulted in an improved SDist, SRImp, and SQ in participants. However, it appeared that a lower GDS score was associated with a decrease in SE which was not expected. No specific reason was found to explain the positive effect of depression on SE. Depression also showed a significant mediating effect on the relationship between lighting exposure and SDist, SRImp, and SQ. This was new information demonstrated in this study. Previous research confirmed the association between depression and various sleep metrics (Fang, Tu, Sheng, & Shao, 2019); however, none evaluated the mediation role of depression in the effect of lighting on sleep. In the present study, we observed that depressive symptoms intervene in the effect of light on sleep.

In addition to depression, it appeared that cognitive functions directly affected SQ and SE, namely, a higher cognitive performance predicted better SQ and lower SE in older adults. In terms of SQ, our results are aligned with literature. In fact, the positive relationship between SQ and cognitive functions has been well-established in previous research (e.g., Lo, Groeger, Cheng, Dijk, & Chee, 2016; Mellor et al., 2018); however, most of these studies limited their findings to the effect sleep on cognition and none investigated the other side of this relationship (impact of cognitive performance on sleep). Future studies should concentrate on examining the direct effect of cognitive functions on various metrics of sleep. With respect to SE, though, the results were not as assumed. One reason might be related to the fact that higher cognitive functions are associated with higher stress levels which may reduce SE in older adults.

Cognitive performance also exhibited a significant mediating role in the relationship between light exposure and SQ and SE. This suggests that cognitive performance in older adults intervenes in how a lighting condition affects SQ. However, as there was a negative direct effect of cognitive performance on SE, a negative confounding effect is evident. Hence, cognitive performance, in fact, underestimates the impacts of lighting on SE, suggesting the direct effect of lighting on SE. There was no significant direct or mediating effect of cognitive performance on depression and other sleep metrics (SDist, SRImp, and NSD).

Regarding the relationship between PA and sleep, apart from the significant prediction of SE by PA, there was no empirical statistical evidence to support the direct or mediating effect of PA on sleep metrics measured in this study. These findings indicate that the impact of lighting on SDist, SRImp, SE, and NSD is independent of mood, depression, and cognitive performance in older adults.

In line with previous studies (Kretschmer et al., 2013; Mellor et al., 2018; Nima, Rosenberg, Archer, & Garcia, 2013), we found a significant bidirectional relationship between PA and depression, where higher PA is associated with lower depression in older adults. Moreover, both PA and depression significantly mediated their relationship with lighting exposure. This was new information, as none of the previous studies evaluated the mediating role of mood on the effect of lighting on depression or inversely.

Additionally, our analysis reflected the direct effect of sleep on depression and PA. While a more SRImp led to more depression and less PA in older adults, improved SQ resulted in a lower depression level and higher PA. However, the results for SE and SDist were in contrast with the assumption that better SE and lower SDist may improve mood and decrease depression in older adults (Fang et al., 2019). As previously mentioned, it might have occurred due to the higher stress levels that might be presented in the depressed population. SRImp was the only sleep metric that exhibited a significant mediating effect on the relation of lighting with PA and depression, suggesting that the effect of lighting on mood and depression is independent of SQ, SE, SDist, and NSD.

There was no empirical statistical evidence to support the direct effect of cognitive functions on depression; hence, no mediating effect existed. Likewise, no mediating effect of cognitive performance on the relationship between lighting and PA was observed. However, the cognitive alternation measured by TMT-B showed a significant direct effect of PA with higher TMT-B scores resulted in a more positive mood.

These analyzes demonstrated the significant relationships between sleep, mood, depression, and cognitive performance in older adults as well as some levels of mediating effects in the relation of lighting with each of them. Although the mediation role of DVs was not the main objective of this study, we performed secondary data analysis to deepen our understanding of how light exposure is linked with sleep, mood, and cognition in older adults. The number of studies evaluating the mediating effects of these DVs in relation to health-related outcomes of light is minimal. In fact, the only study that we found was the one conducted by Kretschmer et al., 2013, where no mediating effect of sleep or mood on cognitive performance was observed. Future studies should expand these results by focusing on the mediation roles of sleep, mood, cognitive functions, perhaps other potential variables on the relationship between light and health in older adults. Such studies could help architects and lighting designers to find the most optimum lighting solution to improve indoor environmental quality in older adults' living spaces. For instance, if it appears that light has a direct momentary effect on mood and cognitive performance that is not mediated by sleep, application of biological lighting even in circulating areas (e.g., corridor, lobby) would matter. On the other hand, if sleep is the primary mediator on the relation of light exposure with mood and cognitive functions, designers should concentrate in providing biological lighting only in rooms that occupants spend an extended time such as living rooms, bedrooms, and communal spaces, as an adequate duration of exposure (usually more than 30 minutes) is needed for light to develop some levels of circadian effects in older adults.

CHAPTER 6: CONCLUSION

This chapter opens with a brief review of the study's major findings with their architectural design implications, provides some design recommendations for designing architectural lighting and daylighting systems in the dwelling units of older adults, and concludes with a discussion of limitations and suggestions for future research.

6.1. Review of Major Findings

The present study demonstrated that lighting conditions in the living rooms of healthy older adults residing in senior living facilities are a significant environmental element affecting their sleep, mood, cognitive functions, and consequently their quality of life.

We found that applying a whole-day lighting scheme with varying intensity (high intensity lighting daytime and dimmed lighting nighttime) and CCT of 2700ºK in living rooms can significantly improve mood, cognitive performance, and nighttime sleep duration in older adults; however, it does not provide any significant effect on other sleep metrics (DSD, SE, SOL, SDist, SRImp, DSle). Nevertheless, adding tuning spectrum could promote the effectiveness of a whole-day lighting scheme with varying intensity. In fact, we demonstrated that a whole-day ambient lighting scheme with varying intensity and CCT that provides a blue-enriched high intensity daytime lighting and yellow-dimmed evening lighting could significantly improve several objective and subjective metrics of sleep (NSD, SE, DSD, SOL, SDist, SRImp, and DSle), mood (depression, PA), and cognitive performance in community-dwelling older adults.

Although the intervention duration was relatively shorter than similar studies (9 days versus 14 – 28 days), we were able to obtain meaningful results. Four related features of the lighting interventions probably led to the successful outcomes: (1) both interventions were designed to improve the ambient lighting in the living rooms of older adults. The ambient application of the interventions allowed participants to perform their daily tasks while they were benefiting from the intervention. (2) The interventions were applied in the actual dwelling units of older adults instead of the lab environment or common areas in senior living facilities. That made our experiment convenient for our participants which probably resulted in them spending more time under the interventions; hence, the duration of exposure increased. To our knowledge, the present study is the first that examined the effectiveness of a whole-day lighting intervention in the actual dwelling units of older adults. (3) The whole-day lighting scheme was designed to provide sufficient corneal illuminance level, spectrum, and duration of exposure in the morning to stimulate circadian rhythms in older adults. This lighting not only met the lighting standard recommendations for visual tasks, but also reached adequately high levels with respect to circadian lighting requirements (0.48 CS and 485 EML). In fact, we could deliver twice more EML than the WELL Building Standard recommendation to compensate for age-related changes in the eyes and circadian system. (4) We delivered the light through a direct/indirect lighting distribution with more indirect lighting. This is the most effective method of delivering high intensity lighting to older adults. While direct light is needed for performing tasks (e.g., reading, writing), indirect lighting distribution provides high corneal illuminance levels by reflecting luminous from the surfaces; hence, it eliminates glare and results in pleasant, bright lighting. This is especially important for older adults as their eyes are very sensitive to glare.

The other interesting finding includes the non-significant influence of daylighting quality in the living rooms on the effectiveness of the lighting interventions. This finding indicates that high quality daylighting alone is not sufficient to meet circadian lighting needs of older adults, particularly during the Fall and Winter seasons or in climates with high ratio of days with overcast sky conditions. Instead, we need to complement daylighting by designing a high-standard electrical lighting system to compensate for lack of daylighting during cloudy days. In the next section, architectural lighting design ideas will be provided to promote healthy indoor environments for older adults.

6.2. Design Implications for Architectural Lighting in Senior Livings

A number of policy and design implications can be derived from this research. Here, we will briefly discuss implications for daylighting design, residential lighting design, and lighting standards for older adults.

Given the rapidly aging population, the need for designing appropriate housing that is responsive to older adults' physical and cognitive needs has increased. Older adults spend most of their time indoors and especially in their dwelling unit (Kunduraci, 2017); thus, the living environments for older adults should fulfill their needs. Our study provides more strong evidence that lighting plays a significant role in creating a healthy, comfortable living environment for older adults by responding to their visual and circadian needs. Lighting allows older adults to identify their surroundings, perform their tasks, and feel safe. Moreover, results of our study proved that lighting in the dwelling units of older adults is one main environmental element affecting their sleep, mood, cognitive function, and consequently their overall health, well-being, and quality of life; yet, lighting is usually overlooked by architects and interior designers, especially when it comes to residential environments.

Lighting design is, in fact, the process of integrating light with architectural design to create a comfortable, healthy, and safe indoor environment. Well-designed lighting for older adults should provide sufficient illuminance levels and spectrum that fulfill their needs and compensate for age-rated changes in visual and circadian systems. What we recommend is a whole-day lighting scheme that provides a high circadian stimulation in the daytime and low circadian effects in the evenings. To achieve that, we suggest that the lighting scheme delivers a high intensity and CCT (blue-enriched spectrum) in the morning and then both the intensity and CCT decrease gradually throughout the day to provide a dimmed warm light in the evenings. The positive effects of such lighting application on sleep, mood, and cognitive function of older adults were shown in this study.

Considering the results from our study and other previous inquiries, we suggest a morning EML of 450 – 500 for older adults. In our study, we obtained the EML of 485 by producing 500 lux corneal illumination at 6500ºK. Corneal illumination could be less if the light source produces more optimized spectrum (higher CCT, or spectrum with peak wavelength of 480 nm). In order to prevent any unwanted circadian disruptions, the EML of 45 – 50 is recommended for the evening light. In this regard, the corneal illumination of 100 lux or less with a low CCT of 2700ºK or less is recommended. We could achieve the nighttime EML of 45 with 100 lux at 2700ºK. The illuminance level should be lower for higher CCTs; however, higher CCTs are not recommended for nighttime. The illuminance levels, both daytime and nighttime, should meet visual lighting needs of older adults. This is especially important for nighttime lighting. We need to be careful about our targeted illuminance levels at nighttime and should not prioritize circadian effects over visual needs at any time; both are equally important. Lighting standards for older adults recommend ambient illumination of at least 200 lux at working plane (i.e., 18 inches high horizontal). We need to ensure that the nighttime lighting meets this threshold. To reduce the circadian impact at night, the best approach is to decrease CCT and provide warm lighting as previously recommended.

Only a whole-day lighting scheme that follows natural light/dark cycles will satisfy our lighting needs and can promote indoor environmental quality in living spaces. This whole-day lighting scheme is best achieved by integrating daylighting systems with electrical lighting and smart control systems. In the next section, we will provide some design approaches for daylighting and electrical lighting systems in the residential units of older adults.

6.2.1. Daylighting Design

"*Architecture appears for the first time when the sunlight hits a wall. The sunlight did not know what it was before it hit a wall.*" Louis Kahn

Daylight is, in fact, the most ideal source of illumination in the buildings. It is natural, sustainable, and energy efficient; at the same time, it possesses everything to satisfy humans' visual, emotional, and biological lighting needs. Humans have evolved under influence of daylight and the natural light/dark cycle. The dynamic nature of daylight delivers the correct spectrum and intensity at the right time; thus, it naturally provides high circadian stimulation during the daytime and no circadian effect at night. Research has demonstrated that proper daily daylight exposure is associated with improved sleep quality, mood, alertness, physical activity, and productivity in different age groups, including older adults (M Andersen, Mardaljevic, & Lockley, 2012; Borisuit, Linhart, Scartezzini, & Munch, 2014; Boubekri et al., 2014; Brawley, 2001; Mirrahimi et al., 2012).

Given all the advantages associated with natural light, daylighting should always be the first and main daytime lighting source in residential units of older adults. Daylighting systems should be designed to provide sufficient corneal and horizontal illuminance levels in dwelling units of older adults, especially in the living rooms. Several design approaches are available for an efficient daylighting design, yet when we design for older adults, it requires specific considerations to provide comfort and safety.

Architects could promote daylighting in the dwelling units of older adults by designing windows of appropriate size. The size of windows is determined based on the climate, window orientation, space size, and room type. A comprehensive study is needed to quantitatively analyze daylighting in interior spaces and so develop the optimum facade design that is energy efficient while transferring enough daylight inside the building.

However, windows alone might not be enough to create quality daylighting in the entire indoor space. Daylight levels in a space dramatically drop as the distance from the window increases. Hence, providing an evenly distributed lighting with daylighting is not always possible. One solution is to design a skylight which is only applicable in single-family houses. Skylights are particularly recommended in cold climates as it increases solar heating in winter. Extra natural light and solar heat from skylights come with some costs, though. On the downside, skylights might cause excessive heat during the summer; that is why they are not usually recommended in hot climates. To reduce extra heat, architects might consider placing skylights on the north-facing roof section, adding shades or blinds (preferably smart shades), and glazing with appropriate U-Factor.

Skylights might also end up generating excessive sunlight and glare in interior spaces. A quality daylighting design for older adults needs to be glare-free as age-related changes in the eyes bring about an extreme sensitivity to glare. Hence, any possible source of glare, such as windows and skylights, should be carefully selected, designed, and located in the dwelling units of older adults. Glazing types with low Visual Transmittance (VT) could reduce glare; this is especially suggested in hot and sunny climates. A more desirable approach is to use interior and exterior shading such as blinds, shades, or drapes. Architecture can be vastly benefitted by designing meaningful shadings that are integrated with the architectural forms to create a residential building for older adults that is beautiful, sustainable, energy efficient, healthy, and comfortable. In this respect, architects might consider promoting their design through utilizing smart daylighting systems and kinetic architecture (Figure 57 – 58).

Figure 57. The Ballet Mécanique apartment block in Zürich has panels that unfold to become balconies or sun louvres. Source: https://howtospendit.ft.com/house-garden/205120-kinetic-architecture-that-s-moving-with-the-times

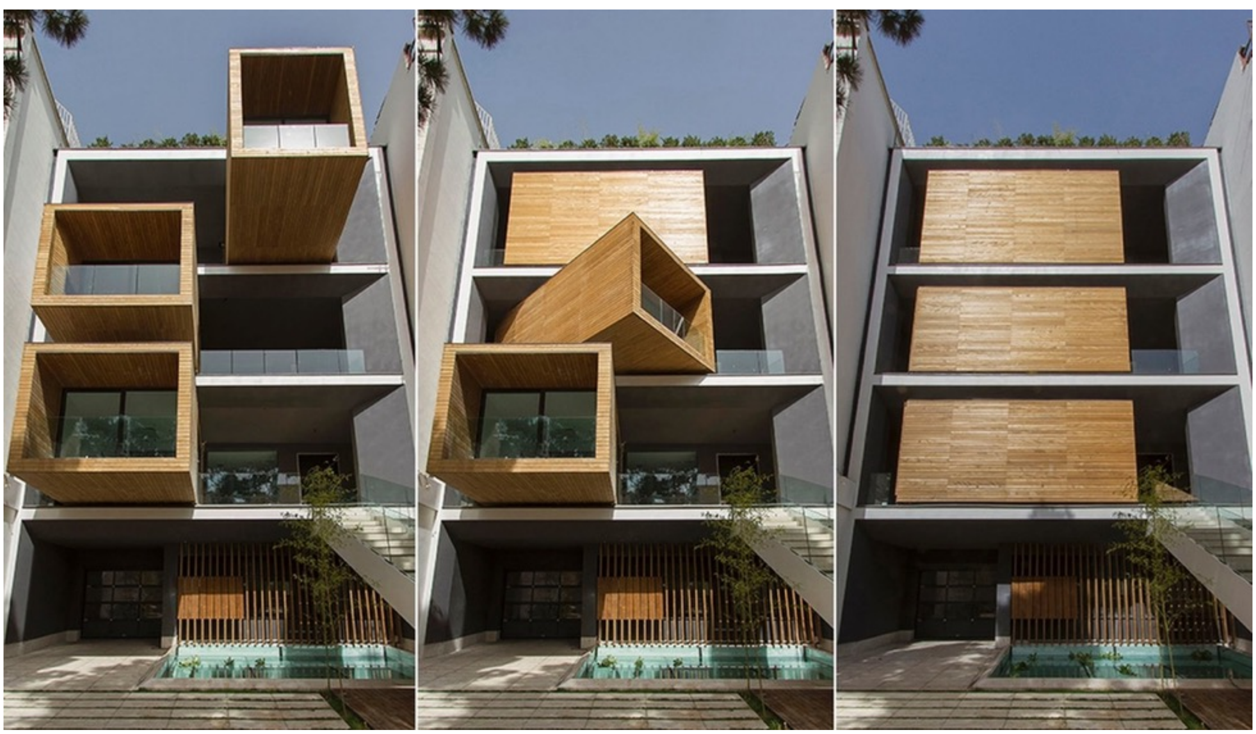


Figure 58. Sharifi-Ha House, designed by dRMM. The rooms turn around and can fold into the building or project out overhanging the street. Source: https://www.commercialinteriordesign.com/thoughts/irans-hogwarts-style-house-has-rotating-rooms

In addition to designing quality daylighting indoors, architects can improve older adults' daily daylight exposure through special configurations and design strategies that connects indoor and outdoor spaces and enhance outdoor activities. Some examples are sun rooms, patios, and small-scale central courtyards, seating and activity spaces near windows, and walkable outdoor spaces. For instance, a well-designed garden that is placed close to the dwelling units (especially close to the living rooms) could be an effective design solution to encourage gardening, which results in more sunlight exposure, social interaction, and physical activity among older adults, while also improving views and aesthetics. These design ideas not only increase daily daylighting exposure indoors and outdoors, but also create destinations of interest, which is an important factor in wayfinding and spatial planning in senior living facilities.

Although there are several benefits associated with daylighting and it should always be the primary lighting source, it alone does not always provide sufficient illuminance levels and spectrum in dwelling units. One main reason is daylighting inconsistency. Daylight availability significantly varies on a cloudy day compared to a sunny day. This is particularly important in climates with a significant portion of annual overcast sky conditions such as those in Saint Louis and Chicago. This issue becomes worse when it comes to northern climates and Scandinavian countries where people deal with an extreme scarcity of daylight during the winter.

Furthermore, as previously mentioned, the daylight levels drastically decrease as we distance from windows as well as by changing the gazing directions. This fact makes it almost impossible to provide sufficient illuminance levels from daylighting everywhere indoors. Other factors effecting daylight access inside the dwelling units include building location, urban density, and surrounding building heights. These factors could limit an architect's ability to provide quality daylighting for all dwelling units in a senior living facility. Therefore, architects need to complement their daylighting design with a quality electrical lighting system that supports the visual and circadian lighting needs of older adults.

6.2.2. Electrical Lighting System

Combined with daylighting, electrical lights should create a pleasant glare-free evenly-distributed lighting in the dwelling units of older adults to fulfill their visual, emotional, and circadian lighting needs. In this regard, we recommend applying a layered lighting design approach which, in general, comprises of three layers: (1) ambient lighting, (2) task lighting, and (3) accent lighting. In this study, our focus was on the ambient illumination layer. Ambient lighting plays a significant role in both the visual and circadian effects of light especially for older adults; hence, it is the main and core lighting layer. Ambient lighting, also known as general lighting, creates an even illumination throughout the space, enabling performance of basic visual tasks such as walking, talking, and identifying the space. Moreover, as the major layer of illumination with the highest exposure time, it significantly impacts the circadian system. However, this is the layer most overlooked by architects in the architectural lighting design of residential buildings, particularly in living rooms and bedrooms. In most residential units, ambient lighting throughout the daytime is provided merely by daylighting. However, as we previously mentioned, daylighting alone cannot satisfy older adults' lighting needs, and we need to complement daylighting with illumination provided by electrical light sources.

An ideal electrical lighting system encompasses TWLs that are integrated with smart time-based control systems and programmed to automatically alter lighting intensity and spectrum (or CCT) to suit visual and circadian lighting requirements throughout the day. In combination with daylighting, this lighting system should deliver illumination with high EML and CS in the morning to stimulate circadian rhythms. Then, it should change gradually throughout the day to decrease

EML and CS. The illumination should provide a very low EML and CS at night to prevent any unwanted circadian disruptions, such as phase shifting delay. Both CCT and intensity of the light should change to achieve sufficient EML and CS throughout the day while satisfying emotional and energy-related aspects of lighting.

In this study, we recommended an EML of 450 – 500 in the morning. This is a relatively high EML obtained through high illuminance levels. For instance, we produced an EML of 480 by 500 lux corneal illuminance level. The high illuminance levels might result in excessive glare in the living spaces. A good lighting design should be glare-free with no direct or reflected view of the light sources and provide unified distributions with soft shadows. To achieve that, we propose an indirect or direct/indirect lighting distribution approach in the design. Indirect lighting distribution is created by utilizing indirect luminaires as well as some architectural lighting design features such as cove lighting, grazers, and wall-washers. Direct/indirect lighting distribution is also highly recommended, as it benefits both ambient and task lighting layers. Direct/indirect lighting can be applied by using direct/indirect luminaires (such as the one we used in this study) or a combination of direct luminaires (e.g., downlights, recessed, and ceiling mounted luminaires) and indirect luminaires (e.g., pendant or wall-mounted luminaires with 100% up-light).

Nighttime lighting is as important as daytime lighting because nighttime lighting plays a significant role in safety and fall prevention among older adults, especially during the rest and sleep hours. An adequate nighttime lighting design in the dwelling units of older adults was found to be positively associated with a reduction in falls (Shikder, Mourshed, & Price, 2012). In contrast to daytime lighting, lighting at night should deliver the least circadian effect. In fact, the only purpose of nighttime lighting is to enable performing visual tasks. Thus, it should provide sufficient illumination for older adults to identify their surroundings and allow them to orient themselves in the environment. Proper illuminance levels for visual and perceptual comprehension in various room types of the living spaces of older adults are provided in ANSI/IES RP-28-16. Architects and lighting designers can refer to this handbook to determine required illuminance levels for each room. With respect to the CCT, we propose a CCT of 2700ºK or lower for nighttime lighting. Moreover, to increase visual and perceptual acuity, we recommend a nighttime accent lighting layer to highlight vertical and horizontal features such as doors and wall extensions. Linear strip lights and wall-mounted step lights with amber light and low intensity are recommended for this purpose. The nighttime accent lighting layer should be integrated with motion sensors to eliminate the need for finding light switches at night.

The key aspect in designing lighting for both the visual and circadian systems is to maintain the difference between lighting in daytime and nighttime. Therefore, TWLs and smart control systems are essential to succeed. TWLs enable altering color and intensity whereas smart control systems automate the color and intensity alteration throughout the day. Smart time-based control systems simplify the application of healthy lighting for older adults by removing the need to change lighting scenes throughout the day. In this study, we proposed a whole-day lighting scheme (L2) and showed the beneficial effects of applying this scheme on sleep, mood, and cognitive performance in older adults. This whole-day lighting scheme provides exact corneal illuminance levels, CCT, and timing, which can be used as a preset to program smart lighting systems in the dwelling units of older adults. However, more studies should be conducted to examine other presets that might work.

Furthermore, to save energy and maintain consistent daily illuminance levels, daylight sensors should be incorporated to integrate the smart lighting system with daylighting. Daylight sensors adjust smart light's intensity based on daylight availability in the room and contribute to saving electrical energy, reducing unwanted light intensity, and sustaining pleasant illumination. More energy can be saved by utilizing occupancy sensors.

Another important factor in designing a successful lighting scheme is to consider each individual's needs. This is usually referred to as personalized lighting or customized lighting. Personalized lighting is a fast-growing approach that considers both visual and non-visual aspects of light according to each individual's needs, allowing architects to conceive the lighting able to meet all physical, psychological, and physiological conditions of their end users. Smart lighting can play an important role in creating successful personalized lighting through promoting controllability, flexibility, and convenience. Incorporating the Internet of Things and machine learning into the smart lighting design is a more recent trend in the lighting industry and will advance the idea of personalized lighting in the years to come.

Higher costs, obligations, and sometimes energy codes are the main obstacle in utilizing quality lighting with smart lighting systems in senior living and the dwelling units of older adults. However, higher costs and code requirements should not allow architects, designers, and developers to easily overlook all the advantages associated with high quality automated lighting and should not stop them from implementing the proposed design lighting solution in the residential spaces of older adults. Increasing public awareness of how residential lighting can make a significant contribution in the lives of older adults may promote changes that we are looking for in the approaches of developers, designers, and policy makers to lighting. More scientific studies similar to this study that propose quantitative lighting design solutions (e.g., illuminance levels, EML, CS, CCT) rather than qualitative solutions (e.g., brighter, cooler) and find firm evidence could foster public awareness and encourage designers and developers to consider lighting more seriously in the design of residential spaces for older adults.

6.2.3. Implications for lighting standards

Given the results from this study, along with previous ones about the effects of lighting on sleep, mood, cognitive performance, and quality of life in older adults, it is essential for lighting design standards to address the non-visual aspects of light as well. Lighting design standards for older adults merely focus on the visual aspects of light and specify the required horizontal illuminance levels for visual tasks. Future improvements to the lighting design standards and guidelines should include the non-visual aspects such as spectrum, corneal illuminance levels, and the timing and duration of exposure. We agree that it is too early to define a threshold for the vertical illuminance levels, CCT, or duration of exposure to satisfy lighting needs of older adults. This prevents defining detailed recommendations for these parameters. However, current research including the present study provides sufficient quantitative information with regards to effective EML and CS values for older adults. Even though circadian lighting metrics need further validation and improvements, proposed numbers can be used to determine corneal illuminance levels and CCT throughout the day. Future research should concentrate on validating current circadian lighting metrics and perhaps propose others.

In addition, lighting design standards as well as nursing home and senior living design guidelines should emphasize the importance of daylighting and specify required design solutions that promote daily indoor and outdoor daylight exposure in older adults. It is essential for architects to remember that daylighting and electrical lighting systems are not separated; they work with each other, affect each other, and complement each other. Hence, a good lighting design integrates electrical lighting and daylighting. Architects usually focus merely on daylighting design without considering the effects of electrical lighting systems, ending up to incomplete and usually unsuccessful lighting in residential units. Future architectural design and lighting design guidelines and standards should emphasize the combination of lighting and daylighting systems. These changes would encourage architects to consider electrical lighting design as an integrative part of the architectural design process.

6.3. Research Limitations and Suggestions for Future Research

The present study contains some limitations that need to be discussed. Perhaps, one main limitation for this study was the small sample size. Research budget and time constrains resulted in only 21 valid set of data from participants for analysis. Another reason for the small sample size might be the study length which required 41 days of participation. Some individuals thought that the compensation was not enough for this long-time commitment. Moreover, the fact that we needed to place lights in the living room sounded inconvenient for most individuals. Hence, although we presented the study in four senior living facilities, only 33 individuals signed up for the study, and after screening and applying the inclusion/exclusion criteria, we were able to obtain data from 21 participants. Future research should Increase sample size and diversity to include gender, living status, physical and psychological health conditions, climate, senior living locations, and activity levels in the analysis. A larger sample size would also allow for greater generalizing of the results.

Another limitation concerns the data collection time. We had specifically aimed for conducting the study during the cold months (mostly Fall and Winter seasons) where the amount of sunlight is normally low in Saint Louis and Chicago. However, this limits us to generalize the results for other seasons. The high contribution of daylighting during summer might depreciate the effectiveness of the whole-day lighting schemes examined in this research. Future research should consider exploring the effects of whole-day lighting interventions in warm months (June –

September) to understand whether there are any seasonal differences in the lighting needs of older adults.

Moreover, a possible limitation worth discussing is the lack a control group. we performed a within-subject analysis in which each participant acted as their own control. This design is chosen to control for most of the possible non-specific treatment effects. However, it is not possible to control all the non-specific treatment effects such participants' excitement about the new lighting system in their living rooms, the excitement about being involved in scientific research, or the compensation. Hence, future research should expand these findings by including a control group that will receive the same lighting systems in the apartments with no alteration in the ambient illuminance levels and CCT compared to the baseline. A control group would allow for a meaningful comparison to be drawn by minimizing the effects of other variables such as excitement about the new lighting systems, research bias, and environmental factors.

Due to research budget constraints, this study is also limited to apply the whole-day lighting schemes only in the living rooms and around the main seating spot. Healthy older adults tend to be more active and usually manage their daily house chores such as cooking, laundry, and cleaning. Hence, they may spend some time in other spaces such as their kitchen or bedrooms. In that case, it is possible that our active participants were not exposed to the lighting interventions as much as we assumed. If research budget allows, future studies should expand these findings by applying the lighting interventions in all rooms in the dwelling units. In addition, future research needs to carefully monitor, daily sunlight exposure, weather conditions, and the number of hours participants spend inside their dwelling units (and perhaps in each room) during the participation period.

Lastly, the present study is limited by the short during of exposure to the lighting interventions (only nine days). We had to keep exposure duration short for two reasons: (1) study time constrains and (2) to decrease participation duration in order to increase the chance of participant recruitment. Most previous studies applied 2 – 4 weeks to affect circadian clock and hence sleep. Although we were able to obtain significant results, a longer duration of exposure would have revealed any long-term effect of lighting interventions on sleep, mood, and cognitive performance as well as how sustainable these effects are. Hence, future studies need to expand intervention duration; this could be a short-term period from 2 – 6 weeks or a long-term period from 2 to 6 months.

Other suggestions for future studies include: (1) exploring older adults' opinion about their current lighting condition at the baseline, the whole-day lighting interventions during the intervention period, and then compare them after the intervention was removed. This will allow researchers to comprehend older adults' lighting preferences and (2) investigating the interactive experience of older adults with smart lighting systems to understand their preferences and behavior as well as their impact on the efficiency of these systems.

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APPENDIX A. DATA ANALYSIS WITH TWO BASELINE MEASURES

A.1. Objective Sleep Quality as Measured by Actigraphy

A.1.1. Night time Sleep Duration (NSD)

A one-way RP ANOVA with four levels of repeated measures factors was conducted to compare the effect of lighting on night time sleep duration (NSD) before, during, and after L1 and L2 interventions. There was a significant effect of lighting condition on NSD (F [3, 60] = 7.786, $p < 0.001$, $MSE = 837.782$, $\eta^2_p = 0.28$). The patterns of the average NSD across the study are illustrated in Figure 59. As shown, the average NSD increased with the L1 intervention, increased even more with the L2 intervention, and start returning to baseline levels after the intervention had been discontinued.

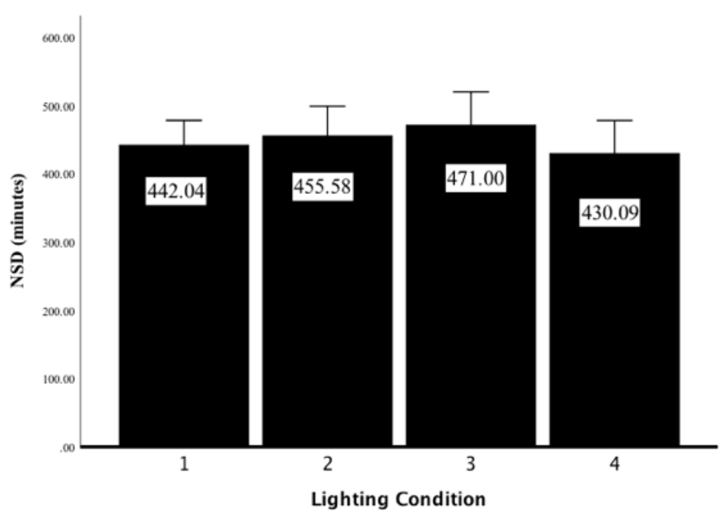


Figure 59. Pattern of NSD across the study.

As the one-way RM ANOVA confirmed the significant effects of lighting, in order to further investigate the effects of interventions on NSD, six paired samples t-tests were employed to make post hoc comparisons between lighting conditions. Results of this analysis are illustrated in Table 44. The pairwise comparison indicated a significant difference between mean score for NSD in participants at B1 and L2 ($df = 20$, $t = -3.37$, $p < 0.001$), L1 and L2 ($df = 20$, $t = -2.60$, $p =$

0.02), L1 and B2 (*df* = 20, *t* = 2.65, *p* = 0.02), and L2 and B2 (*df* = 20, *t* = 3.48, *p* < 0.001). No significant difference was observed between B1 and B2 (df = 20, t = 1.25, p = 0.26), nor between B1 and L1 (*df* = 20, *t* = -2.00, *p* = 0.06). Compared to B1, the average NSD was increased by 13.54 minutes and 28.96 minutes after L1 and L2 interventions respectively.

Table 44. Results from Paired Sample t-test for NSD across the study.

	Mean Difference (min)	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (B1, L1)	-13.55	30.91	-2.01	0.06
Pair 2 (B1, L2)	-28.97	39.39	-3.37	< 0.001
Pair 3 (L1, L2)	-15.42	28.16	-2.51	0.02
Pair 4 (L1, B2)	25.50	44.05	3.48	0.02
Pair 5 (L2, B2)	40.92	53.87	-3.37	0.00
Pair 6 (B1, B2)	11.95	43.71	2.65	0.22

A.1.2. Sleep Efficiency (SE)

A one-way RM ANOVA with four levels of repeated measures factors confirmed the significant effect of lighting condition on the average sleep efficiency (SE) of participants (F [3, 60] = 7.86, $p < 0.001$, $MSE = 9.76$, $\eta^2_p = 0.28$). As shown in Figure 60, compared to B1, L1 intervention slightly increased the average ES by 0.91%, however, L2 intervention increased that more by 3.82%. The average SE started returning to baseline levels after the intervention had been discontinued.

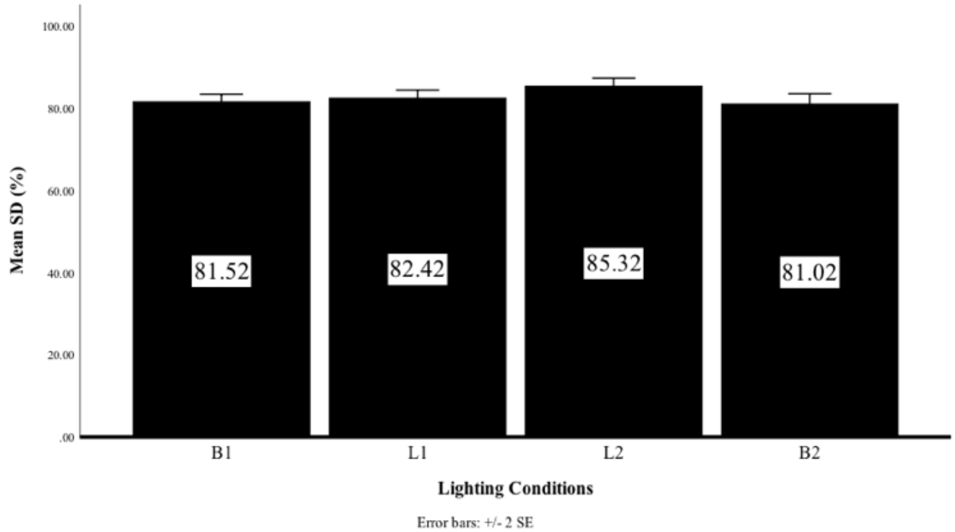


Figure 60. Pattern of SE across the study.

In order to further investigate the effects of interventions on ES, six paired samples t-tests were employed to make post hoc comparisons between lighting conditions. Table 45 shows the t-test results obtained for SE. The t-test analysis revealed no significant difference between the average SE in B1 and L1 (*df* = 20, *t* = -1.19, *p* = 0.25) nor between L1 and B2 (*df* = 20, *t* = 1.38, *p* = 0.18) suggesting that whole-day lighting with varying lighting intensity did not significantly improved SE in older adults. However, there was a significant difference between B1 and L2 (*df* = 20, *t* = -3.68, *p* < 0.001), L1 and L2 (*df* = 20, *t* = -2.82, *p* = 0.01), and L2 and B2 (*df* = 20, *t* = 3.74, *p* < 0.001). These results confirm the significant effects of adding tuning spectrum to the ambient illumination on SE in older adults.

Table 45. Results from Paired Sample t-test for DSD across the study.

	Mean Difference (min)	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (B1, L1)	-0.90	3.48	-1.19	0.25
Pair 2 (B1, L2)	-3.80	4.73	-3.68	< 0.001
Pair 3 (L1, L2)	-2.89	4.70	-2.82	0.01
Pair 4 (L1, B2)	1.37	4.55	1.38	0.18
Pair 5 (L2, B2)	4.26	5.22	3.74	< 0.001
Pair 6 (B1, B2)	0.46	3.56	0.59	0.56

A.1.3. Daytime Sleep Duration (DSD)

For the daytime sleep duration, the one-way repeated measures ANOVA indicates no significant effects of lighting conditions (F [3, 60] = 1.30, p = 0.43, MSE = 2826.96, η^2_p = 0.06) suggesting that the tested lighting interventions did not have any significant effects on DSD. Figure 61 shows the patterns of the average DSD across the study. Although insignificant, this pattern reveals a reducing trend in the average DSD after L2 intervention. In fact, L2 intervention reduced the average DSD in participants by 8.12 minutes. In contrast, L1 increased the average DSD by 10.32 minutes.

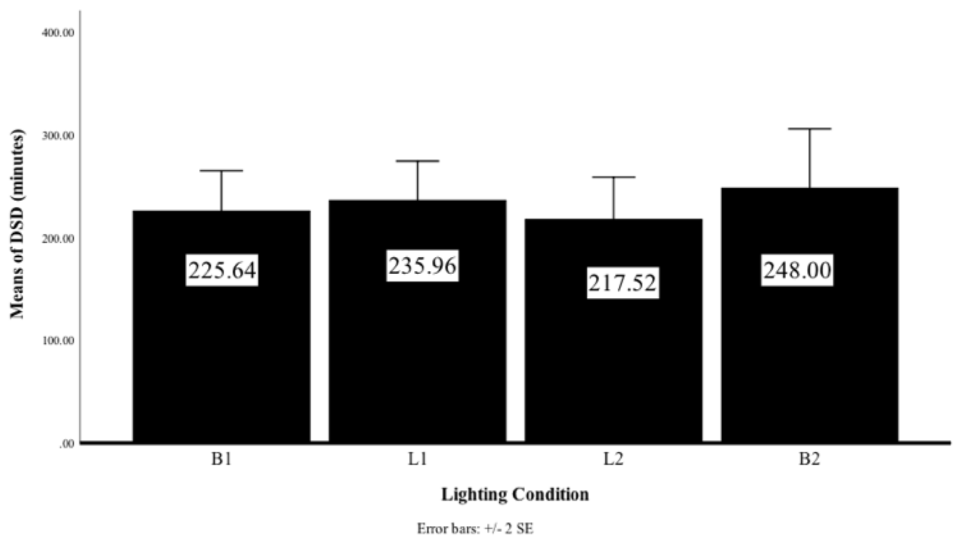


Figure 61. Pattern of DSD across the study.

A.1.4. Sleep Onset Latency (SOL)

Actigraphy data for sleep onset latency (SOL) exhibited a significant main effect of lighting (F [3, 60] = 3.88, p = 0.013, MSE = 171.97, η^2_p = 0.16). The pattern of OSL in the course of the study is illustrated in Figure 62. Whereas the average SOL increased from 26.70 minutes (SD = 19.26) in the B1 to 34.96 minutes (SD = 21.68) at L1, L2 intervention significantly decreased the average SLO to 21.35 minutes (SD = 13.14). Table 46 shows results of t-test analysis. There was no significant difference between the average SOL in B1 and L1 (*df* = 1, t = -1.38, p = 0.18), L1 and B2 (*df* = 20, t = 1.12, p = 0.28), as well as B1 and B2 (*df* = 20, t = -0.07, p = 0.95).

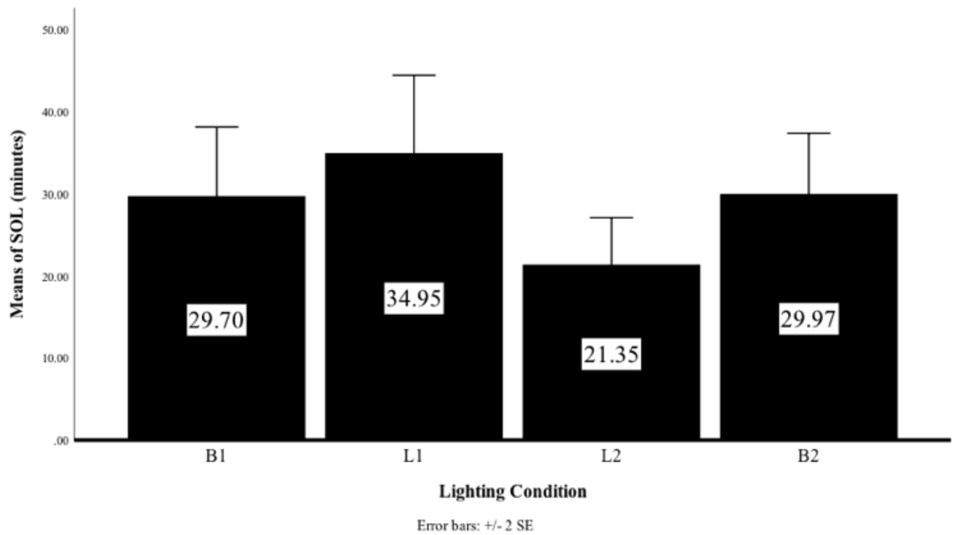


Figure 62. Pattern of SOL across the study.

Table 46. Results from Paired Sample t-test for SOL across the study.

	Mean Difference (min)	SD	*t* (*df* = 20)	*p* Value
Pair 1 (B1, L1)	-5.25	17.47	-1.38	0.18
Pair 2 (B1, L2)	8.35	20.55	1.86	0.08
Pair 3 (L1, L2)	-13.60	21.30	2.93	0.01
Pair 4 (L1, B2)	4.98	20.46	1.12	0.28
Pair 5 (L2, B2)	-8.62	13.11	-3.01	0.01
Pair 6 (B1, B2)	-0.26	17.07	-0.07	0.945

A.2. Subjective Sleep as Measured by Questionnaires

A.2.1. Sleep Disturbance (SDist)

A one-way RM ANOVA revealed a significant effects of lighting conditions on the SDist scores of participants measured by PROMIS-SD (F [3, 60] = 8.71, $p < 0.001$, *MSE* = 66.26, η^2_p = 0.30). The mean score for SDist significantly decreased from 57.48 (SD = 16.70) in B1 to 52.52 (SD =17.00) after L1 and decreased even more to 44.76 (SD = 13.98) after L2 intervention. The difference between the mean score for SDist in L1 and L2 was significant (*df* = 20, t = 3.91, $p <$ 0.001). Figure 63 and Table 47 show the results. The mean score for SDist started to return to the baseline after the intervention had been discontinued. There was no significant difference between mean scores for SDist in B1 and B2 ($df = 20$, $t = 1.59$, $p = 0.13$) nor between L1 and B2 ($df = 20$, $t = 0.12$, $p = 0.91$).

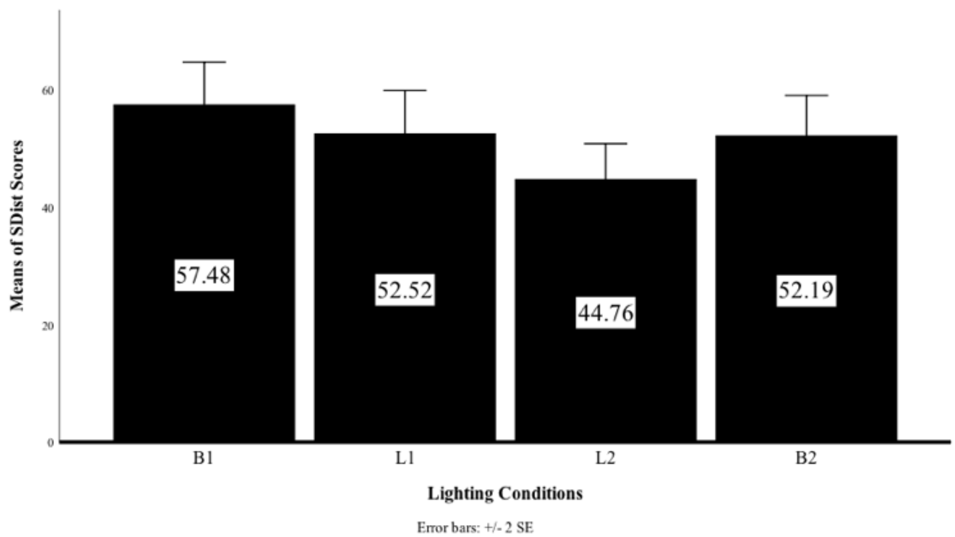


Figure 63. Pattern of SDist across the study.

Table 47. Results from Paired Sample t-test for SDist scores across the study.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (B1, L1)	4.95	8.46	2.68	0.01
Pair 2 (B1, L2)	12.71	12.04	4.84	< 0.001
Pair 3 (L1, L2)	7.76	9.09	3.91	< 0.001
Pair 4 (L1, B2)	0.33	13.15	0.12	0.91
Pair 5 (L2, B2)	-7.43	9.48	-3.59	< 0.001
Pair 6 (B1, B2)	5.29	15.26	1.59	0.13

A.2.2. Sleep-Related Impairments (SRImp)

Results from the PRMIS-SRI exhibited a significant effects of lighting conditions on the SRImp scores in participants (F [3, 60] = 12.29, $p < 0.001$, $MSE = 20.94$, $\eta^2_p = 0.38$). The mean score for SRImp significantly decreased from 35.05 (SD = 11.65) in B1 to 30.67 (SD = 8.67) after L1 intervention. L2 intervention decreased the mean score for SRImp even more to 26.48 (SD = 8.65) which was significantly different from B1 ($df = 20$, $t = 4.83$, $p < 0.001$) and L1 ($df = 20$, $t = 3.88$, $p < 0.001$). Figure 64 and Table 48 show the results. As shown in Figure 23, the mean score for SRImp started to increase after the intervention had been removed, nevertheless, the difference between B1 and B2 remained significant (*df* = 20, *t* = 3.10, p = 0.01).

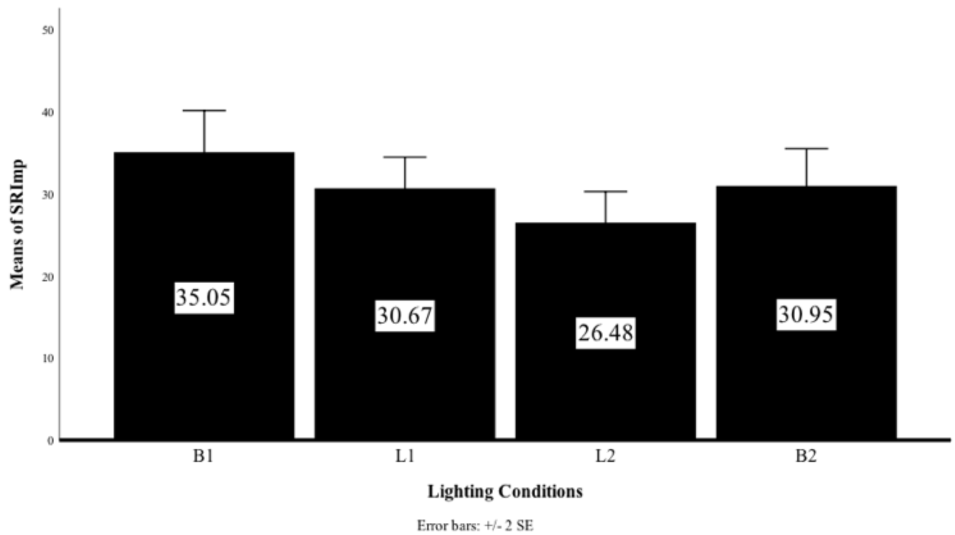


Figure 64. Pattern of SRImp across the study.

Table 48. Results from Paired Sample t-test for SRImp scores across the study.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (B1, L1)	4.38	5.77	3.48	< 0.001
Pair 2 (B1, L2)	8.57	8.14	4.83	< 0.001
Pair 3 (L1, L2)	4.19	4.95	3.88	< 0.001
Pair 4 (L1, B2)	-0.29	6.94	-3.14	0.85
Pair 5 (L2, B2)	-4.48	6.52	-3.14	0.01
Pair 6 (B1, B2)	4.10	6.06	3.10	0.01

A.2.3. Sleep Quality (SQ)

A one-way RM ANOVA confirmed the significant effects of lighting conditions on the subjective sleep quality (SQ) measured by PSQI (F [1.96, 39.21] = 3.63, p = 0.036, MSE = 5.43, η^2_p = 0.36). Here, the GreenHouse-Geisser correction was used to report the RM ANOVA results as the Mauchly’s Test of Sphericity was significant (p = 0.006) and the assumption of sphericity was violated.

Figure 65 shows the pattern of SQ throughout the course of the study with lower mean score indicating a higher SQ in participants. As illustrated, the mean score for SQ decreased from 7.10 (SD = 4.04) in B1 to 6.33 (SD = 3.34) after L1 and decreased even more after L2 and reached to 5.24 (SD = 2.70). After the intervention had been removed, the mean score for SQ score started increasing (mean = 5.86, SD = 2.60), however, after two weeks, the mean score for SQ was still lower than the L1 intervention suggesting the lasting effects of L2 intervention on subjective sleep quality in participants. There was significant difference between B1 and L2 ($df = 20$, $t = 2.47$, $p = 0.02$) and L1 and L2 ($df = 20$, $t = 2.61$, $p = 0.02$). Paired-sample t-test showed no significant difference between other pairs for SQ. Results are shown in Table 49.

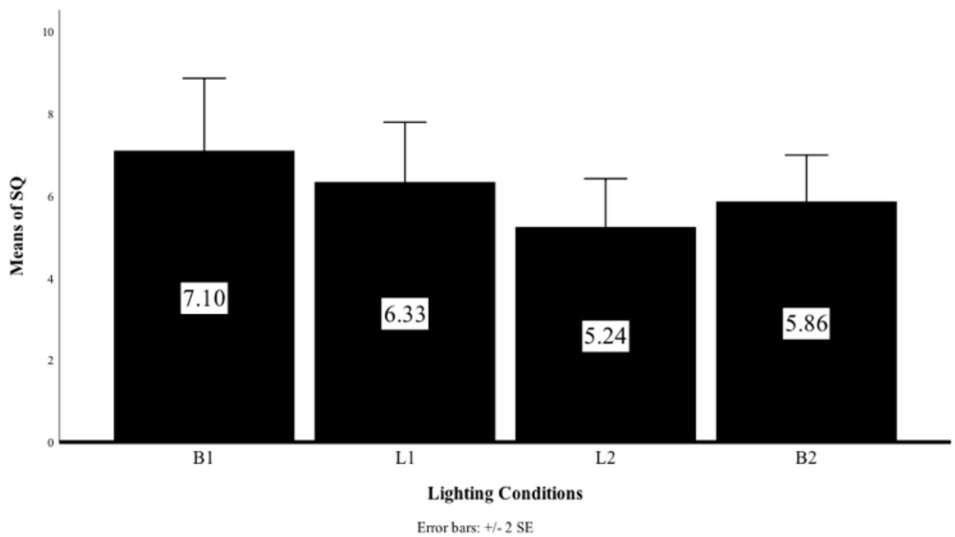


Figure 65. Pattern of SQ across the study.

Table 49. Results from Paired Sample t-test for SQ scores across the study.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* Value**
Pair 1 (B1, L1)	0.76	2.59	1.35	0.19
Pair 2 (B1, L2)	1.86	3.44	2.47	0.02
Pair 3 (L1, L2)	1.10	1.92	2.61	0.02
Pair 4 (L1, B2)	0.48	2.40	0.91	0.37
Pair 5 (L2, B2)	-0.62	1.86	-1.53	0.14
Pair 6 (B1, B2)	1.24	3.35	1.70	0.11

Seventeen participants (81%) had baseline assessment scores of five or greater for SQ measured by PSQI, suggesting they suffered from poor sleep quality. The frequency of participants with poor sleep quality reduced to 62% (n = 13) after L1 and L2 interventions. This frequency started to increase after the intervention was discontinued and reached to 71% (n = 15) at B2.

A.2.4. Daytime Sleepiness (DSle)

Mean scores for DSle measured by ESS exhibited no significant effect of lighting condition (F [3, 60] = 2.00, p = 0.12, MSE = 4.34, η^2_p = 0.09). The mean scores for DSle was dropped from 6.57 (SD = 3.03) in B1 to 5.90 (SD = 3.21) in L1 and dropped even more after L2 and reached to 5.52 (SD = 3.27), suggesting a reducing trend in the mean score for DSle after exposure to the lighting interventions. Figure 66 shows the results.

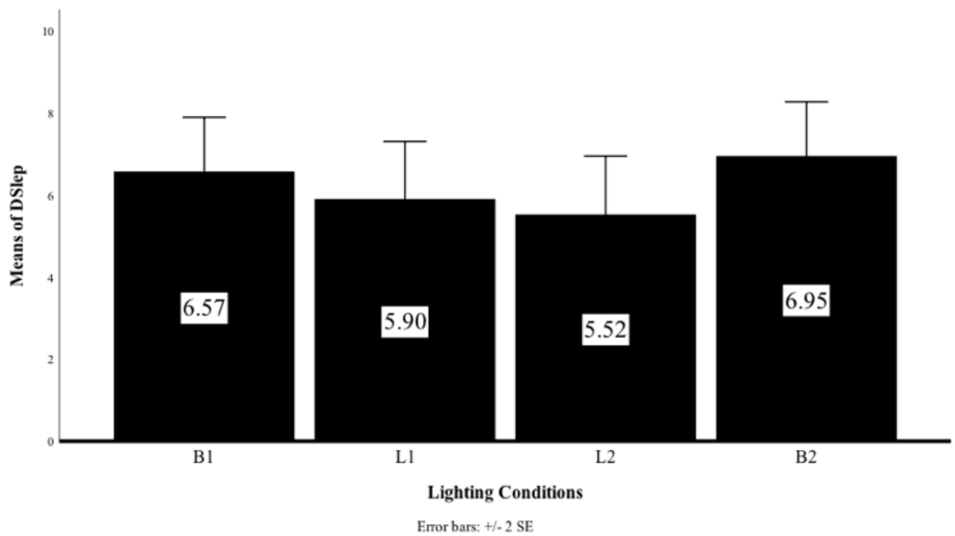


Figure 66. Pattern of DSle across the study.

A.3. Depression

Due to the significant difference between the mean score for depression between buildings, the buildings were analyzed separately in this section. In this regard, two one-way RM ANOVA were run to investigate the effects of lighting on depression scores in older adults. The mean score for depression in the Affordable senior livings exhibited a significant effect of lighting on depression (F [1.84, 23.97] = 8.77, $p < 0.001$, MSE = 9.50, η^2_p = 0.40). As the assumption of Sphericity was violated (Mauchly's Test of Sphericity: p = 0.04), the GreenHouse-Geisser correction was used to report the RM ANOVA results. The patterns of the depression scores across the study are illustrated in Figure 67. As shown, mean score for depression decrease with L1 intervention from 9.50 (SD = 4.67) to 7.29 (SD = 4.25), decreased even more with L2 and reached to 4.93 (SD = 3.39), and started to retain to the baseline after the intervention was discontinued.

Table 50 shows the results of t-test analysis for the Affordable senior livings. There was a significant difference between the mean score for depression between B1 and L1 ($df = 13$, $t = 2.54$, $p = 0.03$), B1 and L2 ($df = 13$, $t = 3.61$, $p < 0.001$), L1 and L2 ($df = 13$, $t = 2.94$, $p = 0.01$), as well as L2 and B2 ($df = 13$, $t = -4.58$, $p < 0.001$). However, no significant difference was found between B1 and B2 ($df = 13$, $t = 1.31$, $p = 0.22$) as well as L1 and B2 ($df = 13$, $t = -1.39$, $p = 0.19$).

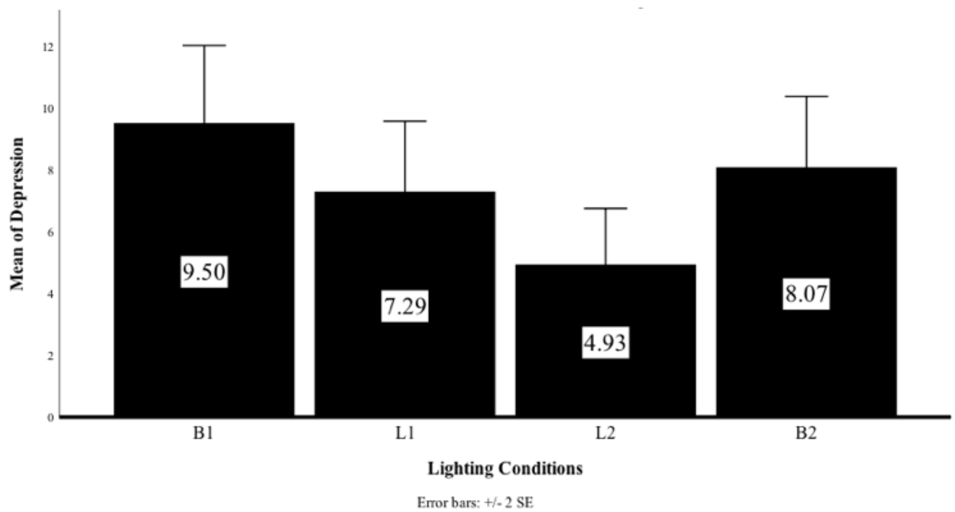


Figure 67. Pattern of deresssion across the study in Affordable senior livings.

Table 50. Results from Paired Sample t-test for depression in Affordable senior livings.

	Mean Difference	**SD**	***t* (*df* = 13)**	***p* Value**
Pair 1 (B1, L1)	2.21	3.26	2.54	0.03
Pair 2 (B1, L2)	4.57	4.74	3.61	0.00
Pair 3 (L1, L2)	2.36	3.00	2.94	0.01
Pair 4 (L1, B2)	-0.79	2.12	-1.39	0.19
Pair 5 (L2, B2)	-3.14	2.57	-4.58	0.00
Pair 6 (B1, B2)	1.43	4.11	1.30	0.22

A one-way RM ANOVA confirmed no significant effect of lighting on depression scores in participants residing at the High-end senior living (F [3, 18] = 2.28, $p = 0.12$, $MSE = 1.07$, $\eta^2_p = 0.28$). Although nonsignificant, the mean score for depression in this group of participants, decreased from 3.71 (SD = 4.72) in B1 to 2.57 (SD = 3.82) after L2 intervention, indicating a decreasing trend (Figure 68).

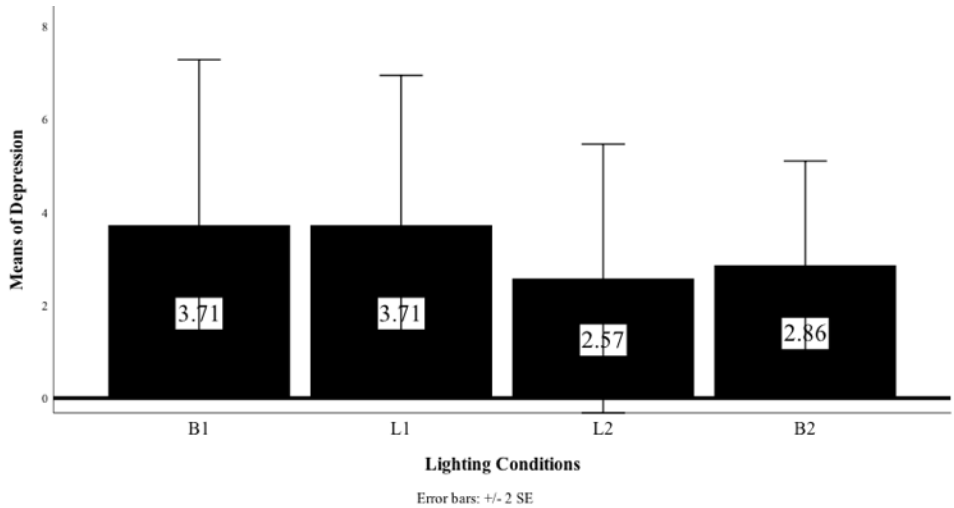


Figure 68. Pattern of depression across the study in High-end senior living.

The interaction between lighting and depression was also tested. In this regard, participants were divided in two groups based on their baseline GSD scores: Depressed (GSD score of 9 or greater) and not depressed (GDS score of 8 or lower). Then, a mixed ANOVA was run to compare the mean score for depression in these two groups as well as the interactions between lighting and baseline depression. There was a significant main effect of lighting (F [3, 57] = 14.68, $p < 0.001$, $MSE = 3.74$, $\eta^2_p = 0.44$), baseline depression (F [1, 19] = 39.57, $p < 0.001$, $MSE = 23.55$, η^2_p = 0.68), and interaction between lighting and depression (F [3, 57] = 6.02, $p < 0.001$, $MSE = 23.55$, $\eta^2_p = 0.24$). This suggested that the effects of lighting on depression depended on the baseline depression level with more effects on depressed participants.

A.4. Mood: Positive and Negative Affects

A one-way RM ANOVA indicated a significant effect of lighting on PA in participants residing in the Affordable senior livings (F [3, 39] = 10.63, $p < 0.001$, $MSE = 15.39$, $\eta^2_p = 0.45$).

The mean score for PA increased with L1 from 26.64 (SD = 6.31) in B1 to 31.29 (SD = 6.32). L2 increased the mean score for PA even more and reached to 35.00 (SD = 3.98). The mean score for PA started to return to the baseline after the interventions had been removed (Figure 69).

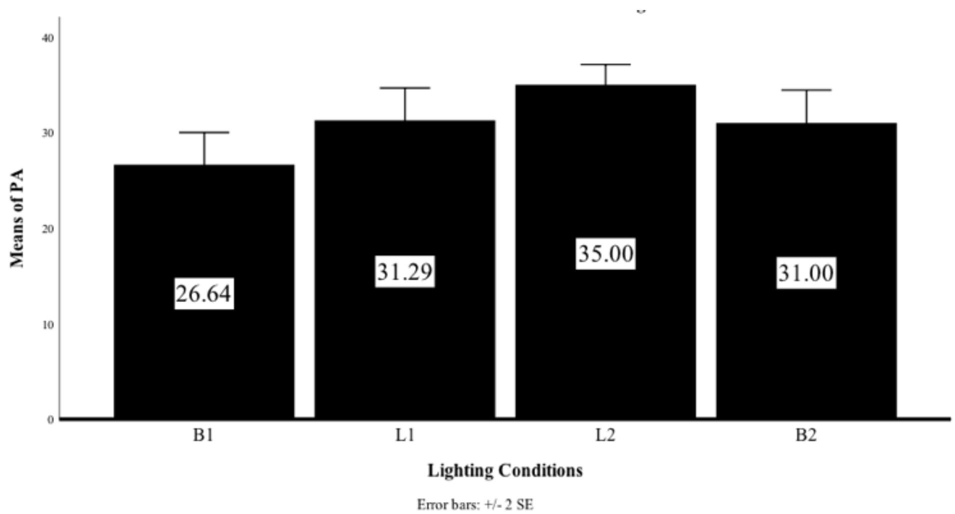


Figure 69. Pattern PA across the study in Affordable senior livings.

The pairwise comparison for the main effect of lighting on PA in the Affordable facilities reflected a significant difference between B1 and L1 ($df = 13$, $t = -3.43$, $p < 0.001$), B1 and L2 ($df = 13$, $t = -4.72$, $p < 0.001$), L1 and L2 ($df = 13$, $t = -3.54$, $p < 0.001$), L2 and B2($df = 13$, $t = 2.77$, $p = 0.02$) as well as B1 and B2($df = 13$, $t = -2.47$, $p = 0.03$). There was no significant difference between L1 and B2 ($df = 13$, $t = 0.19$, $p = 0.85$). Table 51 shows the results.

Table 51. Results from Paired Sample t-test for PA in Affordable senior livings across the study.

	Mean Difference	**SD**	**t (df = 13)**	**p Value**
Pair 1 (B1, L1)	-4.64	5.06	-3.43	< 0.001
Pair 2 (B1, L2)	-8.36	6.31	-4.96	< 0.001
Pair 3 (L1, L2)	-3.71	3.93	-3.54	< 0.001
Pair 4 (L1, B2)	0.29	5.58	0.192	0.85
Pair 5 (L2, B2)	4.00	5.41	2.77	0.02
Pair 6 (B1, B2)	-4.36	6.59	-2.47	0.03

There was no significant effect of lighting on PA in participants residing in the High-end senior living (F [3, 18] = 0.68, $p = 0.57$, $MSE = 4.74$, $\eta^2_p = 0.10$). However, a slight improvement was observed after the intervention exposure as the mean score for PA increased from 36.71 (SD

= 5.31) in B1 to 37.86 (SD = 4.49) in L1 and then increased more after L2 and reached 38.14 (SD = 5.05). In B2 the mean score for PA in the High-end facility started reducing (mean = 37.00, SD = 5.66) to towards the B1. Figure 70 shows this trend.

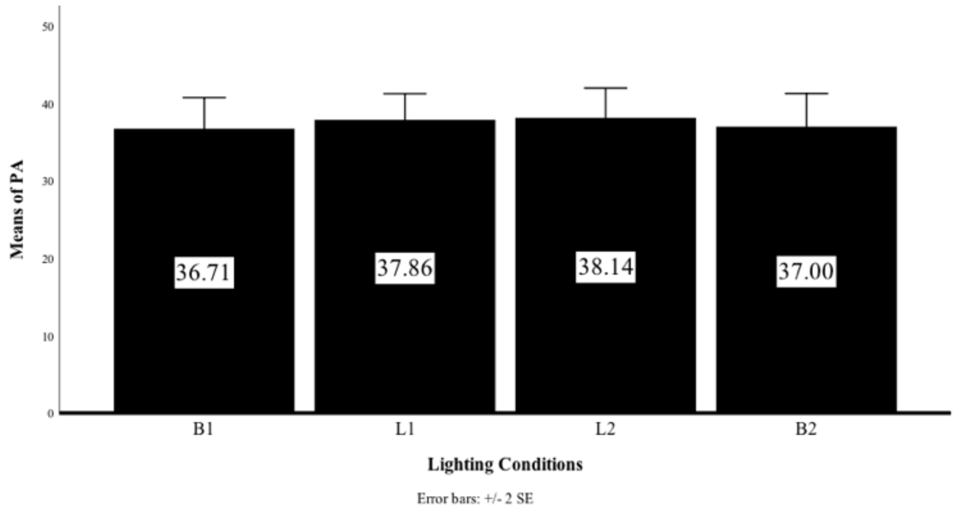


Figure 70. Pattern of PA across the study in High-end senior living.

As there was no significant difference mean score for NA based on buildings, all participants were analyzed in one group. A one-way RM ANOVA indicated no significant effect of lighting on NA in participants (F [1.68, 33.59] = 1.872, p = 0.17, MSE = 9.79, η^2_p = 0.086). However, a reducing trend was observed after the interventions (Figure 71). In fact, the mean score for NA decreased from 14.43 (SD = 4.20) in B1 to 13.71 (SD = 3.38) in L1 and decreased more to 12.76 (SD = 3.38) after L2. The mean score for NA increased to 13.33 (SD = 3.69) two weeks after the intervention was removed in B2.

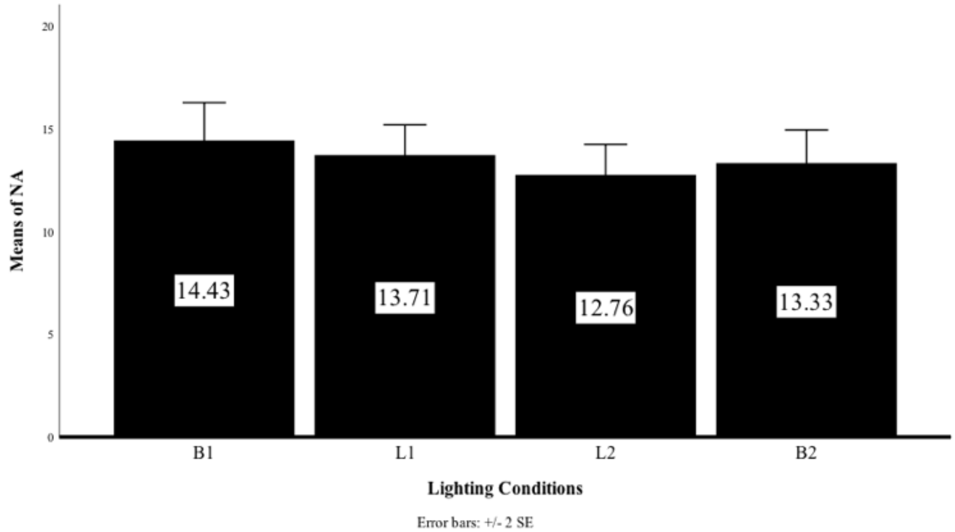


Figure 71. Pattern of NA across the study.

A.5. Health-Related Quality of Life (QL)

Due to the significant difference between the mean score for QL in participants based on buildings, participants of the High-end senior living were analyzed separately from those in the Affordable ones. A one-way RM ANOVA confirmed the significant main effect of lighting on QL in the residents of the Affordable facilities (F [1.55, 20.16] = 5.98, p = 0.01, MSE = 32.698, η^2_p = 0.32). As the sphericity assumption was violated (p < 0.001), the Greenhouse – Geisser correction was used to report the RM ANOVA results. Figure 72 shows the pattern of QL in the course of the study. L1 intervention improved mean score for QL from 23.71 (SD = 7.67) in B1 to 19.21 (SD = 4.41) and then L2 improved that even more to 17.93 (SD = 4.97). The mean score for QL increased in B2 (mean = 18.21, SD = 4.76), suggesting the QL started to demote after the intervention was discounted.

The pairwise comparison for the main effect of lighting on QL in Affordable senior livings reflected a significant difference between B1 and L1 (df = 13, t = 2.29, p < 0.001), B1 and L2 (df = 13, t = 2.74, p < 0.001), and B1 and B2 (df = 13, t = 2.87, p < 0.001). There was no significant difference between mean score for QL between L1 and L2 (df = 13, t = 1.31, p = 0.21), L1 and B2

(df = 13, t = 0.94, p = 0.37), and L2 and B2 (df = 13, t = -0.47, p = 0.65). Table 52 shows the results.

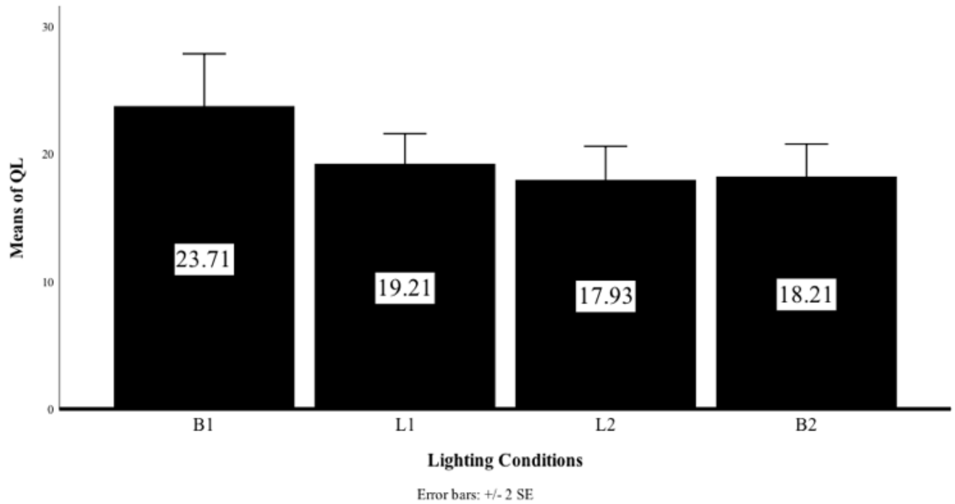


Figure 72. Pattern of QL across the study in Affordable senior livings.

Table 52. Results from Paired Sample t-test for QL in Affordable senior living across the study.

	Mean Difference	**SD**	***t* (*df* = 13)**	***p* Value**
Pair 1 (B1, L1)	4.50	2.37	2.29	0.04
Pair 2 (B1, L2)	5.77	7.91	2.74	0.02
Pair 3 (L1, L2)	1.29	3.67	1.31	0.21
Pair 4 (L1, B2)	1.00	4.00	0.94	0.37
Pair 5 (L2, B2)	-0.29	2.27	-0.47	0.65
Pair 6 (B1, B2)	5.50	7.18	2.87	0.01

No significant effect of lighting was found in the QL for participants residing in the High-end facility (F [3, 18] = 2.22, p = 0.12, MSE = 2.12, η^2_p = 0.27). However, the pattern of mean score for QL exhibited an improvement trend with the L1 and L2 interventions. As shown in Figure 73, L1 improved mean score for QL from 12.86 (SD = 3.13) in B1 to 11.86 (SD = 3.49) and then L2 improved that more to 10.86 (SD = 2.48). The mean score for QL slowly started to return to the baseline after the intervention was removed and reached to 12.00 (SD = 3.32) in B2.

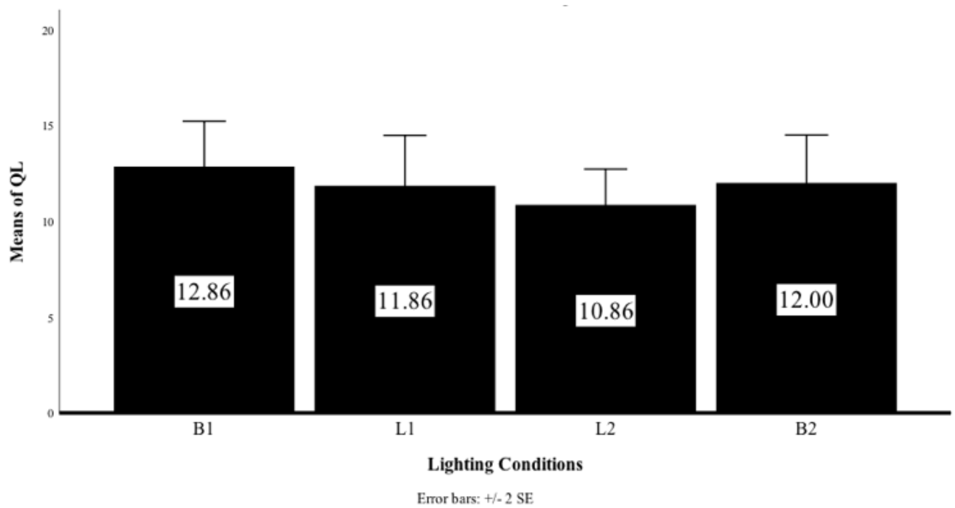


Figure 73. Pattern of QL across the study in High-end senior living.

A.6. Cognitive Performance

A.6.1. TMT-A Test

The score of the cognitive performance obtained from TMT-A test is reported based on the time (seconds) took for each participant to complete the test, with less time indicating greater cognitive performance. A one-way RM ANOVA confirmed the significant effect of lighting on the mean score for TMT-A in participants (F [1.32, 26.34] = 26.26, $p < 0.001$, MSE = 138.52, η^2_p = 0.57). As the assumption of sphericity was violated, the Green-Geisser correction was used to report RM ANOVA results. Both lighting interventions appeared to reduce the time needed to complete TMT-A in participants, suggesting an improvement in the cognitive performance. As shown in Figure 74, L1 intervention improved the mean score for TMT-A from 53.73 sec (SD = 29.19) in B1 to 40.94 sec (SD = 20.58), the mean score improved even more under L2 and reached to 32.52 sec (SD = 15.57), however, it started to worsen after the intervention was discontinued and went up to 42.63 sec (SD = 17.86) in B2.

Paired sample t-test confirmed a significant difference for the mean score for TMT-A between B1 and L1 (df = 20, t = 5.38, $p < 0.001$), B1 and L2 (df = 20, t = 5.87, $p < 0.001$), L1 and L2 (df = 20, t = 5.06, $p < 0.001$), L2 and B2 (df = 20, t = -8.67, $p < 0.001$), as well as B1 and B2 (df = 20, t = 3.55, p < 0.001). There was no significant difference between L1 and B2 (*df* = 20, *t* = -116, *p* = 0.26). Table 53 shows the results.

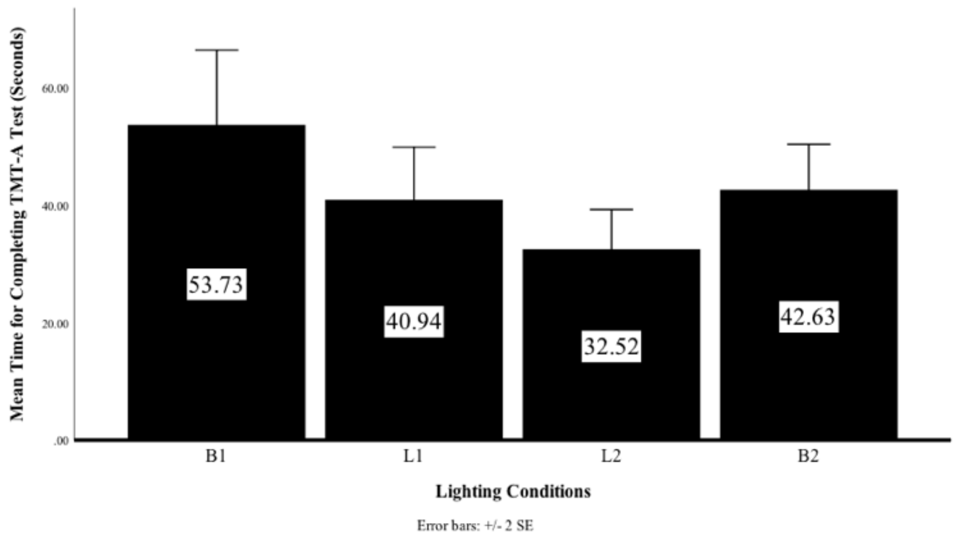


Figure 74. Pattern of TMT-A scores across the study. Less time to complete the task indicates higher level of cognitive performance.

Table 53. Results from Paired Sample t-test for TMT-A test.

	Mean Difference	SD	*t* (*df* = 20)	*p* value
Pair 1 (B1, L1)	12.79	10.89	5.38	< 0.001
Pair 2 (B1, L2)	21.21	16.57	5.87	< 0.001
Pair 3 (L1, L2)	8.42	7.62	5.06	< 0.001
Pair 4 (L1, B2)	-1.69	6.69	-1.16	0.26
Pair 5 (L2, B2)	5.34	5.34	-8.67	< 0.001
Pair 6 (B1, B2)	14.33	14.33	3.55	< 0.001

A.6.2. TMT-B Test

Similar to TMT-A, the score of the cognitive performance obtained from TMT-B test is reported based on the time (seconds) took for each participant to complete the test, with less time indicating greater cognitive performance. There was a significant effect of lighting on TMT-B test scores (F [2.01, 40.28] = 24.17, $p < 0.001$, MSE = 594.55, $\eta^2_p = 0.55$). The mean score for TMT-B improved after L1 (mean = 93.06, SD = 37.66), improved even more after L2 (mean = 67.13, SD = 27.21), and started to return to baseline after the intervention was removed in B2 (mean = 98.09, SD = 44.09) (Figure 75).

The pairwise comparison for the main effect of lighting reflected a significant difference between B1 and L1 ($df = 20$, $t = 3.86$, $p < 0.001$), B1 and L2 ($df = 20$, $t = 6.25$, $p < 0.001$), L1 and L2 ($df = 20$, $t = 5.61$, $p < 0.001$), L2 and B2 ($df = 20$, $t = -4.93$, $p < 0.001$), and B1 and B2($df = 20$, $t = 3.48$, $p < 0.001$). Nevertheless, no significant difference was observed between L1 and B2 ($df = 20$, $t = -1.32$, $p = 0.20$). Table 54 shows the results.

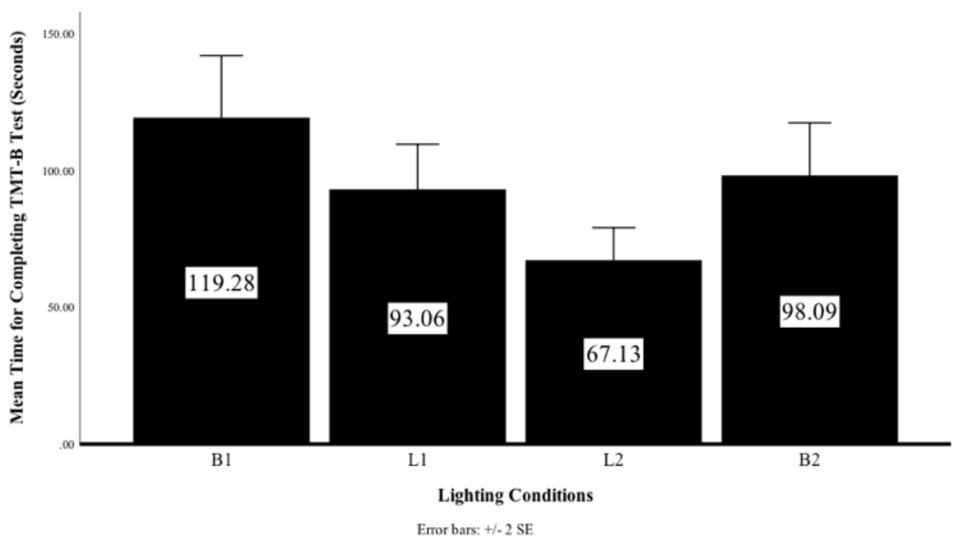


Figure 75. Pattern of TMT-B scores across the study. Less time to complete the task indicates higher level of cognitive performance.

Table 54. Results from Paired Sample t-test for TMT-B test.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* value**
Pair 1 (B1, L1)	26.22	31.12	3.86	< 0.001
Pair 2 (B1, L2)	52.15	38.22	6.26	< 0.001
Pair 3 (L1, L2)	25.93	21.19	5.61	< 0.001
Pair 4 (L1, B2)	-5.03	17.50	-1.32	0.20
Pair 5 (L2, B2)	-30.96	28.76	-4.93	< 0.001
Pair 6 (B1, B2)	21.19	27.89	3.48	< 0.001

A.6.3. Difference Between TMT-A and TMT-B (B – A)

A one-way RM ANOVA confirmed the significant effect of lighting on score difference between TMT-A and TMT-B (B – A) (F [1.99, 39.77] = 5260.83, $p < 0.001$, $MSE = 545.98$, $\eta^2_p =$

0.33). The difference of the two scores decreased from 65.54 seconds in B1 to 52.11 in L1; L2 decreased the difference even more and reached to 34.60. The difference between TMT-A and TMT-B scores started returning to the B1 after the interventions were discontinued (Figure 76).

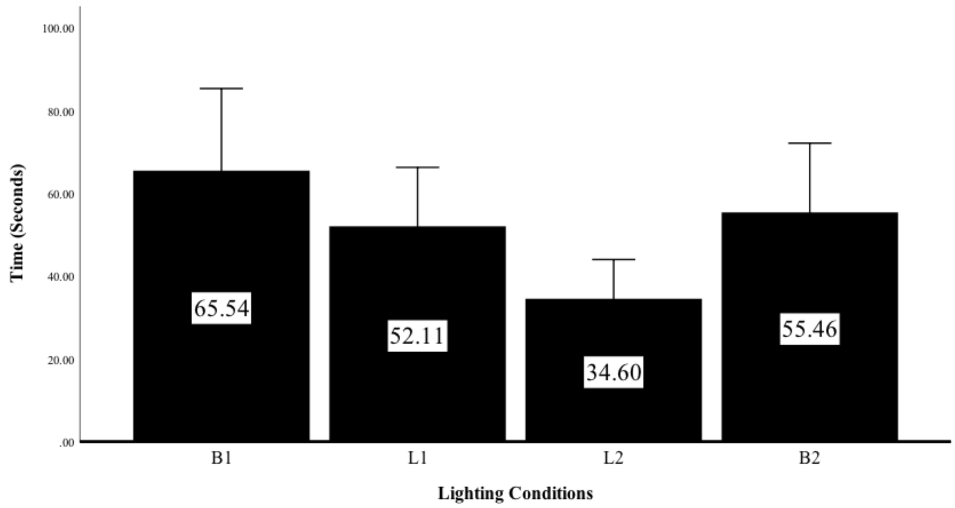


Figure 76. Pattern of difference between TMT-A and TMT-B (B - A) across the study.

A pairwise comparison exhibited a significant difference between B1 and L1 (*df* = 20, *t* = 2.13, *p* = 0.045), B1 and L2 (*df* = 20, *t* = 3.85, *p* = 0.001), L1 and L2 (*df* = 20, *t* = 3.78, *p* = 0.01), as well as L2 and B2 (*df* = 20, *t* = 3.40, *p* = 0.003). There was no significant difference between L1 and B2 was insignificant (*df* = 20, *t* = 0.90, *p* = 0.378) and B1 and B2 (*df* = 20, *t* = 1.86, *p* = 0.078). Table 55 shows the results.

Table 55. Results from Paired Sample t-test for the difference between TMT-A and TMT-B scores.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* value**
Pair 1 (B1, L1)	13.43	28.84	2.13	0.045
Pair 2 (B1, L2)	30.94	36.86	3.85	0.001
Pair 3 (L1, L2)	17.51	21.24	3.78	0.001
Pair 4 (L1, B2)	3.34	16.97	0.90	0.378
Pair 5 (L2, B2)	20.85	28.14	3.40	0.003
Pair 6 (B1, B2)	10.09	24.92	1.86	0.078

A.6.4. DSS Test

A one-way RM ANOVA confirmed the significant effect of lighting on DSST score (F [3, 60] = 25.03, $p < 0.001$, $MSE = 8.73$, $\eta^2_p = 0.56$). L1 and L2 increased the mean score for DSST increased from 41.14 (SD = 12.03) in B1 to 46.29 (SD = 11.47) and 28.90 (SD = 13.32) respectively. The mean score for DSST started worsening after the intervention had been discontinued and reached to 45.67 in B2 which was still higher the B1. Figure 77 the pattern of the mean score for DSST in the course of study.

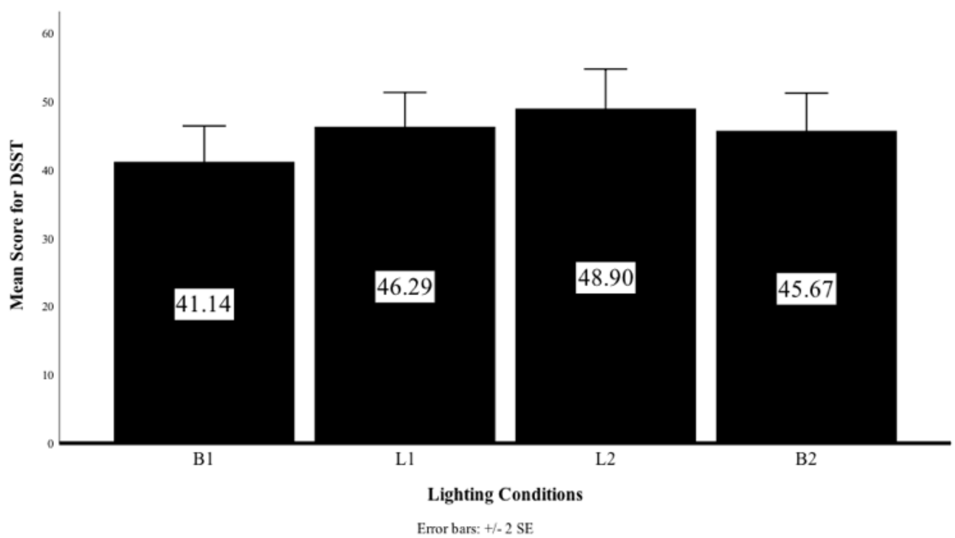


Figure 77. Pattern of DSST across the study.

A pairwise comparison on the main effect of lighting on the DSST score exhibited a significant difference between B1 and L1 ($df = 20$, $t = -5.04$, $p < 0.001$), B1 and L2 ($df = 20$, $t = -7.94$, $p < 0.001$), L1 and L2 ($df = 20$, $t = -2.79$, $p = 0.01$), L2 and B2 ($df = 20$, $t = 4.32$, $p < 0.001$), as well as B1 and B2 ($df = 20$, $t = -4.62$, $p < 0.001$). The difference between L1 and B2 was insignificant ($df = 20$, $t = 0.81$, $p = 0.43$). Table 56 shows the results.

Table 56. Results from Paired Sample t-test for DSST.

	Mean Difference	**SD**	***t* (*df* = 20)**	***p* value**
Pair 1 (B1, L1)	-5.14	4.67	-5.04	< 0.001
Pair 2 (B1, L2)	-7.76	4.48	-7.94	< 0.001
Pair 3 (L1, L2)	-2.62	4.31	-2.79	0.01
Pair 4 (L1, B2)	0.62	3.51	0.81	0.43
Pair 5 (L2, B2)	3.24	3.43	4.32	< 0.001
Pair 6 (B1, B2)	-4.52	4.49	-4.62	< 0.001

APPENDIX B. QUESTIONNAIRES BOOKLET

The Pittsburgh Sleep Quality Index (PSQI)

Instructions: The following questions relate to your usual sleep habits during the past month only. Your answers should indicate the most accurate reply for the majority of days and nights in the past month. Please answer all questions. During the past month,

1. When have you usually gone to bed? ______________
2. How long (in minutes) has it taken you to fall asleep each night? ______________
3. When have you usually gotten up in the morning? ______________
4. How many hours of actual sleep do you get at night? (This may be different than the number of hours you spend in bed) ______________

5. During the past month, how often have you had trouble sleeping because you…	Not during the past month (0)	Less than once a week (1)	Once or twice a week (2)	Three or more times week (3)
a. Cannot get to sleep within 30 minutes				
b. Wake up in the middle of the night or early morning				
c. Have to get up to use the bathroom				
d. Cannot breathe comfortably				
e. Cough or snore loudly				
f. Feel too cold				
g. Feel too hot				
h. Have bad dreams				
i. Have pain				
j. Other reason(s), please describe, including how often you have had trouble sleeping because of this reason(s):				
6. During the past month, how often have you taken medicine (prescribed or "over the counter") to help you sleep?				
7. During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?				
8. During the past month, how much of a problem has it been for you to keep up enthusiasm to get things done?				
	Very good (0)	Fairly good (1)	Fairly bad (2)	Very bad (3)
9. During the past month, how would you rate your sleep quality overall?				

Component 1	#9 Score	C1_______
Component 2	#2 Score (≤15min=0; 16-30 min=1; 31-60 min=2, >60 min=3) + #5a Score (if sum is equal 0=0; 1-2=1; 3-4=2; 5-6=3)	C2_______
Component 3	#4 Score (>7=0; 6-7=1; 5-6=2; <5=3)	C3_______
Component 4	(total # of hours asleep)/(total # of hours in bed) x 100 >85%=0, 75%-84%=1, 65%-74%=2, <65%=3	C4_______
Component 5	Sum of Scores #5b to #5j (0=0; 1-9=1; 10-18=2; 19-27=3)	C5_______
Component 6	#6 Score	C6_______
Component 7	#7 Score + #8 Score (0=0; 1-2=1; 3-4=2; 5-6=3)	C7_______

Add the seven component scores together ________ **Global PSQI Score** ________

Buysse, D.J., Reynolds III, C.F., Monk, T.H., Berman, S.R., & Kupfer, D.J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Journal of Psychiatric Research, 28*(2), 193-213.

Sleep Related Impairment – Calibrated Items

Please respond to each item by marking one box per row.

In the past 7 days...

		Not at all	A little bit	Somewhat	Quite a bit	Very much
Sleep10	I had a hard time getting things done because I was sleepy	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep11	I had a hard time concentrating because I was sleepy	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep119	I felt alert when I woke up	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Sleep120	When I woke up I felt ready to start the day	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Sleep123	I had difficulty waking up	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep124	I still felt sleepy when I woke up	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep18	I felt tired	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep25	I had problems during the day because of poor sleep	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep27	I had a hard time concentrating because of poor sleep	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

In the past 7 days...

		Not at all	A little bit	Somewhat	Quite a bit	Very much
Sleep30	I felt irritable because of poor sleep	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep33	I had a hard time controlling my emotions because of poor sleep	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep4	I had enough energy	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Sleep6	I was sleepy during the daytime	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep7	I had trouble staying awake during the day.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

In the past 7 days...

		Never	Rarely	Sometimes	Often	Always
Sleep19	I tried to sleep whenever I could	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep29	My daytime activities were disturbed by poor sleep	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

Sleep Disturbance – Calibrated Items

Please respond to each item by marking one box per row.

In the past 7 days...

		Not at all	A little bit	Somewhat	Quite a bit	Very much
Sleep105	My sleep was restful.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep106	My sleep was light.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep107	My sleep was deep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep108	My sleep was restless.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep115	I was satisfied with my sleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep116	My sleep was refreshing.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep125	I felt lousy when I woke up.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep20	I had a problem with my sleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep44	I had difficulty falling asleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep65	I felt physically tense at bedtime.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

In the past 7 days…

		Not at all	A little bit	Somewhat	Quite a bit	Very much
Sleep67	I worried about not being able to fall asleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep68	I felt worried at bedtime.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep69	I had trouble stopping my thoughts at bedtime.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep70	I felt sad at bedtime.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep71	I had trouble getting into a comfortable position to sleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep72	I tried hard to get to sleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep78	Stress disturbed my sleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep86	I tossed and turned at night.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep93	I was afraid I would not get back to sleep after waking up.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

	In the past 7 days…	Never	Rarely	Sometimes	Often	Always
Sleep110	I got enough sleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep42	It was easy for me to fall asleep.................	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep45	I laid in bed for hours waiting to fall asleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep50	I woke up too early and could not fall back asleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep87	I had trouble staying asleep........................	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep90	I had trouble sleeping................................	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Sleep92	I woke up and had trouble falling back to sleep.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

	In the past 7 days…	Very poor	Poor	Fair	Good	Very good
Sleep109	My sleep quality was…	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

The Epworth Sleepiness Scale

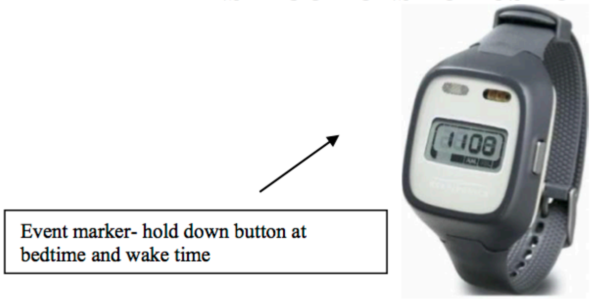
Participant ID: __________________________Date: __________________

How likely are you to fall asleep in the following situations, in contrast to feeling just tired? This refers to your usual way of life in recent times. Even if you have not done some of these things recently, try to work out how they would have affected you. Use the following scale to choose the *most appropriate number* for each situation:

0 = would ***never*** doze
1 = ***slight*** chance of dozing
2 = ***moderate*** chance of dozing
3 = ***high*** chance of dozing

SITUATION	CHANCE OF DOZING
Sitting and Reading	__________
Watching TV	__________
Sitting inactive in a public place (e.g. in a theater or a meeting)	__________
As a passenger in a car without a break for an hour	__________
Lying down in the afternoon when circumstances permit	__________
Sitting and talking with someone	__________
Sitting quietly after lunch without alcohol	__________
In a car, while stopped for a few minutes in traffic	__________

INSTRUCTIONS FOR USE OF ACTIGRAPHY



You have been asked to wear an actigraphy watch for evaluation of your sleep/wake cycle and patterns of movement. Please follow the directions below to ensure that your testing will be successful. If you have any questions, please call Ivy Cheung at (312) 503-1935.

1.) Please do not change your normal routine or the light conditions of your environment while being monitored. It is important that your activities are representative of your normal sleep/wake cycle.

2.) The actiwatch should be worn on your wrist on your **non-dominant arm**, free of binding sleeves and jewelry.

3.) The watch is to be worn both day and night and especially while you are sleeping.

4.) The watch is *not waterproof*. It should be removed any time you immerse your hands in water, i.e. bathing, washing dishes, swimming, etc. The watch will detect when it is off wrist.

5.) **Sleep logs** recording your time of awakening and time you went to sleep are to be kept while wearing the watch. **PLEASE FILL OUT YOUR SLEEP DIARIES WITHIN AN HOUR OF YOUR WAKE TIME!!!**

6.) When you lay down to try to sleep and when you wake up, please **press the event marker button** on the side of the watch (depicted by the arrow on the picture above).

7.) The watch is to be worn for a **period as indicated**. The starting date and time:

START ____________________________

STOP______________________________.

IRB# Version 04/12/18

Geriatric Depression Scale (Long Form)

Patient's Name:_______________________________ Date:____________________

Instructions: Choose the best answer for how you felt over the past week.

No.	Question	Answer	Score
1.	Are you basically satisfied with your life?	YES / NO	
2.	Have you dropped many of your activities and interests?	YES / NO	
3.	Do you feel that your life is empty?	YES / NO	
4.	Do you often get bored?	YES / NO	
5.	Are you hopeful about the future?	YES / NO	
6.	Are you bothered by thoughts you can t get out of your head?	YES / NO	
7.	Are you in good spirits most of the time?	YES / NO	
8.	Are you afraid that something bad is going to happen to you?	YES / NO	
9.	Do you feel happy most of the time?	YES / NO	
10.	Do you often feel helpless?	YES / NO	
11.	Do you often get restless and fidgety?	YES / NO	
12.	Do you prefer to stay at home, rather than going out and doing new things?	YES / NO	
13.	Do you frequently worry about the future?	YES / NO	
14.	Do you feel you have more problems with memory than most?	YES / NO	
15.	Do you think it is wonderful to be alive now?	YES / NO	
16.	Do you often feel downhearted and blue?	YES / NO	
17.	Do you feel pretty worthless the way you are now?	YES / NO	
18.	Do you worry a lot about the past?	YES / NO	
19.	Do you find life very exciting?	YES / NO	
20.	Is it hard for you to get started on new projects?	YES / NO	
21.	Do you feel full of energy?	YES / NO	
22.	Do you feel that your situation is hopeless?	YES / NO	
23.	Do you think that most people are better off than you are?	YES / NO	
24.	Do you frequently get upset over little things?	YES / NO	
25.	Do you frequently feel like crying?	YES / NO	
26.	Do you have trouble concentrating?	YES / NO	
27.	Do you enjoy getting up in the morning?	YES / NO	
28.	Do you prefer to avoid social gatherings?	YES / NO	
29.	Is it easy for you to make decisions?	YES / NO	
30.	Is your mind as clear as it used to be?	YES / NO	
		TOTAL	

This is the original scoring for the scale: One point for each of these answers.
Cutoff: normal-0-9; mild depressives-10-19; severe depressives-20-30.

1. NO	6. YES	11. YES	16. YES	21. NO	26. YES
2. YES	7. NO	12. YES	17. YES	22. YES	27. NO
3. YES	8. YES	13. YES	18. YES	23. YES	28. YES
4. YES	9. NO	14. YES	19. NO	24. YES	29. NO
5. NO	10. YES	15. NO	20. YES	25. YES	30. NO

Yesavage JA, Brink TL, Rose TL, et al. Development and validation of a geriatric depression screening scale: a preliminary report. *J Psychiatr Res* 1983; 17:37-49.

PANAS-GEN

This scale consists of a number of words that describe different feelings and emotions. Read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you GENERALLY feel this way, that is how you feel ON AVERAGE.

Use the following scale to record your answers.

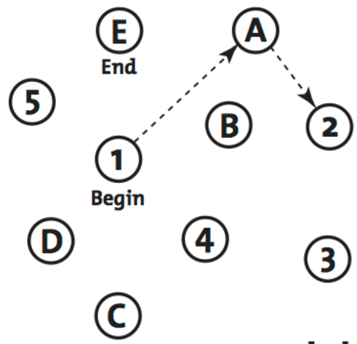
	Very slightly or not at all	A little	Moderately	Quite a bit	Extremely
Interested	☐	☐	☐	☐	☐
Distressed	☐	☐	☐	☐	☐
Excited	☐	☐	☐	☐	☐
Upset	☐	☐	☐	☐	☐
Strong	☐	☐	☐	☐	☐
Guilty	☐	☐	☐	☐	☐
Scared	☐	☐	☐	☐	☐
Hostile	☐	☐	☐	☐	☐
Enthusiastic	☐	☐	☐	☐	☐
Proud	☐	☐	☐	☐	☐
Irritable	☐	☐	☐	☐	☐
Alert	☐	☐	☐	☐	☐
Ashamed	☐	☐	☐	☐	☐
Inspired	☐	☐	☐	☐	☐
Nervous	☐	☐	☐	☐	☐
Determined	☐	☐	☐	☐	☐
Attentive	☐	☐	☐	☐	☐
Jittery	☐	☐	☐	☐	☐
Active	☐	☐	☐	☐	☐
Afraid	☐	☐	☐	☐	☐

MONTREAL COGNITIVE ASSESSMENT (MOCA)

NAME :
Education :
Sex :
Date of birth :
DATE :

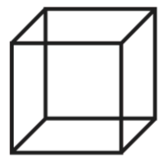
POINTS

VISUOSPATIAL / EXECUTIVE



[ ]

Copy cube



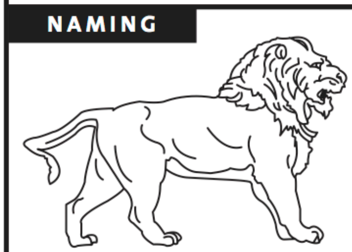
[ ]

Draw CLOCK (Ten past eleven)
(3 points)

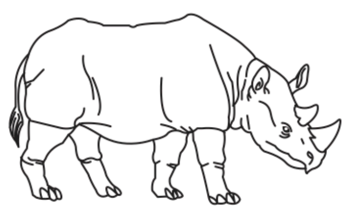
[ ] Contour [ ] Numbers [ ] Hands

___/5

NAMING



[ ]



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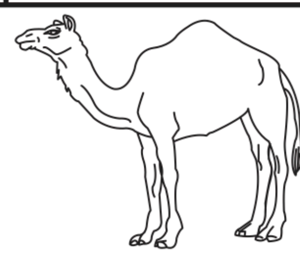


[ ]

___/3

MEMORY

Read list of words, subject must repeat them. Do 2 trials. Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED
1st trial					
2nd trial					

No points

ATTENTION

Read list of digits (1 digit/ sec.). Subject has to repeat them in the forward order [ ] 2 1 8 5 4
Subject has to repeat them in the backward order [ ] 7 4 2

___/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors
[ ] FBACMNAAJKLBAFAKDEAAAJAMOFAAB

___/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65
4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt**

___/3

LANGUAGE

Repeat : I only know that John is the one to help today. [ ]
The cat always hid under the couch when dogs were in the room. [ ]

___/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] ____ (N ≥ 11 words)

___/1

ABSTRACTION

Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler

___/2

DELAYED RECALL

Has to recall words WITH NO CUE	FACE [ ]	VELVET [ ]	CHURCH [ ]	DAISY [ ]	RED [ ]
Optional: Category cue					
Optional: Multiple choice cue					

Points for UNCUED recall only

___/5

ORIENTATION

[ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City

___/6

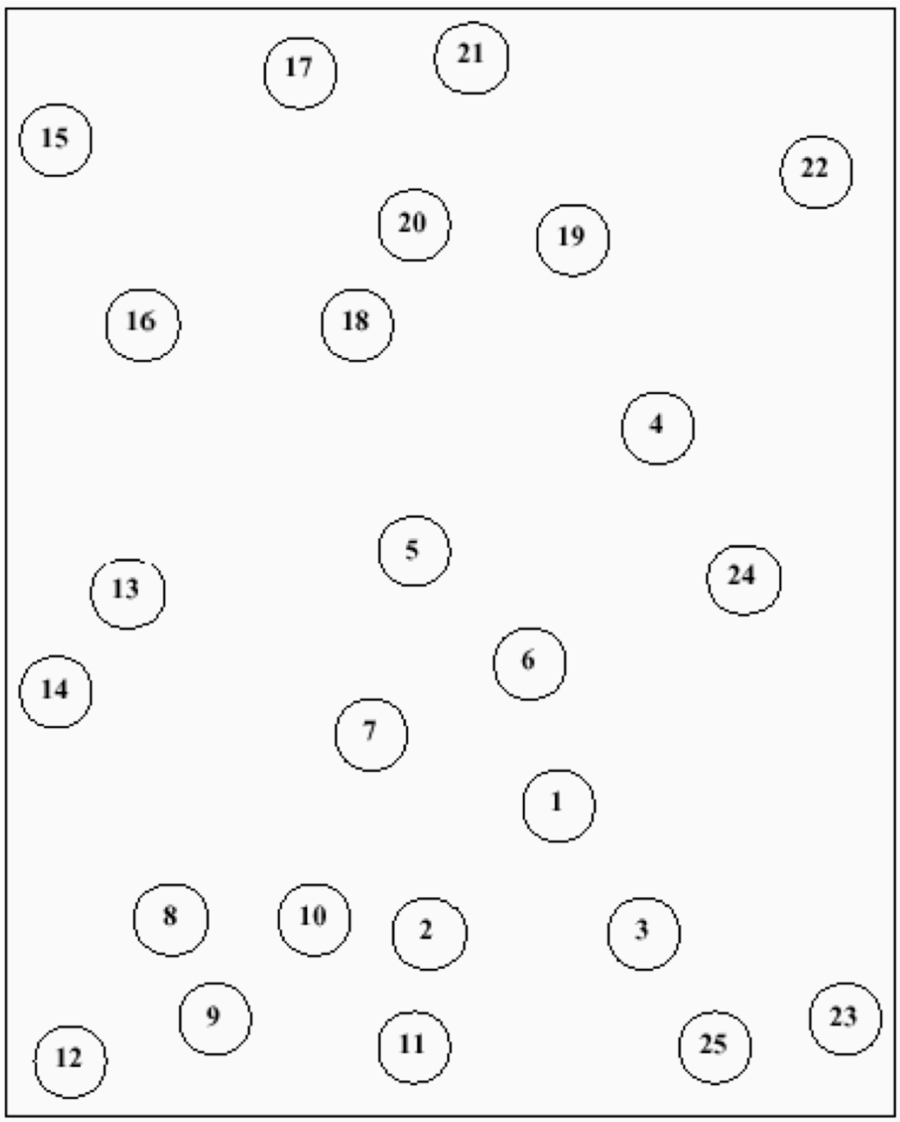
Normal ≥ 26 / 30

TOTAL ___/30

Add 1 point if ≤ 12 yr edu

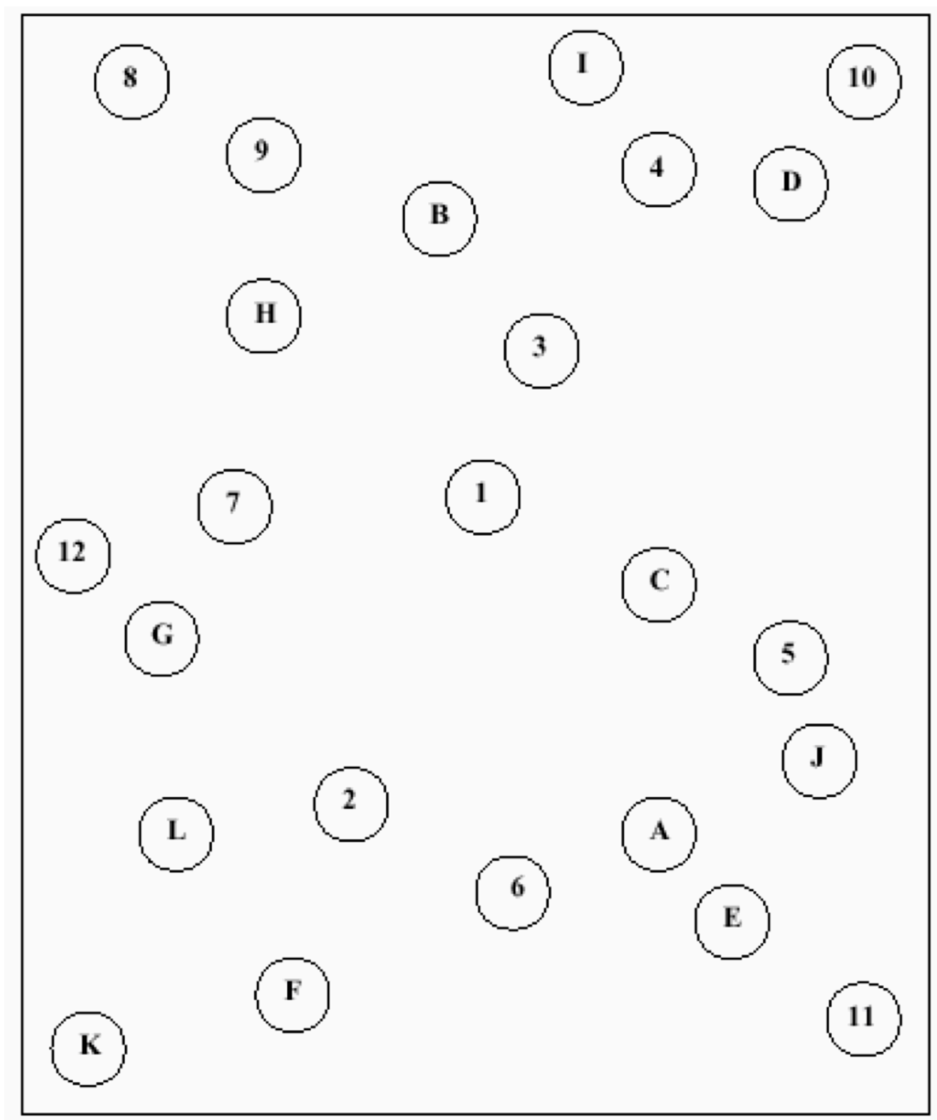
Trail Making Test Part A

Patient's Name: ______________________________ Date: ____________________



Trail Making Test Part B

Patient's Name: ______________________________ Date: ____________________



DIGIT	1	2	3	4	5	6	7	8	9
SYMBOL	—	⊥	⊐	L	U	O	Λ	X	=

SCORE

SAMPLES

2	1	3	7	2	4	8	1	5	4	2	1	3	2	1	4	2	3	5	2	3	1	4	6	3

1	5	4	2	7	6	3	5	7	2	8	5	4	6	3	7	2	8	1	9	5	8	4	7	3

6	2	5	1	9	2	8	3	7	4	6	5	9	4	8	3	7	2	6	1	5	4	6	3	7

9	2	8	1	7	9	4	6	8	5	9	7	1	8	5	2	9	4	8	6	3	7	9	8	6

Date__________________________ **Name**____

SF-8™ Health Survey

This survey asks for your views about your health. This information will help you keep track of how you feel and how well you are able to do your usual activities.
Answer every question by selecting the answer as indicated. If you are unsure about how to answer a question, please give the best answer you can.
For each of the following questions, please mark an [x] in the one box that best describes your answer.

1. Overall, how would you rate your health during the **past 4 weeks**?

☐Excellent ☐Very Good ☐Good ☐Fair ☐Poor ☐Very Poor

2. During the **past 4 weeks**, how much did physical health problems limit your usual physical activities (such as transfers or going places)?

☐Not at all ☐Very little ☐Somewhat ☐Quite a lot ☐Could not do physical activities

3. During the **past 4 weeks**, how much difficulty did you have doing your daily work, both at home and away from home, because of your physical health?

☐Not at all ☐Very little ☐Somewhat ☐Quite a lot ☐Could not do daily work

4. How much bodily pain have you had during the **past 4 weeks**?

☐None ☐Very mild ☐Mild ☐Moderate ☐Severe ☐Very severe

5. During the **past 4 weeks**, how much energy did you have?

☐Very much ☐Quite a lot ☐Some ☐A little ☐None

6. During the **past 4 weeks**, how much did your physical health or emotional problems limit your usual social activities with family or friends?

☐Not at all ☐Very little ☐Somewhat ☐Quite a lot ☐Could not do social activities

7. During the **past 4 weeks**, how much have you been bothered by **emotional problems** (such as feeling anxious, depressed or irritable)?

☐Not at all ☐Slightly ☐Moderately ☐Quite a lot ☐Extremely

8. During the **past 4 weeks**, how much did personal or emotional problems keep you from doing your usual work, school or other daily activities?

☐Not at all ☐Very little ☐Somewhat ☐Quite a lot ☐Could not do daily activities

Thank you for completing these questions.

Revised per Fox 03/14/2012

Appendix C. IRB LETTER

ILLINOIS

OFFICE OF THE VICE CHANCELLOR FOR RESEARCH

Office for the Protection of Research Subjects
805 W. Pennsylvania Ave., MC-095
Urbana, IL 61801-4822

Notice of Approval: New Submission

July 17, 2018

Principal Investigator	Mohamed Boubekri, Ph.D.
CC	Nastaran Shishegar
Protocol Title	*Evaluating the Impacts of Tuning Ambient Illumination on Older Adults' Sleep Quality, Mood, and Cognitive Performance*
Protocol Number	18867
Funding Source	Jim H. McClung Lighting Research Foundation
Review Type	Expedited Categories 4 & 7
Status	Active
Risk Determination	No more than minimal risk
Approval Date	July 17, 2018
Expiration Date	July 16, 2021

This letter authorizes the use of human subjects in the above protocol. The University of Illinois at Urbana-Champaign Institutional Review Board (IRB) has reviewed and approved the research study as described.

The Principal Investigator of this study is reponsible for:

- Conducting research in a manner consistent with the requirements of the University and federal regulations found at 45 CFR 46.
- Requesting approval from the IRB prior to implementing modifications.
- Notifying OPRS of any problems involving human subjects, including unanticipated events, participant complaints, or protocol deviations.
- Notifying OPRS of the completion of the study.

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