STRATEGIES FOR OPTIMIZING LIGHT THERAPY EFFICACY IN ALZHEIMER'S DISEASE PATIENTS.

by

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A Thesis Submitted to the Graduate
Faculty of Rensselaer Polytechnic Institute
in Partial Fulfillment of the
Requirements for the degree of
MASTER OF SCIENCE
Major Subject: LIGHTING

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May 2013

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ACKNOWLEDGMENT

First I would like to thank my thesis committee. To my thesis adviser Mariana Figueiro, thank you for not giving up on me when I took a plane to California. She was right. Working on a thesis from afar is near impossible, but a little encouragement went a long way. To my committee member Mark Rea, thank you for your honesty and your support. I sincerely appreciate your efforts to look over my written work and the sound lessons you taught me as an instructor. And to my committee member Russ Leslie, thank you also for editing my work and always challenging me to think beyond the obvious. I am very glad to have had such a talented group of individuals assisting me through this arduous process.

Secondly, I would like to thank Barbara Plitnick, Brittany Wood, and Ines Berger. Thank you Barbara for driving me to the nursing homes and helping me install the fixtures. Please take care of your back and let the students carry the heavy things for you in the future. Thank you Brittany for also taking me to the nursing homes. I will never forget that snowy November night where I was dropped in front of the double doors with my fixtures in the freezing cold of Troy. Without you, I could not have fixed the mal-functioning timers that night. Finally, thank you Ines for helping me edit my thesis. I am pretty sure that you are as happy as I am that we are done editing this thesis!

Additional people I would like to thank are Robert Hamner and Andy Bierman for their computer programming and physics expertise; Martin Overington and Howard Ohlhous for their patient instruction on building fixtures; Dennis Guyon for his beautiful photos; Patricia Rizzo for her design advice; Ceilia Parquette for looking over my formatting; Jefferson Ellinger and Erin Bermingham for helping me obtain the miracle second extension; and my past instructors not mentioned earlier: Narendran Nadarajah, John Bullough, Jean Paul, and Jennifer Brons.

For their words of encouragement, I would also like to thank everyone else in the LRC and outside for their optimism and sincere support. These wonderful people include the LRC staff, LRC Classes of 2010, 2011, and 2012, my wonderful cousin Amery, and my old-school posse. You guys are the best!

Super special thanks goes to my best friend, my grandparents, and my mom and dad. To my best friend, thank you for picking me up when I felt down and encouraging

me till the end to finish my thesis. I owe you a Red Bull (or two). To my grandparents, I love you dearly. Grandma, I don't think you will ever understand how much your support has helped me or will understand that I have finally finished school when I tell you, but I want you to know that you have inspired me to begin and end this project. To Grandpa, I wish I could have finished this thesis earlier so I could take you out to eat your favorite pork dish, but at least I can finally tell you "I'm done!" And to my wonderful mom and dad, thank you for always sending me chocolate when I needed it, and being my biggest fans. You have always supported me when I needed it the most and guided me to where I am today. I'm your biggest fan too.

ABSTRACT

Studies in the past have confirmed that light consolidates the rest/activity rhythms of Alzheimer's Disease and related dementia (ADRD) patients. Lighting interventions have also been shown to be a successful, non-pharmacological method to reduce depression, agitation, and increase independence in daily activities such as going to the bathroom. While this research continues to confirm the positive outcomes of circadian light therapy, researchers are no further along specifying a lighting dose. Light therapy apparatuses for the ADRD population have also yet to be improved. This study attempts to begin specifying the dose and examines the acceptability and performance of a novel lighting system for ADRD patients.

The study took place in two assisted living facilities in New York's Albany County between the last weeks of November 2011 to the beginning of July 2012. A total of nine mild to moderate ADRD subjects were recruited, and a total of five subjects completed the study. Once recruited, baseline light and activity data were recorded using a wrist-mounted Dimesimeter for 7 days, and primary caregivers were asked to fill out a battery of tests including the Pittsburgh Sleep Quality Index (PSQI), the Minimum Data Set—Activities of Daily Living (MDS-ADL), the Cornell Scale for Depression in Dementia (CSDD) questionnaire, and the Cohen-Mansfield Aggression Index (CMAI). Afterwards, a lighting intervention of four 9325 K CCT novel circadian luminaires averaging 320 lux (CS= 0.46) at eye-level (altogether) were installed in the subjects' bedrooms for a total of 28 days. The final Dimesimeter and battery of tests was dispatched during the last 7 days of the intervention period for additional data collection. At the end of the 28 days, experimenters removed the novel luminaires, retrieved the Dimesimeter, and completed questionnaires. Dependent variables gauging the performance of the novel luminaires include illuminance measured at the eye and corresponding circadian light (CL_A) and circadian stimulus (CS) values. Parameters assessing the circadian efficacy of the luminaires include the inter-daily (IR) repeatability of the circadian rhythm, phasor magnitude, the average activity of the ten most active hours (M10), the average activity of the five least active hours (L5), relative amplitude (RA), PSQI scores, MDS-ADL scores, CSDD scores, and CMAI scores. Variables used to gauge the feasibility of using the Dimesimeter include comparisons between average eye-level illuminances, average

wrist illuminances, average Dimesimeter-recorded illuminances, and all corresponding CL_A and CS values.

The outcome of this study indicated that the novel lighting system successfully consolidated rest/activity rhythms, reduced depression, and reasonably reduced agitated behaviors; however, it did not increase independence in the activities of daily living. Additionally, pros and cons of the dose delivery method and dose measurement are also discussed to advise future research on improving lighting dose delivery.

1. Introduction

Alzheimer's disease and related dementia (ADRD) is an irreversible brain disorder resulting in the loss of cognitive ability, physical abilities, and is commonly accompanied by sleep disruption. In 2012, ADRD was diagnosed in one in eight older Americans, an estimated 5.2 million Americans aged 65 and older, and 200,000 individuals under 65 with younger-onset ADRD (Alzheimer's Association 2012). With the ever-increasing growth of an older population, the prevalence of this disease is projected to double by 2050 (Alzheimer's Association 2012), likely translating to a similar increase in sleep disturbances.

Although sleep disruptions are normally associated with advanced age, the deterioration of the rest/activity cycle is pronounced in people with ADRD. As people age, comorbidities, changes in sleep patterns, and eye degradation restrict light, the body's main time-giver, increasing the risks for sleep disruption (Ancoli-Israel and Ayalon 2006; Cochen et al. 2009; Carpenter et al. 2006). ADRD patients suffer particularly because the parts of the brain responsible for circadian regulation also degrade, and advanced stages of the disease are associated with increased sleep disturbances (Ying-Hui and Swaab 2007; Swaab 2003; Van Someren 2000). These disruptions result in inappropriate behaviors at night and often persuade family members to surrender their loved ones to nursing homes where light signals are further muted (Pollack and Perlick 1991; Hope, Keen, and Gedling 1998; Yaffe et al. 2002; Campbell et al. 1988). According to the National Sleep Foundation (NSF)'s 2003 *Sleep in America* poll, 65% of older adults with memory problems reported sleep disturbances (National Sleep Foundation 2003). The combination of aging, ADRD, and a muted light signal compromises sleep quality in adults with ADRD.

While aging and ADRD are irreversible, previous studies have demonstrated that increasing light exposure at the eye can significantly consolidate sleep in ADRD patients. For example, in 1994, Mishima et al. improved the sleep/wake cycle of ADRD patients by exposing them to 3000-5000 lux for 2 hours every morning for 28 days. After the light exposure, subjects increased their total nocturnal sleep time while considerably decreasing daytime sleep (Mishima et al. 1994). Additionally, studies have also shown that light potentially decreased other negative ADRD effects such as compro-

mised cognitive abilities, increased physical dependence, aggressive behaviors (both verbal aggression and physical aggression), and depression. Riesmersma-van der Lek et al. demonstrated that added light alone increased cognitive and physical functioning, reduced depression, and increased sleep time (Riemersma-van der Lek et al. 2008). Additionally, Lovell et al. determined that light significantly reduced agitated behaviors in institutionalized demented persons (Lovell, Ancoli-Israel, and Gevirtz 1995).

Unfortunately, available light applications for sleep consolidation are not yet well developed for ADRD patients. While many applications specify the timing, duration, and "amount" (light levels) of the light dose for the user, current applications do no agree on the specific dose best suited for the ADRD population. Instead, different products have their own dose protocols, which may or may not be sensitive to the ADRD population. Further, the light applications currently used are not tailored for the ADRD population. Dementia associated with the disease usually prevents patients from adhering to protocol for increasing their light exposure from applications such as light boxes, box-like devices with one face emitting specified amounts of light. Other applications, such as retrofitting entire nursing homes for more light, may be too costly.

The objective of this thesis is to begin defining the dose of light for ADRD patients using novel floor lamp luminaires designed for the ADRD population. The luminaires would be installed into the subjects' homes for 4 weeks and the dose of light they received would be recorded using a circadian light calibrated data logger. Using the data logger's information, we can begin to define the dose of light that best affects ADRD patients. Rest/activity patterns were also recorded with the data logger to verify that the lighting intervention effectively entrained the circadian system. Subjective questionnaires charting the changes in sleep quality, depression, aggression, and independence in daily activities were also assessed. As a secondary goal, the acceptability of the novel luminaire and the data logger were also gauged to determine the usability of these applications for future ADRD applications.

2. Background

2.1 Human circadian system

With "*circa*" meaning "approximate," and "*dia*" meaning "day" in Latin, "circadian" refers to processes exhibiting an estimated 24-hour periodicity. Endogenous human circadian rhythms have an average period of 24.2 hours, resetting themselves daily to coincide with the 24-hour solar day (Czeisler et al. 1999). The human circadian system is a multi-stepped system where the suprachiasmatic nucleus (SCN) primarily controls the human circadian rhythm by directing various clocks and oscillators in the brain and various organs to coincide with the endogenous rhythm. For entrainment to the 24-hour day, the human circadian system relies on *zeitgebers* —external timegivers (Hofstra and Weerd 2008). These *zeitgebers* include scheduled sleep, activity, temperature, and meals, but the strongest *zeitgeber* is the 24-hour light/dark cycle (Duffy and Wright Jr. 2005). Particularly, the human circadian system is maximally sensitive to short-wavelength light between 450 nm and 480 nm (Brainard et al. 2001; Thapan, Arendt and Skene 2001; Rea et al. 2005). In response to light, the circadian system advances or delays the phase of the biological clock. Advancing describes pushing the endogenous circadian rhythm forward towards a shorter day (lark-like pattern). Delaying describes holding the circadian rhythm back, thereby extending the circadian day (owl-like pattern). The rest of body's oscillators are entrained using melatonin, a "darkness hormone" secreted by the pineal gland. This hormone also entrains the pineal gland itself by feeding signals back to its origin (Arendt 1995). It should be noted that melatonin is cyclic, normally declining in the morning and rising in the evening, is an essential antioxidant (Allegra, Reiter, and Tan 2003), a stimulant to release other antioxidants (Rodriguez, Mayo, and Sainz 2004), and a known neuroprotector that guards against ADRD (Pappolla, Chyan, and Poeggeler 2000).

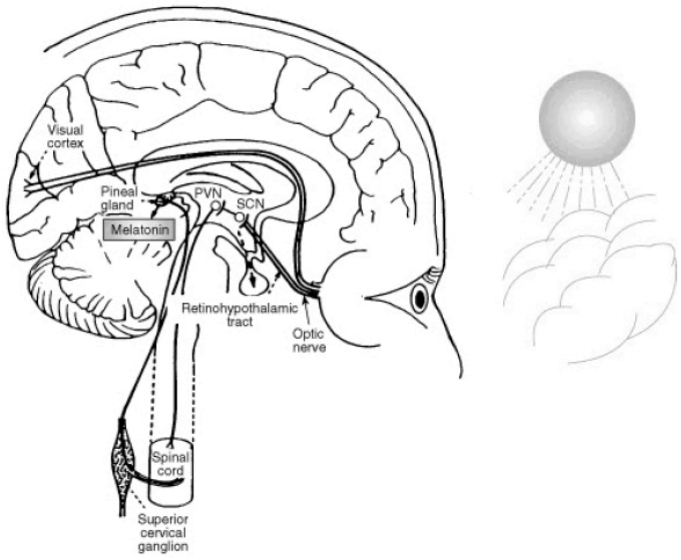


Figure 1: Physiology of the human circadian system (Rea 2000).

2.2 Visual System

As light is the circadian system's most influential *zeitgeber*, parts of the visual system, particularly the eye and the retina, can significantly affect circadian rhythmicity. The eye is an organ usually compared to a camera, but the analogy fails once light is focused on the retina and converted into electrical signals. Unlike exposure of light on film to form images, the human visual system is comprised of both the eye and the brain working together to form images (Boyce 2003). In the process where images are captured, light information is also manipulated and sent to the circadian system.

2.2.1 Eyeball

The eyeball is a spherical organ roughly 24 mm in diameter with the purpose of gathering environmental information. Figure 2 is a cross-section of the eyeball showing its concentric structure. Three layers comprising the eyeball are: the external layer, the intermediate layer, and the internal layer. The external and intermediate layers provide the optics for focusing light on the retina. The internal layer is the retina, where phototransduction, the conversion of light signals into electrical signals, begins to transpire.

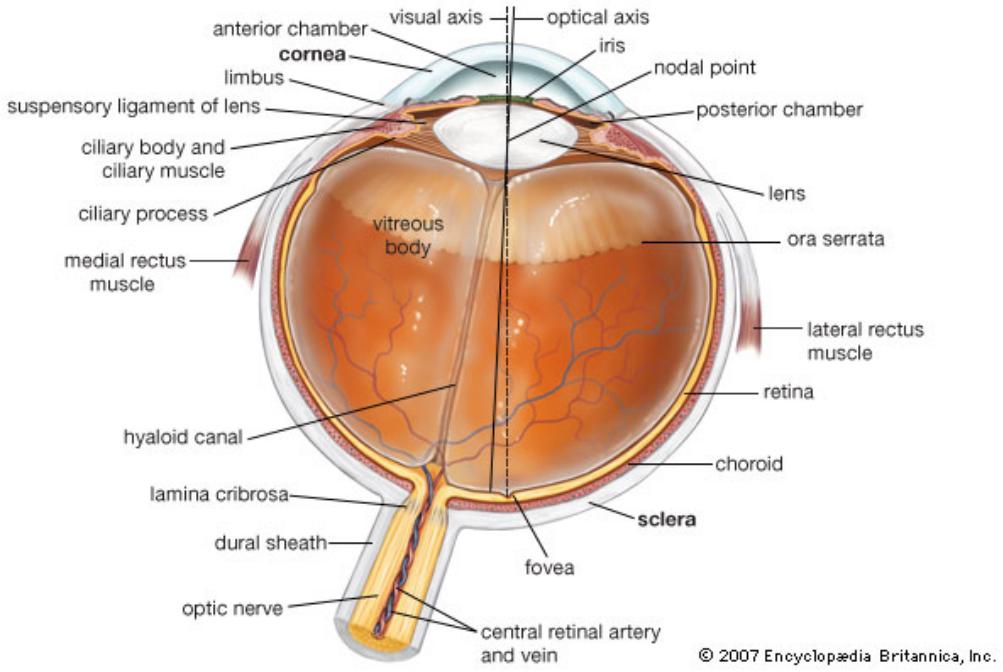


Figure 2: A horizontal cross-section of the human eye (Encyclopedia Britannica Inc. 2007).

2.2.1.1 The external and intermediate layers

The external layer of the eye encompasses the sclera and the cornea that are continuous with one another. Two-thirds of ocular light bending occurs on the cornea. The intermediate layer of the eye is further divided into two parts: the anterior which encompasses the iris, lens, and ciliary body, and the posterior choroid, a layer producing aqueous humor located beneath the sclera. The final one-third of ocular light bending is controlled by the crystalline lens before passing the vitreous body to be absorbed in the internal layer.

2.2.1.2 The retina

The retina itself is the final, internal layer. Considered an extension of the brain, the retina collects light and partially processes its information before passing it on to the brain. Anatomically, the retina is separated into layers beginning in reverse order from the back. Covering the "topmost" layer is the pigment epithelium directly attached to the back of the eye (see Figure 3). The melanin granules in the pigment epithelium protect photoreceptors from radiation damage by absorbing stray light. Layers directly following

the pigment epithelium are the photoreceptor layer, outer plexiform layer, the inner nuclear layer, the inner plexiform layer, and ganglion cells. Light must travel past the entire retina before exciting the photoreceptors (Kolb 2004).

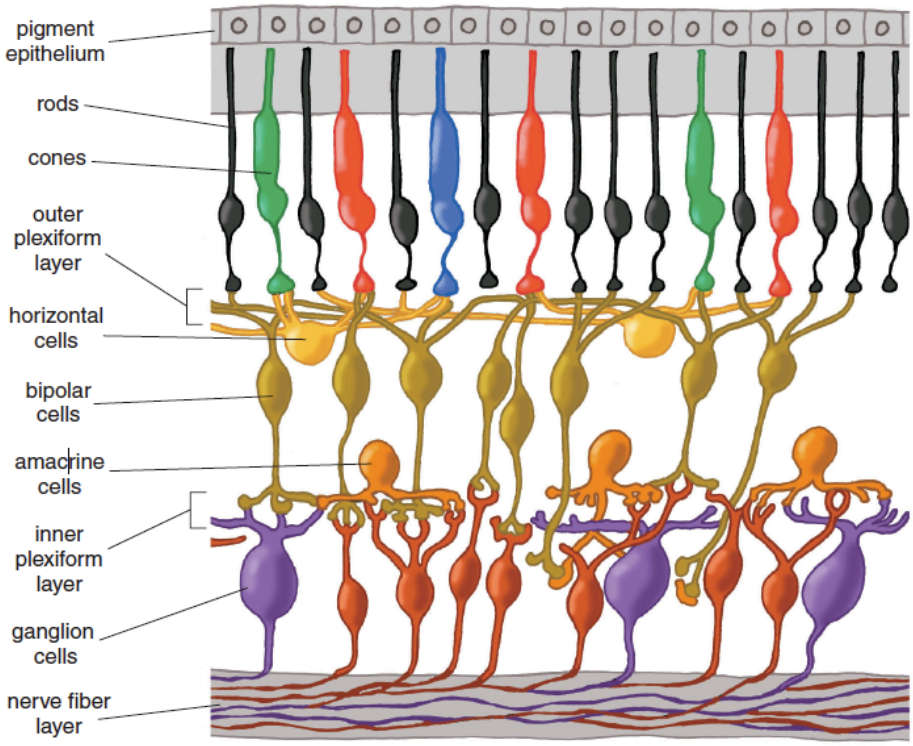


Figure 3: Discrete layers of the retina (Kolb 2004).

2.2.1.2.1 Photoreceptors

Photoreceptors are located in the outer nuclear layer of the retina, and four photoreceptors are divided into two types: rods and cones. Both photoreceptor types are named for their relative shapes under a microscope and contain unique opsins that contribute to their photosensitivity. Rods, the thinner of the two, all contain the photopigment rhodopsin, have peak sensitivity at 498 nm, and are located outside the fovea. Cones are divided into three variations depending the type of iodopsins they contain. Cones with erythrolabe are considered long-wavelength cones (L-cones), cones containing chlorolabe are considered middle-wavelength cones (M-cones), and cones containing cyanolabe are short-wavelength cones (S-cones). L- and M-cones have a sensitivity of 564-580 nm and 534-545 nm, respectively, and are both are located primarily on the 2° fovea of the retina. S-cones have a sensitivity of 430-440 nm, and are located primarily between the

2° and 5° fovea. Note that some L-, M-, and S-cones do exist in the periphery of the fovea. See Figure 4 for the spectral sensitivity of all rods and cones.

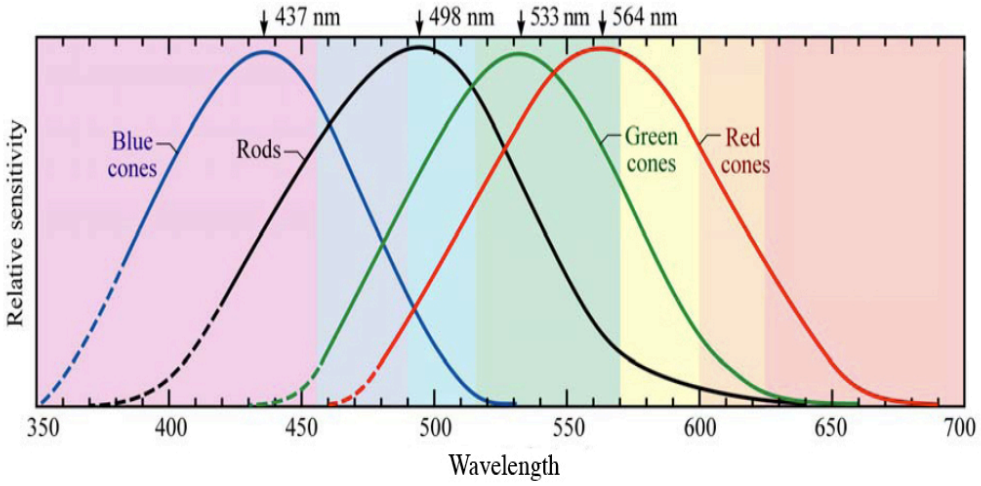


Figure 4: S-, M-, and L-cone and rod sensitivity estimates before lens filtering (Dowling 1987).

2.2.1.2.2 From photoreceptors to retinal ganglion cells and color opponency

Once photons are converted into electrical signals, they are filtered through the outer plexiform layer, inner nuclear layer, and inner plexiform layer, which further process spectral information in a color opponent manner. Color opponency refers to antagonistic retinal color processing between blue-yellow (b-y) channels and red-green (r-g) channels. When short-wavelength "blue" or "green" signals are equal to long wavelength "yellow" or "red" signals respectively, the signals cancel each other out. Cells that process color opponency within these layers include several types of bipolar and horizontal cells. Bipolar cells receive input from one cone, several cones, or several rods, and release an ON (depolarizing) or OFF (hyperpolarizing) signal. Horizontal cells then form a center-surround antagonistic signal—an opposing signal to the bipolar cell—around the bipolar signal. These signals are communicated to amacrine cells in the inner plexiform layer before finally being processed by retinal ganglion cells in the ganglion cell layer. Color opponent mechanisms are also present in the ganglion cell layer where a bi-stratified retinal ganglion cell determines the b-y channel response. This is significant to the circadian system because color opponency in the b-y channel potentially decreases the short-wavelength signals, the strongest influence to the SCN. Figueiro et al. first

demonstrated that the circadian system is subadditive by employing custom goggles where the left and right eyes were exposed to one unit of blue light (λ_{max} = 450 nm, 0.077 W/m^2) or one unit of green light (λ_{max} = 525 nm, 0.211 W/m^2) respectively. The third condition employed custom goggles mixing the two units of light and dividing them into two equal parts per eye. Since the mixed third condition induced significantly less melatonin suppression than the other two—which yielded similar results— color opponency was apparent at the retinal level (Figueiro, Bierman, and Rea 2008).

2.2.1.2.3 Intrinsically photosensitive retinal ganglion cells (ipRGCs)

Aside from rods and cones, the only other known photosensitive cells in the retina are the intrinsically photosensitive retinal ganglion cells (ipRGCs) located in the ganglion cell layer. Containing melanopsin, a novel vitamin-A based opsin, these cells are maximally sensitive to short wavelengths at approximately 480 nm (Berson 2007). Considered the primary cells in the retina responsible for human circadian phototransduction, ipRGCs project through the retino-hypothalamic track directly to the SCN (Sollars et al. 2003). Despite their influence, ipRGCs only make up 1 to 3% of RGCs; however, their large receptive fields compensate for their numbers by covering most of the retina (Provencio, Rollag, and Castrucci 2002). Note that ipRGCs also receive input from rods and cones since they are located in the pathway between photoreceptors and the optic nerve. This is significant because these cells indirectly receive color opponent signals from photoreceptors, affecting melatonin suppression as mentioned earlier (Figueiro et al. 2004; Figueiro, Bierman, and Rea 2008). It should also be noted that studies with blind mice also demonstrated that ipRGCs have the ability to influence the circadian system independent of rods and cones (Panda et al. 2003).

2.3 Circadian Light

Spectrum is significant as ipRGCs are maximally sensitive to shorter wavelengths as previously mentioned (see section 2.1); however, the other factors affecting the efficacy of light on the circadian system are light levels, duration, timing, and recent photic history (Czeisler and Gooley 2007; Lovell, Ancoli-Israel, and Gevirtz 1995). The ideal combination of these properties in varying degrees must be achieved to induce a

circadian response. For example, the activation threshold of the circadian system is higher than the activation threshold of the visual system (Rea et al. 2005), but the duration of the light exposure can also affect the impact of light on the circadian system (Figueiro et al. 2009). Thus, the efficacy of the lighting stimulus is dependent on a combination of stimulus characteristics such as spectrum, light level, and duration. Two additional characteristics are timing and recent photic history. Timing of the stimulus is also important because the effect of light on the circadian rhythm depends on when the stimulus is introduced as determined by a circadian phase-response curve (PRC). PRC describes the magnitude and direction of phase resetting at the circadian phase that the stimulus is introduced relative to the minimum core body temperature. In humans, the maximum phase delay (-3.5 hours) was observed in a response to light during early subjective night where the body temperature rhythm almost reaches nadir. Maximum phase advances (+3.0 hours) were observed after light exposure to late subjective night (see Figure 5; Khalsa et al. 2003).

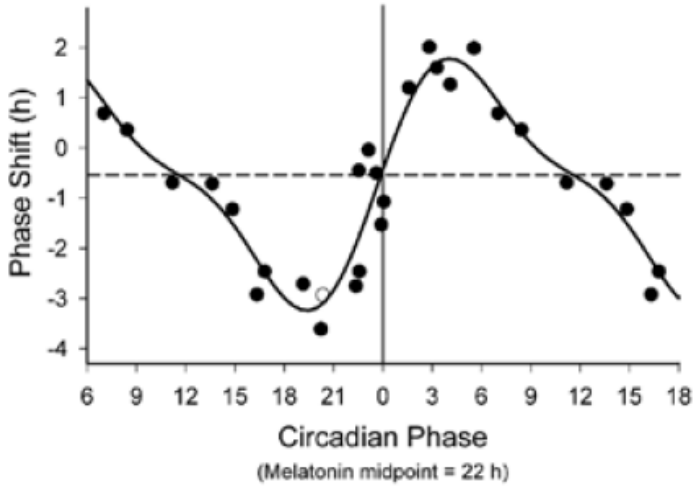


Figure 5: Phase-dependent resetting of the human circadian system (Khalsa et al. 2003).

Recent photic history has also been shown to change the magnitude of phase shifting and acute melatonin suppression. For example, after being exposed to 3 days of 200 lux of interior light for 6.5 hours, melatonin suppression to a stimulus of 200 lux was weaker than the same stimulus after <3 days of interior dim light (0.5 lux) exposure. This implies that the circadian system adjusts its threshold of sensitivity given recent photic history (Smith, Schoen, and Czeisler 2004).

2.3.1 Human phototransduction model

To calculate the strength of a light stimulus to affect circadian rhythms as measured by acute melatonin suppression, Rea et al. proposed the human phototransduction model, which mathematically addresses spectral opponency and rod shunting, and specifies the circadian efficacy of a given light source for acute melatonin suppression (Rea et al. 2005; Rea et al. 2010; Rea et al. 2011). Note that the timing of the calculated stimulus during the circadian phase was defaulted at midnight, and the duration was kept at 1 hour of light exposure for consistency. Photic history was not accounted for. See Figure 6 for a conceptualized illustration of the human phototransduction model:

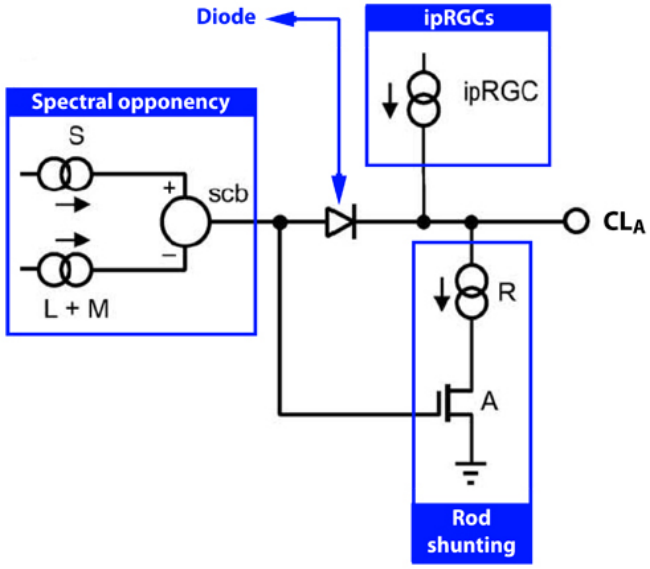


Figure 6: Electrical circuit model of the human circadian phototransduction model (Rea et al. 2005; Rea et al. 2011).

In the Figure 6, S symbolizes the S-cones, L+M symbolizes L- and M-cones, and scb represents the S-cone bipolar cell carrying signals to the ganglion cell layer and ipRGCs. R represents rod shunting, and A is the AII amacrine cell transmitter.

The mathematical model of the circadian phototransduction analogous to the circuit model is as follows:

$$CL_A = 1622\left[\int Mc_\lambda P_\lambda d\lambda \triangleleft \left(a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda}P_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda}P_\lambda d\lambda\right) - a_{rod}\left(1 - e^{\frac{-\int V'_\lambda P_\lambda d\lambda}{RodSat}}\right)\right)\right]. \quad (1.1)$$

CL_A symbolizes circadian light and represents the circadian efficacy of a light source normalized to the Commission Internationale de L'Eclairage's (CIE's) standard Illuminate A (standard 2756K tungsten A lamp) at 1000 lux. Mc_λ represents the spectral efficiency function of melanopsin weighted by lens spectral transmission (Rea et al. 2011). S_λ is the spectral efficiency function of S-cones, V_λ is the photopic luminous efficiency function of the 2^o fovea (L- and M- cones), V'_λ is rod (scotopic) spectral efficiency function, and mp_λ represents the spectral transmittance of the macular pigment. P_λ represents the spectral power distribution (SPD) of the desired light input. Figure 7 illustrates the photopic, scotopic, melanopsin, and macular pigment spectral efficiency functions used in the mathematical circadian phototransduction model:

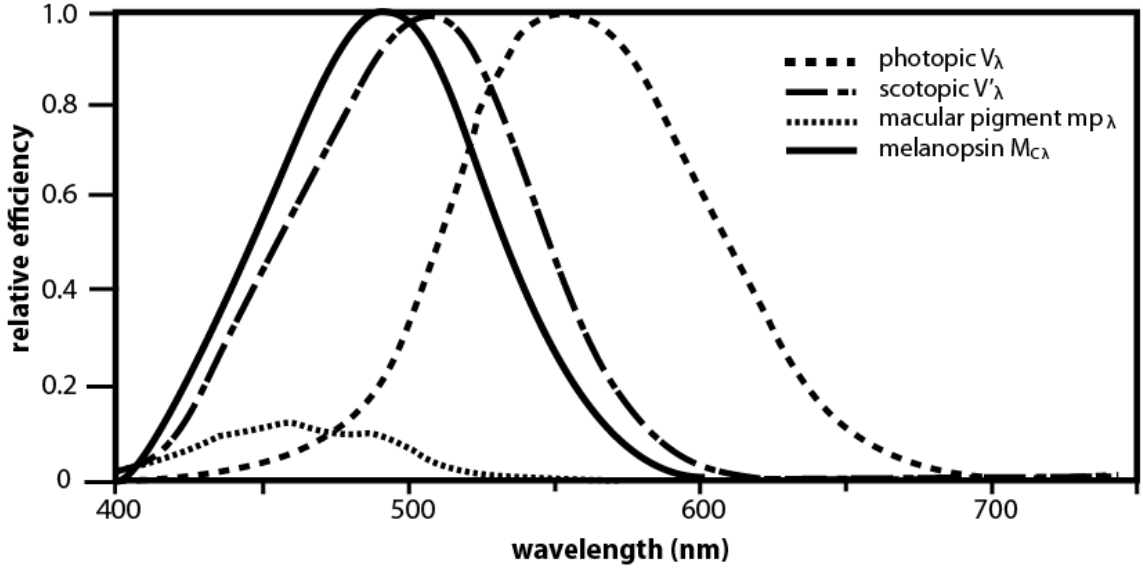


Figure 7: Compilation of spectral efficiency functions: photopic and scotopic (Commission Internationale de I'Eclairage 1987), macula pigment (Stockman and Sharpe 2000), and melanopsin (Panda et al. 2005).

Corresponding to the circuitry diagram, the mathematical evaluation begins with gauging the impact spectral opponency on the light stimulus. The spectral opponency portion of the equation is as follows:

$$a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda}P_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda}P_\lambda d\lambda\right). \qquad (1.2)$$

In this equation, $a_{b\text{-}y}$ is a constant strength of the opponent signals and k is the constant strength of sum of the L- and M-cone signals. In this equation, S_λ and V_λ are divided by mp_λ to remove macular pigment spectral absorption for a more accurate representation of

peripheral spectral sensitivity, since S_λ and V_λ were measured at the fovea (Rea et al. 2011). The P_λ is weighted by S_λ and V_λ, and finally the difference between the two is multiplied by a constant. Next, rod shunting is considered with the following equation:

$$-a_{rod}\left(1-e^{\frac{-\int^{V'_\lambda} P_\lambda d\lambda}{RodSat}}\right). \tag{1.3}$$

Here, a_{rod} represents a constant strength of the rods' response, and RodSat is a constant for the shunting threshold. The negative in the exponent of "*e*" represents the double negative effect of rods where rod inhibition becomes a positive value in the equation (Rea et al. 2005).

Once the rod shunting is calculated, the difference between the spectral opponency and rod shunting values determines if the difference is added to the left side of the equation. Due to the diode mechanism in the equation represented by a left pointing arrowhead, if the sum of the right-side value is positive, the overall value would be added to the left; however, if the right side sum is negative, then the entire value would not be included in the left equation. In the equation, the equation within the parentheses reduces to:

$$\int Mc_\lambda P_\lambda d\lambda. \tag{1.4}$$

Finally, the entire equation is multiplied by 1622 to obtain the illuminate A normalized CL_A value.

2.3.1.1 Circadian stimulus

CL_A can be converted to a circadian stimulus (CS) value representing the percent of predicted melatonin suppression over 1 hour of a specified light stimulus at midnight. The formula was derived from a four-parameter logistic equation (Zeitzer, Kronauer, and Czeisler 2005). The equation is as follows (Rea et al. 2005; Rea et al. 2010; Rea et al. 2011):

$$CS=\left(\frac{-0.7}{1+\left(\frac{CL^A}{0.037}\right)^{0.864}}\right)+0.7\times 100. \tag{1.5}$$

CS values below 15% are not considered significant, and relevant CS values are limited at 70%, where 70% is max suppression (Brainard et al. 2001; Thapan, Arendt, and Skene 2001).

2.4 Degeneration of the circadian system

While light is the body's strongest zeitgeber, biological changes over time eventually lower the effectiveness of the eye's ability to receive light, transmit light-dark signals to the SCN, and the SCN's output. The combination of these aging symptoms derails the rhythmicity of the aging 24-hour circadian rhythm.

2.4.1 Aging and the eye

Aging deteriorates the eyes, compromising the retina's ability to transmit adequate light signals to the SCN. Older adults are more prone to conditions such as increased lens yellowing, senile miosis (constricted pupils), and lens opacity (Weale 1963). Lens yellowing is caused by ultraviolet absorption over time, causing lenses to discolor and yellow. This is significant because lens yellowing reduces the amount of short-wavelength light reaching the retina for circadian stimulation. With aging, the pupils also lose their ability to expand due to muscle atrophy in the sphincter pupillae and dilatator pupillae, causing senile miosis. A younger pupil can dilate to approximately 8 mm when exposed to light, whereas senile miosis restricts the pupil to approximately 2 mm in diameter (Larsson and Österlind 1984). Smaller pupils further reduce the amount of light reaching the retinas of older adults. Finally, light is also reduced with lens opacity as the lens naturally grows thicker by forming layers like an onion. On average, a 60-year-old only receives about one-third the retinal illuminance of a 20-year-old (Weale 1963). Such conditions weaken the strength of the light stimuli reaching the SCN.

2.4.2 Aging and the circadian system

Age physically degrades the ability of the SCN to consistently regulate the circadian rhythm of various functions in the body. In a literature review gleaning over 100 articles on sleep and aging, Cochen et al. concluded that with increasing age, sleep becomes "lighter" and more fragmented; the time spent in the lighter stages of sleep increase, and

the percentage of deep sleep is decreased (Cochen et al. 2009). Sleep efficiency, defined as the amount of actual sleep (hours) divided by the time spent in bed (hours), also decreases with age. For example, sleep efficiency declines from 86% at age 45 to approximately 45% at age 70 (Redline et al. 2004). The most common complaints from older adults include: waking not rested, waking too early, trouble falling asleep, daytime napping, and nocturnal awakenings (Ancoli-Israel 2005).

Aging also changes the circadian rhythm melatonin levels beginning around age 40. Zhou et al. showed that the amplitude of the melatonin cycle in middle-aged subjects (41-53 years of age) was only 60% of that of the young subjects (Zhou and Liu 2003). As stated previously, melatonin is not only a synchronizing hormone, it is also a direct antioxidant (Allegra, Reiter, and Tan 2003), an indirect antioxidant simulating the release of other antioxidants (Rodriguez, Mayo, and Sainz 2004), and a known neuroprotector that helps prevent ADRD (Pappolla, Chyan, and Poeggeler 2000). No studies currently implicate lowered nighttime melatonin production with increased ADRD risk; however, it can be surmised that decreased melatonin levels may compromise neural protection from degeneration.

2.4.3 ADRD symptoms and the circadian system

The effects of aging on sleep for older adults amplify in adults with ADRD (Swaab et al. 2002). ADRD patients suffer from neuro-anatomical and neurochemical changes that degenerate the SCN and pineal gland (Ying-Hui and Swaab 2007; Swaab 2003, Van Someren 2000). A study conducted by Harper et al. with one group of healthy elderly men, (mean age ± standard deviation (SD) = 72.8 ± 2.1 years) and late-stage ADRD men (mean age ± SD = 70.2 ± 1.0 years) exemplifies the differences that occur in core body temperature rhythms and rest/activity rhythms in those with ADRD (Harper et al. 2001). The study spanned 72 hours starting at noon. All subjects were studied in a control unit where the lights were turned on at 6:00 a.m., and off at 10:00 p.m. Activity data were recorded every 5 minutes using actigraphs, and core body temperatures were recorded every 6 minutes using a rectal thermometer connected to a temperature monitor. The dependent variables studied were the average activity of the ten most active hours in a 24-hour period (M10), the average activity of the 5 least active hours in a 24 hour period

(L5), interdaily stability [IS] (measuring the stability of the rest/activity rhythm day-to-day), intradaily variability [IV] (measuring the fragmentation of the activity rhythm), and consinor analysis to model the circadian rhythm with temperature and activity data. Compared to the control group, the ADRD group had significantly lower M10 values, higher L5 values, lower average diurnal activity, lower rest/activity stability, higher rest/activity fragmentation, higher nocturnal activity, and lower diurnal activity. ADRD patients also had a significantly more delayed minimum core body temperature onset. These results were consistent with ADRD patients having less circadian rhythmicity in their rest/activity cycles than their healthy counterparts. Under the same controlled lighting, ADRD patients suffered more circadian disruption than healthy older adults because their illness degrades the mechanisms of their biological clocks. It should be noted that no baseline data were collected on all subjects before the controlled lighting, so no conclusions can be drawn as to how the controlled lighting affected the ADRD patients. This study was to purely demonstrate the differences in circadian rhythmicity between groups.

Another more recent study by Figueiro et al. (2012) also compared the sleep of healthy older adults with ADRD patients and found that ADRD patients have significantly more circadian disruption than their healthy counterparts (Figueiro et al. 2012). In this study, 17 healthy older adults (mean age ± SD = 73 ± 6 years) and 18 ADRD patients (mean age ± SD = 81 ± 6 years) were recruited for the study. Both groups wore light/activity data loggers for 24 hours every day for 1 week to record their daily activity and circadian light levels. Using 5 days of consecutive data with the strongest protocol adherence, average light and activity profiles were calculated for each subject. The two measures to evaluate circadian entrainment were RA and phasor analysis. RA determined how consolidated sleep was based on the comparison between the activity during the ten most active hours and the activity during the five least active hours. Higher RA scores represented higher consolidation. Phasor analysis included both phasor magnitude and phasor angle. Phasor magnitude determines how closely the 24-hour light cycle and activity pattern coincide with one another. The higher the number, the better the consolidation. Phasor angle describes whether the circadian rhythm was shifted more towards owl-like or lark-like patterns. The results showed that ADRD patients have significantly

lower phasor magnitude and RA compared to their healthy counterparts. ADRD patients simply did not perform much more activity during their ten most active hours compared to their five least active hours. Interestingly, the light exposure of both parties were not significantly different. Under similar lighting conditions, ADRD patients still had more sleep disruption than the healthy older adults. Overall, ADRD patients have been shown to suffer from more circadian disturbances than their healthy counterparts.

2.4.3.1 ADRD and independence

As ADRD progresses, independence is also compromised as ADRD patients lose the ability to perform activities of daily living activities that are needed on a daily basis to ensure health and well-being. These activities can include daily hygiene, going to the bathroom, dressing, and eating. Increasing physical dependence is likely due to decreasing cognition. Given the nature of ADRD, cognition becomes increasing impaired over time. Sleep disruption from compromised circadian rhythms likely compounds impairment, as there is a well-known relationship between neurodegenerative diseases, sleep, and cognition. Recent research has even indicated that circadian disruption is a reliable predictor of future dementia in older women (Schlosser et al. 2012). Hence, circadian disruption and compromised cognitive skills decrease the physical independence of seniors with ADRD.

2.4.3.2 ADRD and depression

Given the nature of ADRD where patients begin to lose cognitive function and memory, most patients begin to suffer from depression during early to mid stages of ADRD, while they are aware of their declining brain function.

2.4.3.3 ADRD and aggression

ADRD is also associated with aggression commonly timed during the late afternoon/early evening also known as "sundowning." Physical behaviors associated with sundowning include loud vocalization, wandering, physical aggression, combativeness, maladaptive physical behaviors, and overall agitation (Weldemichael and Grossberg 2010). Interestingly, studies suggest that sundowning expresses a circadian rhythm more robust than activity in ADRD supposedly related to light exposure, sleep, and medica-

tion (Martin et al. 2000). Approximately 12% to 25% of ADRD patients demonstrate sundowning (Kryger, Roth, and Dement 2000).

2.5 Bright light therapy

To treat the symptoms of ADRD such as sleep disruption and increased agitation, bright light therapy has been used as a non-pharmacological treatment shown to consolidate sleep, reduce depression and aggression, and increase independence in older adults with ADRD (Riemersma-van der Lek et al. 2008). The therapy generally consists of using a light-emitting apparatus to expose patients to more light as treatment for the patients. Unfortunately, none of these light therapies agree on an exact dose to best treat the ADRD population; furthermore, existing apparatuses used for bright light therapy are not appropriate for ADRD populations.

2.5.1 Light box

The light box method is loosely defined as having a patient sit in front of a "light box" apparatus to receive light. Some apparatuses allow or recommend reading or other activities in front of the light box while receiving light. Others light boxes require looking directly at the apparatus for a set period of time. Although timing, duration, light levels, and spectrum are usually specified for this application, some light specifications are often missing, the light specified is usually glary, and the duration specified is arduous. For example, Mishima et al. (1994) conducted a light box study with fourteen ADRD subjects ages 61-83 years and ten control subjects ages 65-81 years. All subjects were either moderately or severely demented, and the subjects in the experimental group were all diagnosed with various types of sleep disorders from irregular, fragmented sleeping cycles to insomnia. For a 4-week period, light therapy was given daily for 2 hours from 9:00 a.m. to 11:00 a.m. at 1 meter away from a "full-spectrum" light therapy device emitting 3000-5000 lux at the eye. All subjects were instructed to glance at the light source frequently, and one caregiver ensured their compliance. Caregivers were also instructed to keep hourly records of sleep, activity, and agitated behaviors in a sleep diary. By the end of the experiment, the experimental group with sleep disorders had statistically increased sleep duration during the night ($p<0.05$), decreased diurnal sleep

($p<0.05$), increased total sleep ($p<0.05$;see Figure 8), and decreased agitated behaviors ($p<0.05$), according to the sleep diaries. While this experiment was successful, the light box protocol required too much time in front of the light box, and the light was likely glary at 3000-5000 lux. Further, unless caregivers were willing to sit with patients for 2 hours every day, this experiment would not have been successful. Caregivers, however, often do not have the luxury to sit with an ADRD patient for 2 hours of light therapy. Unfortunately, such requirements are generally needed across light box usage as a whole for ADRD patients because of inherent dementia.

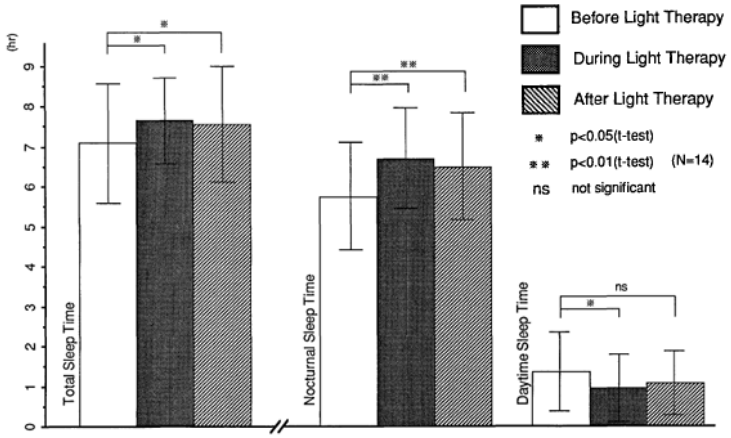


Figure 8: Increased consolidation of ADRD sleep with light box therapy. Subjects slept more overall, slept more at night, and slept less during the day (Mishima et al. 1994).

In another study exemplifying the low feasibility of using light boxes for ADRD patients, Satlin et al. (1992) recruited ten subjects meeting the Diagnostic and Statistical Manual of Mental Disorders criteria for degenerative dementia, the National Institute of Neurological and Communicative Disorders and Stroke definition for dementia, and the Alzheimer's Disease and Related Disorders Association criteria for moderate to severely demented ADRD. Their subjects' average Mini-Mental State Examination (MMSE) score was a 6, indicating severe dementia, and their average ADL score was 5.3, indicating high dependence. Subjects also sundowned, and were highly agitated between 2:00 p.m. to 4:00 p.m. In a 3-week period, Satlin et al. collected baseline data the first week and light intervention data during weeks two and three. Although they also found that increasing light exposure (1500 lux -2000 lux) for 2 hours in the morning (7:00 a.m. to 9:00 a.m.) consolidated sleep and lowered aggression, the research team needed to

restrain patients in a geri-chair (adjustable chair with a tray) facing the light box in order to increase compliance (Satlin et al. 1992). Again in this experiment, both the dose and delivery of the lighting intervention is not appropriate for ADRD patients. Staring at a 1500-2000 lux box while strapped in a geri-chair is certainly unpleasant. Thus light box therapy may not be a feasible option for ADRD patients because the dose and delivery of the lighting intervention is not sensitive towards the ADRD population.

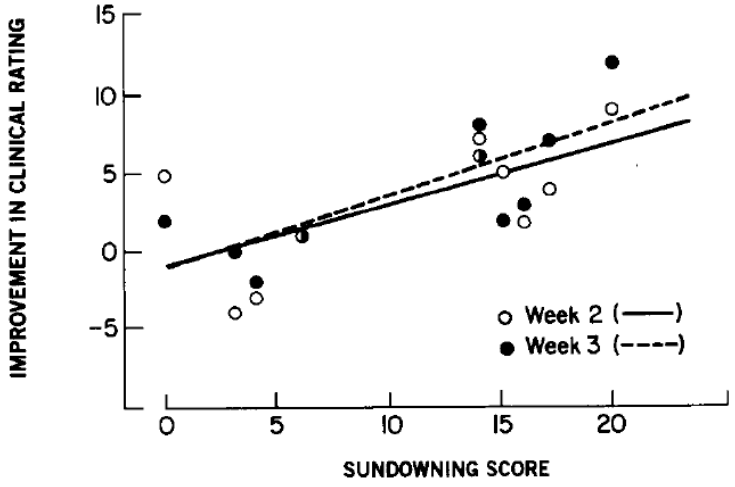


Figure 9: Relation between the severity of sundowning and the response to the light treatment. Results were taken from subjective scores given by caregivers gauging the agitation of ADRD patients. Higher numbers represent increased agitation (Satlin et al. 1992).

2.5.2 Light visors/goggles

Light visors or goggles are an improvement to light boxes. Light visors/goggles are eyewear designed to emit light at the eye and do not require restraints to use. However, supervision may still be required since these novel items may be easy to lose, misplace, or break; therefore, light visors/goggles may still not be the appropriate delivery method for the ADRD population. Furthermore, past studies also show that some of these products still do not consider the comfort of the user as some light visors/goggles emit the same light levels as light boxes, and light visors/goggles may be even more uncomfortable since they sit at or near level. Current studies are researching dimmer goggles; nonetheless, light visors/goggles may still not be appropriate for the ADRD population. Some doses used in light visors/goggles are still uncomfortably glary, and overall the apparatus may be too fragile.

To illustrate, in one study assessing the feasibility of a light visor application, Colenda et al. recruited eight subjects that met the clinical ADRD criteria and scored 16.4 ± 3.5 on the MMSE indicating mild to moderate dementia (Colenda et al. 1997). The protocol consisted of 5 days of baseline data collection using an actigraph, 10 days of light intervention using a Bio-brite Light Visor (Bio-brite, Inc., Bethesda, MD, U.S.A.) to emit 2000 lux at the eye from 7:00 a.m to 9:30 a.m., and a 14-day post-intervention period monitoring activity. Five of the eight subjects completed the study. Unfortunately, using cosinor analysis to fit the circadian rest and activity data, researchers found no significant changes in subjects' circadian rhythms. Researchers reasoned that the inability to show rest/activity consolidation could have been a result of exposure timing, exposure duration, or simply that the visors were not feasible bright light therapy applications (Colenda et al. 1997). By blasting 2000 lux at the eye, Colenda et al. did not cater to the comfort of their ADRD subjects, possibly dissuading them from using the application; hence an optimal light dose is needed that is both effective and sensitive to the user.

Light goggle studies on healthy older persons with dim light have been more successful. In 2009, Figueiro et al. recruited 12 subjects ages 50-80 years (mean ± SD = 59 ± 10 years) with no major health problems, eye disorders, or use of over-the-counter melatonin. In a within-subjects protocol, these subjects were exposed to high (53 ± 15.5 lux) and low (10.4 ± 2.6 lux) levels from light goggles peaking at 470nm for 90 minutes from 12:00 a.m. to 1:30 a.m. on two separate nights (Figueiro et al. 2008). During the exposure, subjects watched a movie projected 4 m away in a large dim room lit with red light emitting diodes. The measured illuminance from the room and movie was less than 5 lux. An in-dwelling catheter was used to collect blood at prescribed times, and saliva samples were also collected at prescribed times to study melatonin levels. Eleven subjects total completed the study. Using light goggles that employed dim, 470 nm short-wavelength light, Figueiro et al. significantly suppressed melatonin levels after both lighting interventions. Unlike Colenda et al. who could not produce significant results because of the light dosage or inefficiency of the apparatus, Figueiro et al. took advantage of the circadian system's sensitivity to short-wavelength light and specified a more effective lighting dose. Still, Figueiro et al. were only able to show results using a

healthy population. Thus, light visors/goggles may not be the best delivery method for ADRD patients, and an ideal light dose still must be developed for ADRD patients to optimize circadian entrainment.

2.5.3 Ambient lighting

Bright light therapy using ambient lighting is perhaps the most low-maintenance type of light therapy available. Because ambient lighting usually employs installed ceiling fixtures and emits higher light levels in an entire, supervision or restraint is not necessary for ADRD patients to receive light. One caveat is that the application may be expensive, requiring entire retrofits of one or several areas and higher energy costs. Further, lighting doses in past studies were not specified. Although ambient lighting seems to be the best light delivery application currently, advancement still needs to be made to define the ideal light dose.

One example of a successful ambient light study conducted by Van Someren et al. (1997). This study was conducted using ambient light from existing ceiling fixtures in three living rooms to consolidate the rest/activity cycles of ADRD patients. In their study, 29 severely demented patients were recruited, and 22 patients (15 female; mean ± SD ages 79 ± 2 years) completed the study. These 22 subjects were part of a repeated measures design study. The rest/activity cycles of all subjects were assessed for 5 days before, during, and after the light treatment using actigraphs. During the first baseline period, all subjects were exposed to 436 ± 90 lux of light at eye-level, provided by low-intensity Philips TLD18W fluorescent lamps installed. During the intervention period, all low-intensity fluorescent lamps were replaced with UV-filtered, higher-output Philips TLD32W fluorescent lamps producing 1136 ± 89 lux at the eye, and during the second baseline, subjects were exposed to 372 ± 65 lux at the eye. Light exposure during the first baseline did not statistically differ from the second baseline. For all three periods, the subjects were allowed to roam unsupervised in and out of the space. In general, none of the patients were in the living rooms between midnight and 6:00 a.m., and none of the patients were in bed between 9:00 a.m. and 9:00 p.m. The measured outcome variables of the experiment were IS, IV, and RA. Intervention IS was statistically higher than baseline values ($p=0.002$), and IV was statistically lower than baseline ($p=0.01$) indicat-

ing significantly better correlation between the rest/activity cycle during the intervention period (IS) and significantly decreased fragmentation of the rest/activity rhythm (IV). No significant difference was found between baseline and intervention RA. Van Someren et al. demonstrated that unsupervised ambient lighting can statistically consolidate the rest/activity cycle of ADRD patients. (It is important to note however, that these statistically significant values were only feasible with the exclusion of data from five subjects with visual impairment as these subjects did not show any statistically significant improvement from baseline measures.)

Another example of a successful ambient study was conducted by Riemersma-van der Lek et al. in 2008. This study was able to improve sleep, reduce depression, and maintain cognition and independence in ADRD patients using light (Riemersma-van der Lek et al. 2008). For 3.5 years (1999-2004), 189 ADRD residents in 12 group care facilities in the Netherlands took part in a double-blind, placebo controlled, 2x2 randomized trial with light and melatonin. For both the "light only" condition group and the "light and melatonin" groups, the light stimulus was delivered by installing a large number of ceiling mounted fixtures with Plexiglas diffusers containing Philips TLD 840 and 940 fluorescent lamps in the common living room. Lights were turned on daily from 9:00 a.m. to 6:00 p.m., and aimed to shine ±1000 lux at gaze direction. Actigraphs were worn, and standardized tests were used to measure the following outcome measures: MMSE for cognition, Cornell Scale for Depression in Dementia (CSDD) for mood, the Philadelphia Geriatric Centre Morale Scale (PGCMS) for self-esteem, Philadelphia Geriatric Centre Affect Rating Scale (PGCARS) for negative and positive moods, the Multi-Observational Scale for Elderly Subjects (MOSES) scale for withdrawn behaviors, Neuropsychiatric Inventory (NPI-Q) for the severity of psychopathological behaviors, Cohen-Mansfield Agitation Index (CMAI) for aggression, and Activities of Daily Living (ADL) for limitations on daily living activities. Results revealed that light significantly increased sleep, reduced depression, and maintained cognition and independence. Sleep duration was increased at a significance of $p=0.04$, and MMSE scores showed that light had a slightly positive effect on cognition, raising MMSE scores by a average of 0.9 ($p=0.04$), which indicates cognitive stabilization. Light also had a stabilization effect on the performance of activities of daily living, preventing the deterioration of remaining

independence in ADRD patients (p=0.003). Finally, light treatment ameliorated depression by 1.5 points on the CSDD (p=0.02), but had no effect on PGCARS, PGCMS, NPI-Q, or CMAI scores.

By far, ambient lighting is the best type of delivery method, as it does not involve supervision from caregivers; further, light therapy through this application also has been shown to improve independence, depression, and agitation in addition to sleep consolidation. Unfortunately, ambient lighting can also be expensive; therefore, in some cases, the application may still not be the most appropriate. And nonetheless, dose specification is still needed to advance bright light therapy.

2.5.4 Light as an ineffective method to consolidate sleep in ADRD

While many studies have validated the effectiveness of light to consolidate circadian rhythms and ameliorate various symptoms of ADRD, it is important to note that some studies also demonstrated that light was not able to produce such promising results. In 2005, Dowling et al. conducted a randomized, controlled design experiment to compare the effects of light, melatonin, and a combination of light and melatonin on the ability to improve circadian rhythmicity. Subjects received 1 hour of morning light exposure (>2,500 lux) at gaze direction for five consecutive days per week and 5 mg of melatonin or a placebo during the evening. Control subjects received usual indoor light only (150-200 lux). The variables measured using an actigraphy were nighttime sleep variables (activity), daytime sleep, daytime activity, day:night sleep ratio, and rest/activity parameters. The results demonstrated that only the light + melatonin group showed any significant improvement in strengthening the rest/activity rhythm (Dowling et al. 2008). Previous studies from Dowling et al. also verified that light exposure alone did not improve measures of circadian rhythmicity (Dowling et al. 2005; Dowling et al. 2005).

Repeated light box studies by Mishima et al. (1998) also failed to demonstrate that light consolidated ADRD patients. The repeated study exposed 12 subjects (six with clinical vascular dementia and six with clinical ADRD-type dementia) to two conditions of 300 lux and 5000-8000 lux of “bright light” from 9:00 a.m. to 11:00 a.m. every morning for 2 weeks in a cross-over study. Patients were seated alone in a reclining chair, while 18 full-spectrum fluorescent lamps were set in front and on either side of the

subjects' faces. Researchers monitored the subjects "every minute" to assure protocol compliance (Mishima, Hishikawa, and Okawa 1998). And data were collected using actigraph one week prior to the light intervention, for two weeks during the intervention, and one week post-intervention. Based on an actigraphy data, researchers found that both 300 lux and 5000-8000 lux of bright light therapy significantly consolidated sleep for vascular demented patients only. Even with the impracticality of caregivers monitoring individual patients in front of a lighting apparatus every morning, researchers were still unable to demonstrate that light consolidated rest/activity rhythms in ADRD.

It should also be noted that previously mentioned studies also disputed the ability of specified light exposure to consolidate sleep and activity or agitation. Colenda et al. did not find any statistically significant improvement of rest/activity cycles after their light goggle intervention, and Riemersma-van der Lek et al. (2008) did not find any significant decrease in agitation in a long-term 3-year study using ambient light.

All mentioned studies may have failed to show significant results because they did not record the 24-hour light exposure of the subjects, leaving room for outside interventions that may have disrupted circadian entrainment (See Figure 5).

2.6 Proposed 24-hour lighting scheme for older adults

In light of varying bright light therapy methods proposed by researchers, a recommended dose of lighting for the circadian system was proposed by the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute (RPI). This proposal considered the circadian response to light, user comfort, and energy efficiency for a lighting dose to consolidate the rest/activity cycle.

It should be noted that a 24-hour scheme is particularly emphasized because the circadian system is sensitive to the timing of the light. High circadian stimulation for the duration of the day is needed for good circadian stimulation during the day, and low circadian stimulation is needed at night to minimizes sleep disruption. Deviation from this generalized 24-hour scheme potentially risks increased sleep disruption as added light during the nighttime in particular might delay the circadian system (see section 2.3 and refer to Figure 5 for the circadian phase response curve).

The proposed 24-hour lighting scheme for older adults also takes into account the short-wavelength sensitivity of the human circadian system, timing of the lighting, and light level (Figueiro 2008). To maximally impact the circadian system, Figueiro suggests using energy-efficient fluorescent lights with high correlated color temperatures (CCT). A fluorescent solution was suggested because these sources are the most efficacious (emit the most light per Watt) at a low price-point. Higher CCTs (5,000+ K) are suggested because they tend to be bluish-white whereas lower CCTs (2,700-3,000 K) tend to be yellowish-white. The bluish-white hue of higher CCT light sources will more likely impact the circadian system as suggested by the circadian photoransduction model (Rea et al. 2011; Rea et al. 2005; Rea et al. 2010). These circadian effective lights should be used during the day and emit at least 400 lux at the cornea, and 100 lux of a lower CCT light source should be used during the evening (Figueiro 2008).

2.7 Dimesimeter

Given the absence of an ideal light dose for ADRD patients, one critical step to developing a dose is having the ability to measure the lighting intervention received by the ADRD patient to determine the amount of light received for a circadian response and rule out subjects not receiving light or not following protocol. For field studies, a data logger was developed for such reasons by the LRC at RPI in Troy, New York. The Dimesimeter is a 2-cm device mounted on a watchband that has the ability to record weighted light and activity data continuously for 7 days. (see Figure 10).

Figure 10: Watch-mounted Dimesimeter.

The device's microprocessor (Texas Instruments MSP430) allows the device to record data from an red/blue/green optical sensor array and an accelerometer, providing timing signals, performing calculations to process light and activity data and keep track of time relative to the time-stamped start log among other tasks. The optical sensor employs an infrared filter and an opal diffuser that shifts the red, green, and blue sensitivities to 595nm, 535nm, and 470nm respectively. The accuracy of the clock is typically ±20 parts per million (ppm), or a drift of less than ±2 seconds per day (Lighting Research Center 2011). The Dimesimeter is also reliable. When the spectral responses of three Dimesimeters were compared, the variation for a given channel was always less than 2.5% when normalized to the spectral peak (Lighting Research Center 2011).

2.8 Summary

The main *zeitgeber* of the circadian system is light, but varying characteristics of the light exposure such as spectrum, light levels, duration, timing, and photic history determine how light will affect the circadian system. As previously mentioned, varying combinations of these characteristics can be used to shift the circadian system. Whereas high light levels are effective, long durations of low-level, short-wavelength light can also reset the circadian rhythm in humans. Few studies however, have systematically narrowed down the most effective combinations of these characteristics that most efficiently shift the circadian system for ADRD patients. One recent solution that has been developed to computationally gauge the circadian efficaciousness of a given light source is the human phototransduction model by Rea et al. 2005. With the exception of duration and timing, the model can estimate CS values for light source spectra and light levels.

The model can be used to develop tailored lighting systems to create acceptable delivery methods considering ADRD users. Currently used applications include direct methods such as light boxes and light goggles/visors, which can be readily rejected by the patient and too time-consuming for caregivers to monitor compliance. Additionally, these direct methods cause glare since these solutions entail long periods of gazing directly into bright energy-consuming light sources. Current indirect methods are more practical, but also more expensive since they may require electrical building alterations,

which are impractical since lighting interventions do not always yield the desired results. A new method of light delivery with more efficacious light sources that deliver high circadian simulation needs to be developed for the ADRD population.

3. Objective and Hypothesis

3.1 Objective

The objective of this thesis is to develop an affordable, effective tailored lighting system that is sensitive to the comfort of the ADRD population. Using the human phototransduction model, an all day (6 a.m. to 6 p.m.), low light level (≥400 lux a eye-level as suggested by Figueiro et al. 2008), high CCT (9325 K) source was predicted to be adequate for shifting the circadian system. This light level was considered because most previous direct and indirect lighting interventions required a least 1000 lux a eye-level, but lower light levels may be more comfortable. To deliver the light, a novel floor-lamp type dose delivery application was developed with both direct and indirect lighting installation options for more variable luminaire placement. This delivery method was designed for its small footprint and variable application.

Finally, to determine if this application is successful, Dimesimeters were used to monitor the dose received by the ADRD subjects. Dose entails light levels, spectrum, timing, and duration of the light stimulus. Dimesimeters were specifically used because they are also calibrated to measure CL_A, and CL_A allows for the calculation of CS. However, since Dimesimeters are still fairly new, this experiment will also determine if Dimesimeters can be can be accepted by ADRD patients and their caregivers.

3.2 Hypotheses

1) The lighting intervention will significantly improve measures of rest/activity rhythm consolidation compared to baseline.

   a) Inter-daily repeatability (IR), the resemblance of activity patterns during individual days, will be significantly higher during the intervention than during baseline.

   b) Phasor analysis will show that phasor magnitude will be significantly higher than during baseline.

   c) The average activity of the 10 most active hours (M10) will be significantly higher during the intervention period than during baseline.

d) The average activity of the 5 least active hours (L5) will be significantly lower than during the intervention period than during baseline.

e) The relative amplitude of the circadian rhythm (RA) will be significantly higher during the intervention period than during baseline.

f) Activity during daytime will be significantly higher during the intervention period than during baseline.

2) The lighting intervention will significantly improve sleep quality and behavioral measures compared to baseline.

a) Pittsburgh Sleep Quality Index scores will be significantly lower during the intervention period, indicating better subjective sleep quality.

b) The Minimum Data Set-Activities of Daily Living Scale—Long Form (MDS-ADL) scores will be significantly lower during the intervention period than during baseline, indicating improved independence.

c) Cornell Scale for Depression in Dementia (CSDD) scores will be significantly lower during the intervention period, indicating decreased depression.

d) Cohen-Mansfield Aggression Index (CMAI) scores will be significantly lower during the intervention period, indicating decreased agitation.

3) ADRD patients and their caregivers will accept the Dimesimeter as confirmed through caregiver interviews and general observations during the experiment.

4. Pilot Study

A pilot study was conducted before the final experiment. This study lead to the addition of subject exclusion criteria, increased the compliance procedures in the methodology, changed the questionnaires, and re-scaled the independent variable in the final experiment.

4.1 Methodology

The pilot study was conducted from Hawthorne Ridge assisted living center in East Greenbush, New York. With the Institutional Review Board (IRB)'s approval of the experimental procedure, four female ADRD subjects were recruited Hawthorne Ridge. To be eligible, potential subjects had to have been diagnosed with mild to moderate ADRD, primary family members had to provide written consent, and agreement had to be obtained to release medication records to monitor changes in type and dosage of medication throughout the study. Since subjects were required to see light, exclusion criteria included obstructing cataracts, macular degeneration, and blindness.

Once recruited, a battery of tests was completed by primary caregivers on their own time prior to the intervention. These tests were used to assess baseline conditions and included the MMSE, the Pittsburgh Sleep Quality Index (PSQI) for subjective sleep quality, the MDS-ADLs for physical independence, and the CSDD for depression, and the Geriatric Depression Scale (GDS) also for depression. (Note: the CSDD is a questionnaire answered by primary caregivers about the patient, rating queries on a 1-3 scale, whereas the GDS is a yes/no questionnaire answered by the patient). Baseline and activity data were also collected in the manner of the final experiment with a Dimesimeter worn uncovered on a watch mount for 24 hours for 1 week. For all periods during which the Dimesimeter was required, caregivers were called at 2:00 p.m. every other day to check for Dimesimeter compliance. Afterwards, three to four custom, high CCT (9325 K) floor lamps were installed in each bedroom to provide an average of 400 lux at eye in accordance with the proposed 24-hour lighting scheme for older adults suggested by Figueiro (2008). The intervention light levels delivered were verified using a light meter and procedures from the final experiment. At the last week of the intervention period,

one more battery of tests was distributed and light and activity data were collected with a Dimesimeter. The pilot experiment was ended before the post-intervention phase.

The pilot study ended prematurely because preliminary data analyses comparing the baseline data with the intervention data showed that despite statistically increasing (p=.006) the light levels in the bedrooms (in gaze direction as determined by the chairs and beds), none of the data logging devices recorded a statistically significant (p=0.09) increase in light exposure. Interviews with the primary caregivers revealed that the subjects did not receive increased light because the facility primarily encouraged their residents to stay out of their bedrooms. This is consistent with our observations that the subjects were not in their bedrooms when the lighting intervention was installed or removed. Hence, the absence of a recorded increase in light and sleep consolidation during the intervention period for all subjects was likely due to the absence of the subjects' presence in their bedrooms. Figure 11 and Figure 12 illustrate the differences in illuminance levels between spot-measured values and Dimesimeter values:

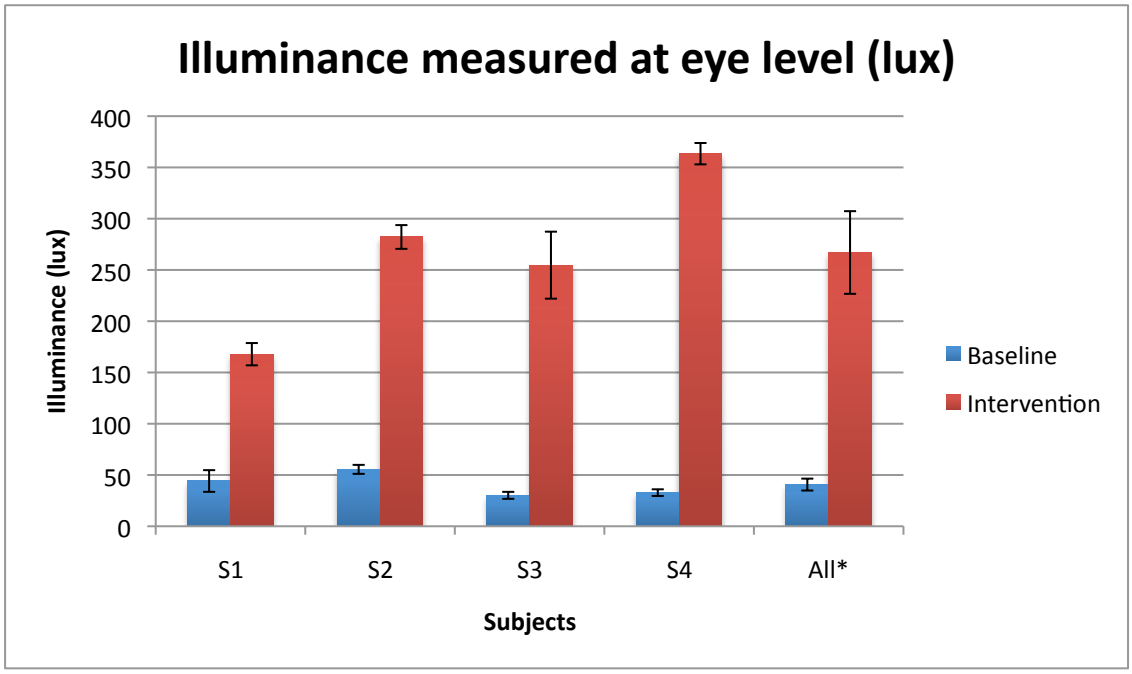


Figure 11: Intervention illuminance values measured by experimenters at eye-level were statistically higher than measured baseline values (p<0.05).

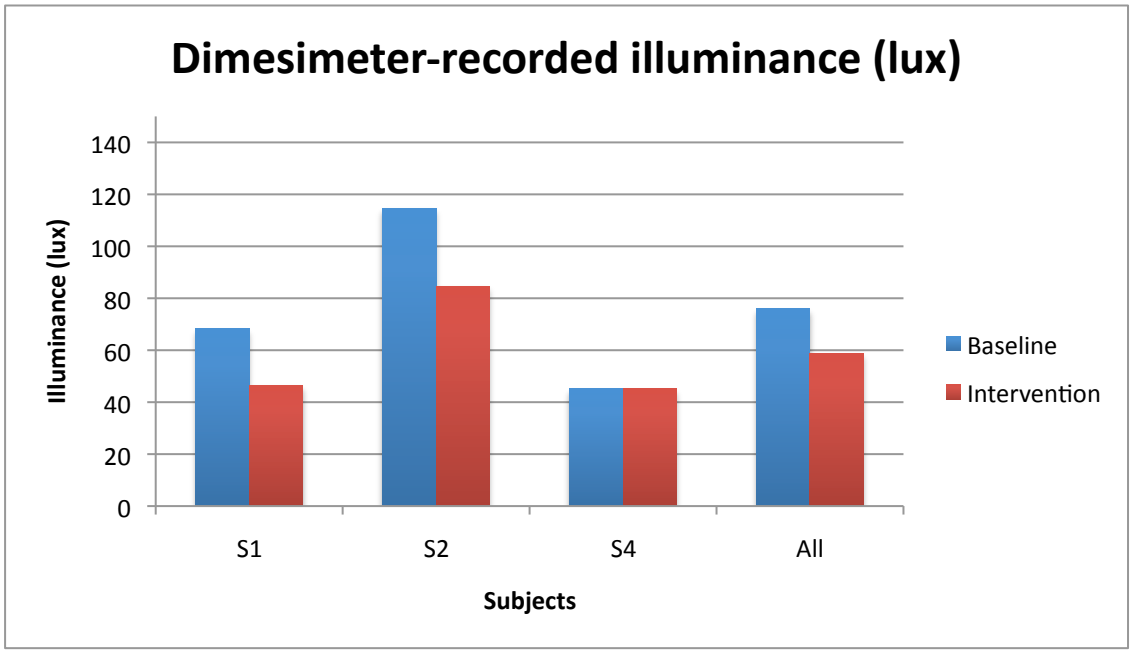


Figure 12: Intervention illuminance values recorded by the Dimesimeter were not statistically higher than measured baseline values (p=0.09). Subject 3 is not shown because the subject lost the data logger at the end of baseline data collection.

Due to the inherent need for subjects to receive a light intervention for this experiment, a prerequisite of "mainly staying in the bedroom" was added to the final experiment. Figure 12 illustrates the amount of light actually received by the subjects, as recorded by the Dimesimeter, during the baseline and intervention periods. Note that no significant differences were found between the baseline and intervention period. Consistent with these data, the difference in the measured inter-daily repeatability (IR) between the baseline and intervention period (representing sleep consolidation) was not statistically significant (Figure 13; see section 5.2.3.1.1 for full IR definition).

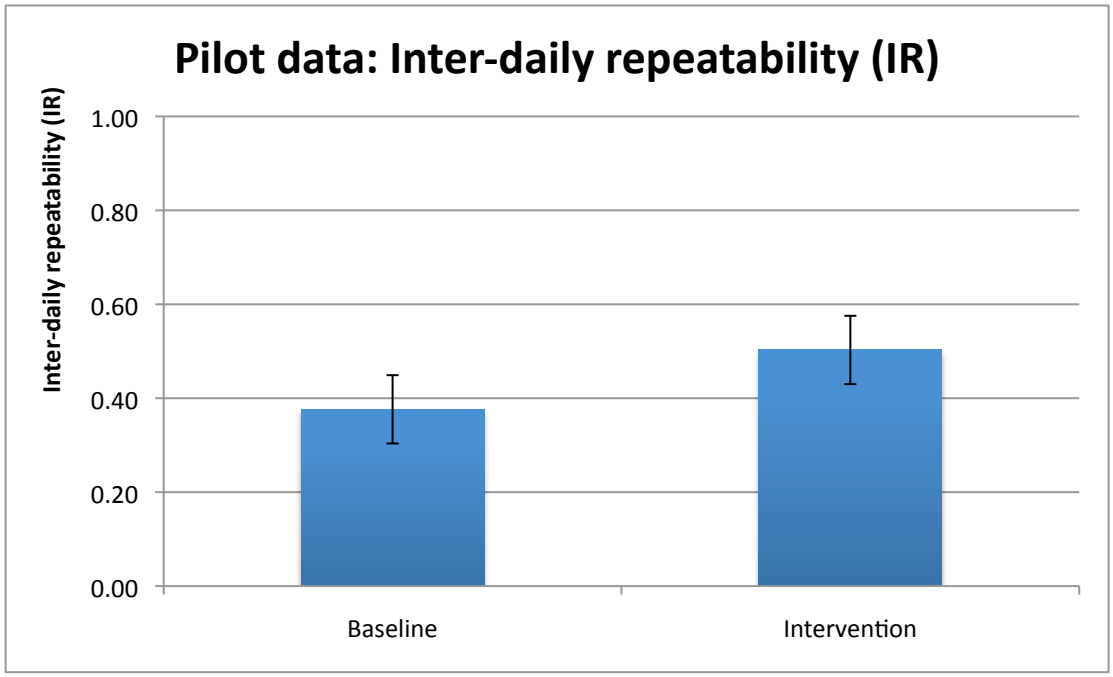


Figure 13: Inter-daily reliability indicates rest/activity consolidation. No statistical significance was found between baseline and intervention data ($p>0.05$).

Another challenge in the pilot study was ADRD patient Dimesimeter compliance. Although the primary caregivers were contacted by phone every other day at 2:00 p.m. to verify that subjects wore their Dimesimeters uncovered, large portions of data were still missing from the Dimesimeter records due to Dimesimeter misplacement or being covered by sleeves. Subject 3 lost his/her intervention period Dimesimeter just before data collection. Perhaps telephoning may not have been the best method of contact; often, the primary caregivers were not available and messages were unchecked. To increase Dimesimeter compliance in the final experiment, primary caregivers in the final experiment were emailed instead. This assured that they would receive the message at least sometime during the day. Due to transportation limitations and the length of time patients wore their Dimesimeters (168 consecutive hours), experimenters were unable to oversee Dimesimeter compliance.

Low compliance was also observed in questionnaire completion. The questionnaires were given to the caregivers to answer on their own time and return in a week. While the first set of tests were completed with no problems, the intervention set was never returned. In the final experiment, experimenters were required to stay with the primary caregivers while they completed all sets of questionnaires.

Changes were also made to the final questionnaires. GDS was removed due to redundancy and replaced by CMAI. GDS was removed due to redundancy. Both GDS and CSDD gauged depression, but a study that compared GDS to CSDD found that CSDD alone was equally valid on demented and non-demented subjects, whereas GDS only validly assessed demented subjects (Kørner et al. 2006) Due to its broader range, CSDD was retained while GDS was removed from the final questionnaire set. CMAI is an aggression questionnaire that was added at the request of the caretakers who were interested in the possibilities of light curbing aggressive behavior in dementia patients to ease workload. CMAI was chosen as it was considered the gold-standard for aggression assessment for demented elderly in nursing homes (Saliba and Buchana 2008).

Finally, additional guidelines were considered for choosing future rooms. The three to four luminaires used were not enough to add 400 lux of light at eye-level as intervention light levels were only 267.02 ± 80.64 lux during the intervention period compared to the average baseline illuminances of 40.66 ± 11.61 lux. The room size and furniture spacing of all four rooms did not allow for additional luminaires without compromising the space for medical equipment and safety. Since the fixtures themselves cannot be changed due to financial limitations and the goal of the hypothesis to use affordable, easy-to-install equipment reasonable for widespread application—the light level was lowered to "a minimum of 320 lux of additional 9325 K CCT light" in the final experiment. This value was obtained by averaging the intervention illuminances of Subjects 2 and 4 who utilized four luminaires. According to the CS function, exposure to the light source at 320 lux still resulted a CS of 0.46 at a 2.3 pupil diameter. Compared to the original baseline CS of 0.05, a CS of 0.46 should significantly increase circadian stimulation (Rea et al. 2010; Rea et al. 2011).

5. Methodology

5.1 Subjects

Recruitment was similar to the methodology of the pilot study. With the Institutional Review Board (IRB)'s approval of the experimental procedure, nine subjects (seven female) aged 82-92 (88 ± 5.4 years) were recruited from various assisted living facilities in New York's Albany and Rensselaer counties: Teresian House Center for the Elderly, and the Daughters of Sarah Senior Community. To be eligible, potential subjects must have been diagnosed with mild to moderate ADRD. Primary family members were required to give written consent. Primary caregivers were asked to confirm that the subjects mainly stayed in their bedrooms and to release medication records to monitor changes in medication type and dosage throughout the study. Since subjects were required to see light, exclusion criteria included obstructing cataracts, macular degeneration, and blindness. Out of the subjects accepted into the study, a total of five subjects (four female) completed the study. One subject withdrew from headaches induced by the lighting, one withdrew after health complications from an unrelated fall, one subject could not keep the Dimesimeter on, and the last subject disliked the lighting intervention.

5.1.1 Mini-Mental State Exam (MMSE)

Subjects also had to meet mild to moderate ADRD criteria assigned by completing an MMSE, a short mental status exam evaluating the severity of cognitive impairment (Folstein and Folstein 1975). Administered by a clinician, the MMSE is an 11-question test divided into two sections. The first section requires vocal responses only, covering orientation, memory, and attention, totaling 21 points. The second portion totaling 9 points, gauges the ability to name, follow verbal and written commands, write a sentence spontaneously, and copy a complex polygon developed to test visual-motor skills. In a 69-sample experiment confirming the validity of this exam, the test successfully separated the subjects into three diagnostic groups: dementia, depression, and cognitive (Folstein and Folstein 1975). The reliability of the test was confirmed by a Person coefficient of 0.887 when comparing the variability between the initial test scores by the 69 subjects sample and a second test administered 24-hours later by the same clinician;

none of the scores significantly changed (Folstein and Folstein 1975). Another study summarizing 26 years regarding the psychometric properties and utility of the MMSE defined the following cut-off ranges for cognitive classification as follows: 24–30 = no cognitive impairment; 18–23 = mild cognitive impairment; and 0–17 = severe cognitive impairment (Folstein and Folstein 1975). For the present study, the inclusion criterion was a score ranging from 18–23 indicating mild to moderate ADRD.

5.1.2 Brief Interview for Mental Status (BIMS)

In residences where MMSE score were unattainable due to facility policy, BIMS scores were obtained from the primary caregivers. Administered by a clinician, the BIMS is a brief questionnaire containing only memory and orientation queries to assess cognitive function, and delirium (Chodosh et al. 2008). Unlike the MMSE, the BIMS gives partial credit to answers close to correct answers with a score of 0 indicating an absolutely incorrect answer, 1 or 2 for partially correct answers, and 3 for absolutely correct answers. The range of answers constituting as "partially correct" varies between questions. A global score can range between 0–15 where 13–15 = cognitively intact, 8–12 = moderately impaired, and 0–7 = severely impaired. No published study currently compares the BIMS to the MMSE, but in a validation study comparing the BIMS to the Modified Mini-Mental State Exam (3MS), an alternative version of the MMSE, the BIMS administered by nurses yielded a 0.73 correlation to the 3MS, denoting a fair correlation between the two tests in assessing cognitive ability (Chodosh et al. 2008; Alexopoulos et al. 1988). Further, in a study comparing the validity of the MMSE and 3MS to correlate with neuropsychological assessments, both tests adequately and reliably detected cognitive impairment in patients with stroke; however, 3MS was more sensitive (Grace et al. 1995). For the present study, the BIMS inclusion criterion was a score of 8–12. Note: due to a lack of subjects, Subject 7 was also included in this study even though his/her BIM score was 7.

Table 1: Subject profiles.

Subject	DOB	Age	M/F	MMSE	BIM	Baseline	Intervention
S5	1/23/30	82	M		10	3/5/12	3/12/12
S7	2/6/26	86	F		7	4/9/12	4/16/12
S8	12/9/20	91	F		9	5/21/12	5/30/12
S10	8/4/20	91	F	8		7/2/12	7/9/12
S11	4/28/20	92	F	9		7/2/12	7/9/12

5.2 Experimental Setup

5.2.1 Independent variable

5.2.1.1 Novel luminaires

Two novel luminaire types were constructed for this experiment. Funding for these luminaires was acquired through a grant awarded to the Lighting Research Center from the National Institute of Aging. All the lamps were provided as donations from Mary Beth Gotti of General Electric. Both luminaires were designed and constructed in the photometry lab and the health lab at the LRC.

Although two luminaire types were used in this experiment, both were considered the same variable because both used the same lamps, thus they had the same SPD. SPDs provide visual profiles of the color characteristics of a light source by showing the radiant power emitted by the source at each wavelength over the visible region (380 nm to 760 nm). This is relevant because the circadian system is more sensitive to SPDs with more short-wavelength content than SPDs with less short-wavelength content. (Refer to section 2.2.1.2.2). Using the same lamps in either luminaire type constructed for this experiment did not change the SPD of the lamps; therefore, they can both be considered as the same independent variable. This was verified in the photometry lab at the LRC at RPI using the PR-705 SpectraScan (calibrated 2012) to compare the SPDs of both fixtures; the SPDs between the two fixtures were not significantly different.

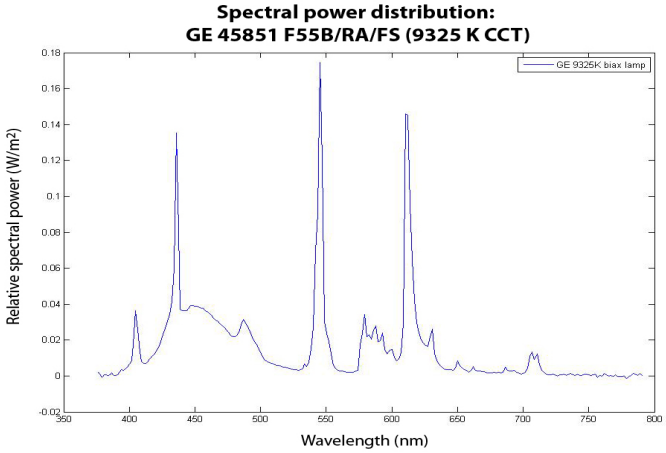


Figure 14: Spectral power distribution (SPD) of the 9325K GE 45851 F55BX/AR/FS lamp.

To further assure the consistency of the lamp performance, all lamps were seasoned at least 100 hours at full output in compliance to the National Electrical Manufactures Association (NEMA) LSD-23-2010. This process clears residual manufacturer impurities within new lamps that cause flicker (NEMA 2010).

5.2.1.1.1 Novel luminaire version 1 (NL1)

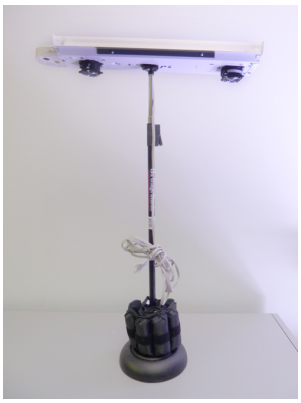
A)  B) 

Figure 15: Fixtures were hinged to a microphone stand for versatility. A) Horizontal position. B) Vertical position.

Subjects 5 and 7 used the NL1s. These luminaires were constructed by retrofitting Utilitech low profile fluorescent wrap fixtures (model #PLW217R8) with two GE 45851 F55BX/AR/FS fluorescent lamps each. Since the fixtures originally used two single pin florescent lamps, all ballasts and sockets were replaced by GE F40/30BX/2G11 ballasts and Leviton 660W/600V biax sockets.

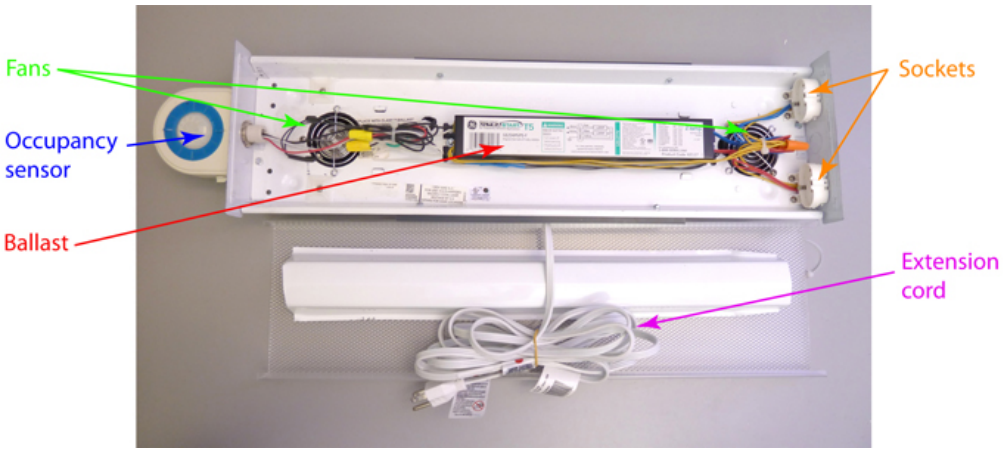


Figure 16: Retrofitted NL1 interior.

Originally not Underwriters Laboratories (UL) rated for biax lamps, additional features were added to avoid overheating. Two Digi-Key 115V 60x30 2600RPM axial fans were installed per fixture for temperature control. To control the timing of the lighting stimulus and conserve energy, all luminaires were plugged into a GE 15079v2 SunSmart Digital Timer or Woods TD2200A Digital Timer. This timer automatically turned all luminaires on at 6:00 a.m. in the morning and off at 6:00 p.m. at night for all subjects. During the day when the luminaires were turned on, an additional layer of control was added by installing a Leviton infrared occupancy sensor (OSFHU-ITW) directly onto each luminaire, automatically turning the lamps off after 20 minutes of no motion and on when movement was detected. Finally, an extension cord was attached through a strain release for assess to a standard 120V wall power supply. The completed luminaire was hinged on a 34” 9.6lb microphone stand with a quick release to optionally extend the pole to 62.” During use, two 5lb sandbag weights from Gold’s Gym were also wrapped around the base to prevent the top-heavy luminaire from falling.

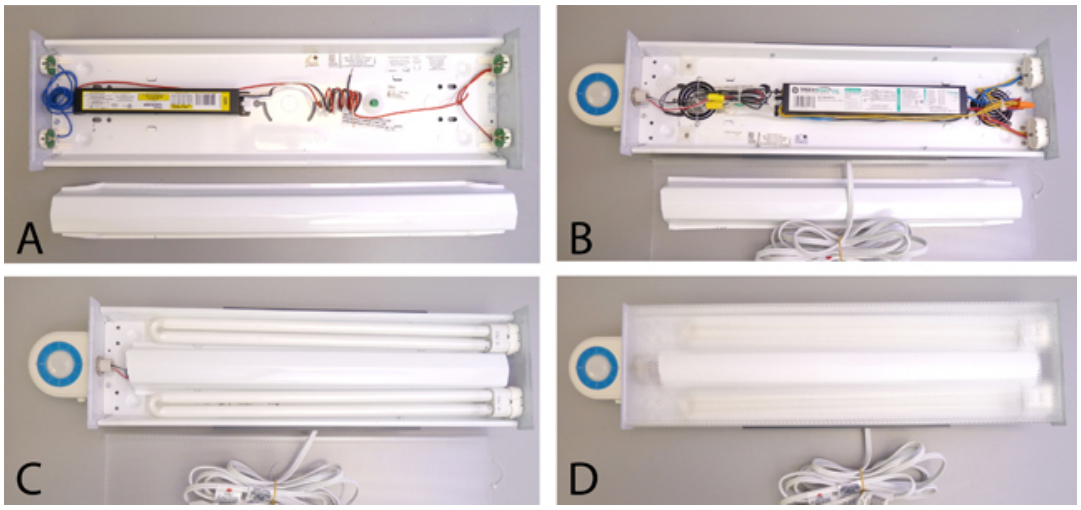


Figure 17: NL1 floor lamp construction from original to finished fixture head.

5.2.1.1.2 Novel luminaire version 2 (NL2)

Unlike NL1, the fixture head for NL2 was originally UL rated for two biax lamps (Elco Lighting, ETC 454, Line Voltage T5 Fluorescent Wall Washer); therefore the only electrical retrofits made to the fixture was installing the same Leviton infrared occupancy sensor and the extension cord as NL1. Otherwise, the fixture was also hinged on the same microphone stand with two additional 5lb sandbags for stability. Advantages of using this fixture included a more flexible head, which could tilt independently from the microphone stand, and more reliability.

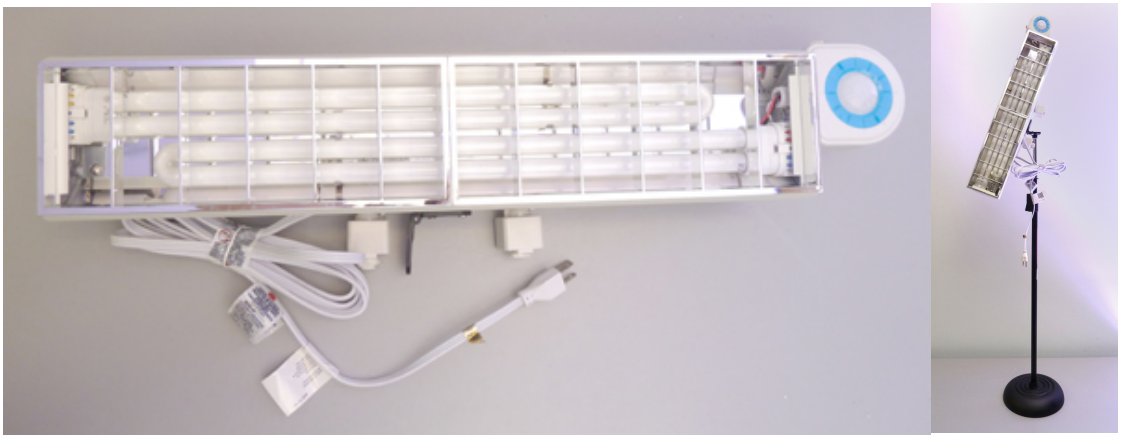


Figure 18: NL2 fixture head and completed luminaire.

5.2.1.1 Experimental lighting condition

The independent variable for this experiment was the following lighting scheme: increasing the ambient illuminance at the eye by a minimum of 320 lux from 6:00 a.m. to 6:00 p.m. every day in the bedroom with 9325 K CCT novel luminaires, and reducing light levels to baseline nighttime values with 2700 K CCT after 6:00 p.m. 320 lux was chosen because it was the average illuminance at the eye achieved in the pilot study using four novel luminaires. As previously described, the four luminaires were the maximum amount of floor lamps that could fit in subjects' rooms before safety was jeopardized; funds and the goal of the hypothesis for an affordable solution also limited the luminaire design from becoming smaller or more architecturally integrated. To provide 320 lux, four 9325K CCT novel luminaires were introduced into the subjects' bedrooms. According to calculations, this additional stimulation alone—excluding existing lighting— should provide a CS of 0.46 at a 2.3-mm pupil size for one hour (Rea et al. 2011).

5.2.2 Independent variable outcome parameters

To verify that the intervention lighting was providing the intended stimulus of at least 320 lux at 9325 CCT, illuminance, CL_A and CS were all spot-measured on site with an illuminance meter and recorded 24 hours a day for 1 week with a Dimesimeter.

5.2.2.1 Spot measurements

Spot measurements describe the light levels (lux) measured at eye-level (vertical) and at wrist-level (horizontal) of the subject at various resting areas frequented in the subject's bedroom (bed and chairs) to determine the baseline and intervention illuminances of the experiment. These measurements were then converted into CL_A and CS for comparison. The Photometer SN2340M-0 calibrated June 2010 was used to measure all baseline and intervention illuminances.

5.2.2.2 Dimesimeter data

All subjects wore Dimesimeters for 1 week during baseline and 1 week during the intervention period (see Table 1). Once the Dimesimeters were retrieved from the

subjects at the end of each week, they were returned to the LRC and placed on an external mounting device where a software client downloaded the data, and a separate software post processed the data and derived data sets of log time, photopic illuminance (lux), CL_A, CS, and activity (Rea et al. 2010).

5.2.3 Dependent variable outcome parameters

The dependent variables in this experiment are the rest/activity consolidation, sleep quality, and behavior parameters calculated with Dimesimeter data and the responses from the questionnaires competed for this experiment. The parameters calculated using Dimesimeter data are IR, phasor magnitude, phasor angle, M10, L5, RA and sleep quality. All sets of questionnaires used include the PSQI, MDS-ADL Long Form, CSDD, and CMAI. The following are descriptions of the dependent variables separated into the following two categories: 1) rest/activity consolidation and 2) sleep quality and behavior.

5.2.3.1 Rest/activity consolidation

Outcome measures within this category were used to gauge the statistical significance of the changes in the rest/activity rhythms of the subjects.

5.2.3.1.1 Inter-daily repeatability (IR)

Inter-daily repeatability (IR) is a metric that approximates the percent of variance of a "typical" 24-hour daily pattern to the activity data. This metric was used to determine the regularity of the activity patterns. In IR, the first 96 terms with an integral number of cycles per day (i.e., 1 cycle per day, 2 cycles per day, etc.) are fit to the data, and these fits are then summed to make an approximate 24-hour profile as follows

$$IR = \frac{\sigma Activityfit}{\sigma Activitydata}. \tag{1.6}$$

In this equation, *Activity fit* is defined as:

$$M + \sum_{i-1}^{N} AI \times cos(2 \times i \times \pi \times time + \varphi i). \tag{1.7}$$

M is the offset, A is the amplitude, φ is the phase, and N is 96. This profile is then compared with the data, and the r^2 value is the IR value. The closer the result is to 1 on a 0-1 scale, the better the activity data "fits" to the 24-hour cosine curve.

It should be noted that when using complete data sets, IR is analogous to inter-daily stability (IS), another circadian variance assessment method (Someren et al. 1997). IR was used in place of IS because this metric would work with gaps of missing data from the Dimesimeter logs, did not require that the number of days be an integer, and did not require a constant sampling rate. (Hamner 2010).

5.2.3.1.2 Phasor Magnitude

The collected light and activity data sets from the Dimesimeters were analyzed using phasors. Phasors represent the correlation and phase relationship between the activity-rest data and the 24-hour light-dark cycle (Rea et al. 2008).

Phasor magnitude is the length of the phasor, representing the relative strength of the 24-hour components of the light-dark and rest/activity patterns; magnitude is calculated by correlating the 24-hour light and activity data with the 24-hour light activity cosine fit:

$$|phasor| = \frac{\sqrt{2}A_{Activity}A_{Light}}{\sigma_{Activity}\sigma_{Light}} = \frac{\sigma_{Activityfit}\sigma_{Lightfit}}{\sigma_{Activity}\sigma_{Light}}. \qquad (1.8)$$

Here, A_{Light} and $A_{Activity}$ are the amplitudes of the 24-hour period least-squares cosine curve fits for the activity and light time series. $\sigma_{Activity}$ and σ_{Light} are the SDs of the light and activity curves. Phasor magnitude is the ratio of the product of the 24-hour variance over the product of the total variance of the Activity and Light data.

Ideally, the closer the phasor magnitude is to 1, the closer the data corresponds to the 24-hour light activity cosine fit; however given that the data are non-sinusoidal, a phasor magnitude of 1 is difficult to achieve. Using data sets, one study demonstrated that the average, minimum, and maximum phasor magnitude of Alzheimer's patients were 0.30, 0.40, and 0.62 respectively (Lighting Research Center 2011). Comparatively, the calculated average, minimum, and max phasor magnitudes of healthy adults >65 year-old and healthy caregivers are 0.40, 0.25, and 0.55 and 0.42, 0.26, and 0.54 respectively (Lighting Research Center 2011).

5.2.3.1.3 Average of 10 most active (M10)

M10 describes the most active period of the day by averaging the activity during the 10 hours of highest activity (Witting et al. 1990). M10 is an adequate approximation of amplitude of the 24-hour circadian activity cycle (Witting et al. 1990).

5.2.3.1.4 Average of 5 least active (L5)

L5 is the average of the 5 least active hours in the 24-hour activity profile (Witting et al. 1990). This measure indicates the nadir of activity rhythm and is sensitive to nighttime arousals. Lower relative values correspond to more restful and regular sleep patterns.

5.2.3.1.5 Relative amplitude (RA)

The RA represents the stability of sleep consolidation (Van Someren et al. 1997). The amplitude is calculated as the difference between M10 and L5 divided by the sum of M10 and L5 (Van Someren et al. 1997; Witting et al. 1990).

$$RA = \frac{M10 - L5}{M10 + L5}. \tag{1.9}$$

Higher values indicate more sleep consolidation.

5.2.3.1.6 Activity

Activity is simply the overall 24-hour activity data recorded with the Dimesimeter. Higher values may indicate sleep consolidation as well rested patients may be more active during the day.

5.2.3.1 Sleep quality and behavior parameters

Outcome measures within this category were used to gauge the statistical significance of the changes in sleep quality, independence, depression, and agitation in subjects between baseline and intervention periods of the study. The PSQI measure sleep quality, the MDS-ADL measures independence, the CSDD measures depression, and the CMAI measures agitation.

5.2.3.1.1 Pittsburgh Sleep Quality Index (PSQI)

The PSQI consists of 19 self-rated questions and five questions rated by a primary caregiver (Buysse et al. 1988). Note that for this experiment, primary caregivers also completed the self-rated 19 questions due to the subjects' ADRD conditions. The 19 self-rated questions assess sleep quality and include estimates of sleep duration, latency, frequency and the severity of specific sleep-related problems. Once rated, these 19 items are grouped into seven component scores and weighted equally on a 0-3 scale, culminating in a global score ranging from 0-21. A score of ≥5 has a diagnostic sensitivity of 89.6% and a specificity of 86.5% in distinguishing good and poor sleepers (Buysse et al. 1988).

5.2.3.1.2 Minimum Data Set-Activities of Daily Living Scale–Long Form (MDS-ADL Long Form)

The MDS-ADL Long Form is an assessment test administered by a clinician to gauge the ability of nursing home residents to independently perform seven basic everyday personal care activities over a period of 7 days: dressing, personal hygiene (i.e., brushing teeth, makeup, shaving etc), toilet use, locomotion on unit (i.e., walking or on a wheelchair), transfer (i.e., moving from bed to chair), bed mobility (i.e., positioning in bed), and eating **(**Morris, Fries, and Morris 1999). Performances are rated on a number scale where 0 = independent, 1 = supervision, 2 = limited assistance, 3 = extensive assistance, 4 = total assistance, and 8 = activity did not occur in 7 days. Compared to the current three principal summary MDS-ADL scales available, MDS-ADL Long Form is most sensitive to minor, incremental changes (Morris, Fries, and Morris 1999). The MDS-ADL Long Form scale detects clinically meaningful changes in the physical function of nursing home residents with moderate to severe dementia (Carpenter et al. 2006). Recent studies also suggest that this test may indicate the severity of dementia where a score of 10 or more indicates severe dementia (van der Steen et al. 2006).

5.2.3.1.3 Cornell Scale for Depression in Dementia (CSDD)

The CSDD is a 19-item, clinician-administered questionnaire using information from both patients and primary caregivers to gauge the prevalence of depression in dementia subjects one week prior to using the scale (Alexopoulos et al. 1988). The 19

items include anxiety, sadness, lack of reactivity to pleasant events, irritability, agitation, retardation (i.e., slowed moments, speech, reaction), multiple physical complaints, acute loss of interest (i.e., for hobbies), appetite loss, weight loss, lack of energy, diurnal variation of mood (timed agitation), difficulty falling asleep, multiple awakenings during sleep, early morning awakenings, suicide, self-depreciation, pessimism, and mood congruent delusions (i.e., delusions of poverty, illness, or loss). These items are rated on a 0-2 severity scale where 0 = absent, 1 = mild or intermittent, and 2 = severe. The sum of these scores indicate the rater's impression of the depression where <6 = an absence of significant depressive symptoms, >10 = probably major depression and scores >18 = definite major depression. This questionnaire has a high inter-rater reliability of 0.67, an internal consistency of 0.84, and sensitivity indicating its validity as a reliable tool (Alexopoulos et al. 1998).

5.2.3.1.4 Cohen-Mansfield Aggression Index (CMAI)

The CMAI uses 29 items to assess the frequency of agitated behaviors in elderly persons on a 7-point scale (Cohen-Mansfield, Marx, and Rosenthal 1989). Several of these items include pacing and aimless wandering, inappropriate dressing or disrobing, spitting, cursing or verbal aggression, repetitive sentences or questions, and hitting. Clinicians interview primary caregivers about their AD patients and rate these items as follows in accordance their responses: 1 = Never, 2 = Less than once a week but still occurring, 3 = Once or twice a week, 4 = Several times a week, 5 = Once or twice a day, 6 = several times a day, and 7 = Several times an hour. Overall CMAI scores can range from 0-203 where higher values indicate higher frequencies of aggressive behavior. Based on cross-sectional and longitudinal analyses, evidence suggests that CMAI adequately describes the overall level of behavioral agitation in community-dwelling persons with ADRD using a summed CMAI score (Weiner et al. 2001). The test and re-test ability of the CMAI is also reliable for monitoring the frequency of manifested agitation in ADRD patients (Koss et al. 1997).

5.2.3.2 Reason for the dependent outcome variables

Noticeably, this experiment utilizes many dependent variables to determine whether or not the circadian tailored lighting will improve the quality of life in general for ADRD patients. The rest/activity consolidation parameter list is particularly long. The experimenter realizes that using many parameters may not be experimentally favorable since the instance of one significant result out of the group does not necessarily indicate statistical significance; however, this method was chosen regardless. One reason in for this decision was the small sample size. Still, if more than one rest/activity parameter reaches statistical significance in a small sample size, the statistical significance of the outcome becomes more powerful.

5.3 Procedure

The experiment lasted 6 weeks per subject between the end of November 2011 to the beginning of July 2012. For each experimental trial, week 1 was a period of baseline data collection. Primary caregivers were asked separately from the subjects to complete a battery of pre-assessment tests for the subjects. Tests included the PSQI, MDS-ADL Long Form, the CSDD, and the CMAI. In addition to the questionnaires, a watch-type Dimesimeter was also attached to the subject's wrist of choice for one week of activity and light data collection. Both the subjects and their primary caregivers were instructed to keep the Dimesimeter attached to the subject's wrist for 24 hours with the exception of during showers. Caregivers were also specifically instructed to keep the device uncovered. Once attached, the time of Dimesimeter attachment was recorded to ensure at least one full week of data collection by the following week, and primary caregivers were emailed every other day to maintain compliance to the Dimesimeter protocol.

Week 2 marked the intervention period when the Dimesimeter from the previous week was retrieved and the lighting intervention was installed for 4 weeks from the beginning of week 2 to the end of week 5. Installation included bringing the luminaires inside the bedroom, plugging them into a preset timer via an extension cord or power strip, and plugging the power into a 120V wall socket. When no space was available, the fixture heads were changed into the vertical position. All illuminance measurements were taken with the Gigahertz-Optik X91 Photometer SN2340M-0 calibrated June 2010.

Vertical baseline and intervention illuminance measurements were taken from the eye-level seated on the bed and the reclining chairs gazing to the television, window, and door (as applicable). Horizontal illuminance measurements were taken on the bed plane and on either side of the reclining chair's armrests. Once the luminaires were plugged in, experimenters adjusted the pole height and directed the light distribution of the luminaires to best provide the highest illuminance levels at known resting areas such as the bed and reclining chair. Effort was also made to keep the luminaires against the wall as not to obstruct equipment, furniture, or movement (Figure 19A). Luminaires posted on either side of the main reclining chair were positioned behind the chair, angled towards each other to reduce glare (Figure 19B). Most other luminaires were faced up to provide ambient up-lighting.

A  B 

Figure 19: A) Fixtures were positioned against the wall horizontally to face the ceiling or vertically to face into the room. B) Luminaires were positioned behind the main reclining chair on either side and angled towards the subject.

At the beginning of week 5 of the intervention period, another Dimesimeter was deployed to the subject on the same wrist previously used to record light and activity, and a second set of assessment questionnaires were also completed by primary caregivers at the end of week 5. At the beginning of week 6, the Dimesimeters were retrieved, and the light intervention was removed.

Table 2: Experimental schedule by week.

	W1	W2	W3	W4	W5	W6
Baseline (B.) Assessment tests						
B. Dimesimeter data collection						
Intervention (I.)						
I. Dimesimeter data collection						
I. Assessment tests						
Intervention removed						

6. Results

This section outlines the processes used to analyze collected data, and the results derived from the data. The data are organized to first analyze the ability of the luminaire to provide the lighting intervention by examining spot-measured illuminance values, the CL_A and CS from these measured values, Dimesimeter-recorded illuminance, Dimesimeter recorded CL_A and Dimesimeter recorded CS. Afterwards, the results are organized by the hypotheses where the ability of the lighting intervention to consolidate the rest/activity cycle using IR, phasor magnitude, M10, L5, RA, and activity will be assessed first. And finally, PSQI scores, MDS-ADL scores, CSDD scores, and CMAI scores will be examined to see if the lighting intervention significantly improved sleep quality measures compared to baseline. Since the lighting intervention was predicted to improve sleep and consolidate rest/activity patterns, one-tailed Student's t-tests were used to determine the significance between baseline and intervention conditions. Medians were also examined in addition to averages in Dimesimeter light output data in order to exclude outlier data, which may skew averages. To compare baseline and intervention median values of any applicable parameter, the non-parametric Wilcoxon sign-rank test was used for its statistical strength.

All Dimesimeter data were processed using the mathematical software program MATLAB from MathWorks®. It is important to note that all the calculated Dimesimeter statistics shown in this section have been derived from the same set of altered data. Since several Dimesimeter recordings indicated time slots where the Dimesimeter was removed from the subjects' wrists, areas of missing data were removed from the data analysis. These areas were identifiable by a period of 10 minutes or more of "flat-line" activity of ≤0.2. Table 2 shows the amount of Dimesimeter data omitted per subject per baseline and intervention period:

Table 3: Percent of Dimesimeter data omitted during the data analysis.

Percent of Dimesimeter data omitted		
Subjects	Baseline	Intervention
S5	4.56	10.04
S7	28.90	35.14
S8	41.50	10.20
S10	0.00	0.00
S11	49.71	0.00

6.1 Measured light levels

Statistics comparing baseline values to intervention values were performed on both spot-measured and Dimesimeter-recorded intervention illuminance, CL_A, and CS values to ensure that intervention light doses were received.

6.1.1 Spot measured illuminance values

As stated in the "Methods" section, the baseline and intervention illuminance values of the bedroom were spot-measured before and after the lighting intervention by using an illuminance meter. Eye-level illuminances (EI) were measured to determine the amount of light reaching the cornea, and wrist-level illuminances (WI) were measured as references for the wrist-mounted Dimesimeter readings.

The average baseline EI for all subjects was 139.95 ± 210.67 lux and average intervention illuminance was 505.42 ± 266.19 lux. Note that the SD of EI baseline is higher than the average because Subject 7 had significantly higher illuminance levels in his/her room than the other subjects due to a large window. For example, the median baseline and intervention EI values are 63.00 lux and 494.17 lux respectively. A one-tailed Student's t-test between the mean baseline and intervention values determined that the intervention illuminances were statistically greater than baseline values ($p=0.01$). Figure 20 shows the comparison of EI baseline illuminances and intervention illuminances.

The statistical analysis performed on EI data was repeated with WI values. The average WI for all subjects was 188.79 ± 308.38 lux and average intervention illuminances was 718.07 ± 438.92 lux. Intervention WI was also statistically higher than baseline values ($p=0.001$). These results indicate that the lighting intervention indeed statistically provided higher illuminances than baseline values at eye- and wrist-levels. Figure 21 represents the comparison between baseline and intervention WI illuminances.

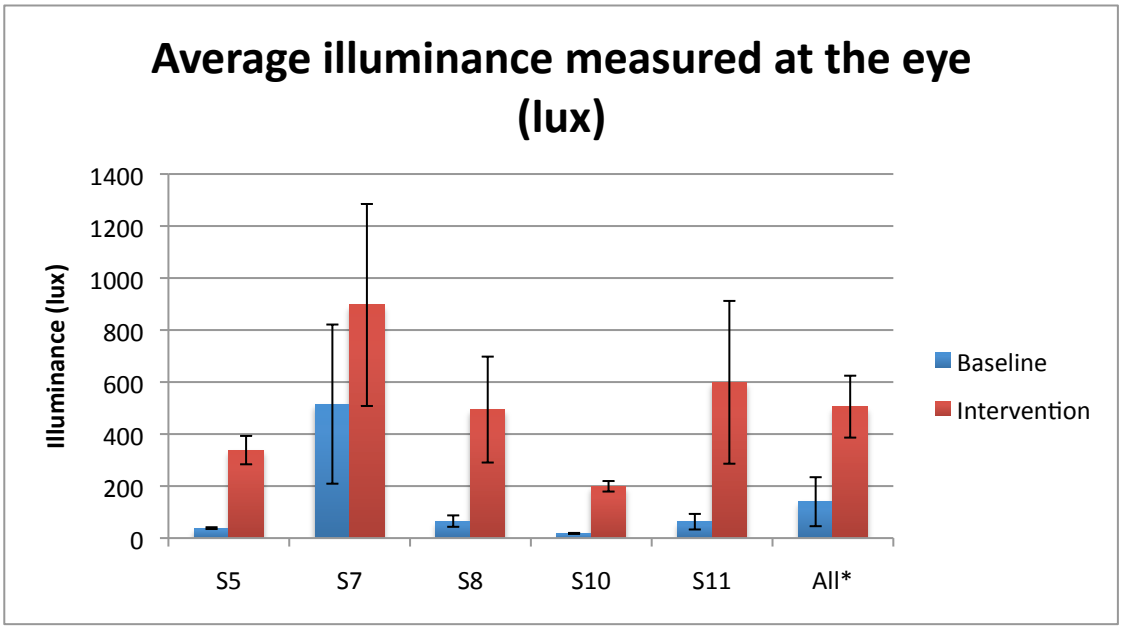


Figure 20: Comparison of average illuminances (lux) at the eye. Average intervention period illuminance was statistically higher than the average baseline value (p=0.01)*

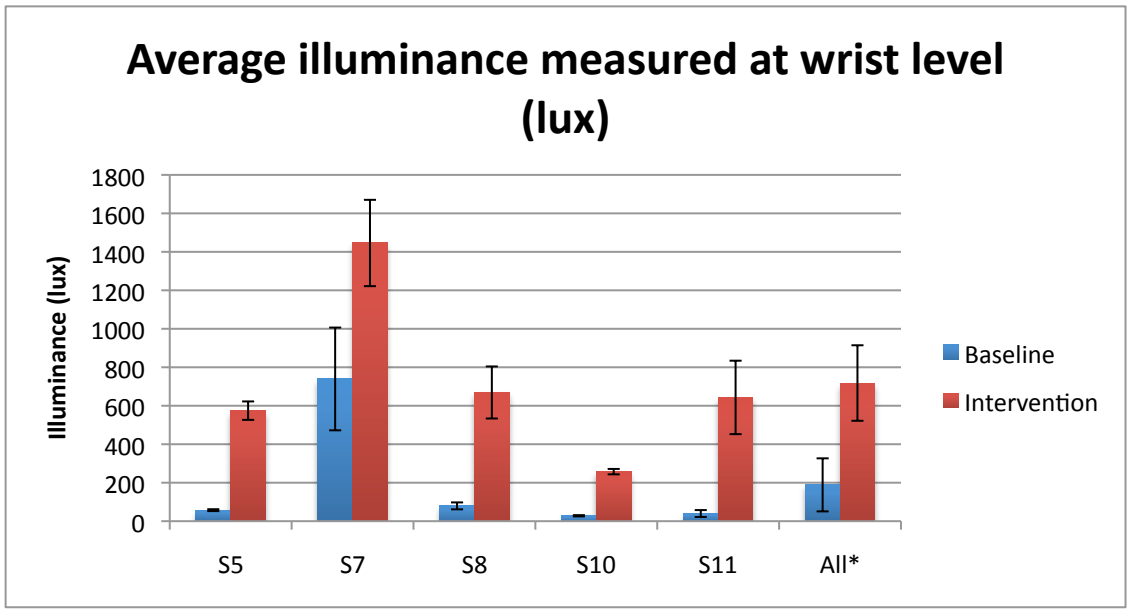


Figure 21: Comparison of average illuminances (lux) at the wrist. Average intervention period illuminance was statistically higher than the average baseline value (p=0.001)*.

Intervention EI and WI were also compared since wrist-level Dimesimeters would be used to record light levels after initial eye-level measurements. Figure 22 represents the comparison between eye and wrist illuminance measurements. WI intervention light

values were statistically higher than EI values (p=0.04), indicating that the Dimesimeter measurements should overestimate eye-level illuminance measurements. Additionally, a ratio between the intervention EI "All (subjects)" value and the intervention WI "All (subjects)" value was calculated to gauge the relationship between the two. WI is roughly 35% greater than EI.

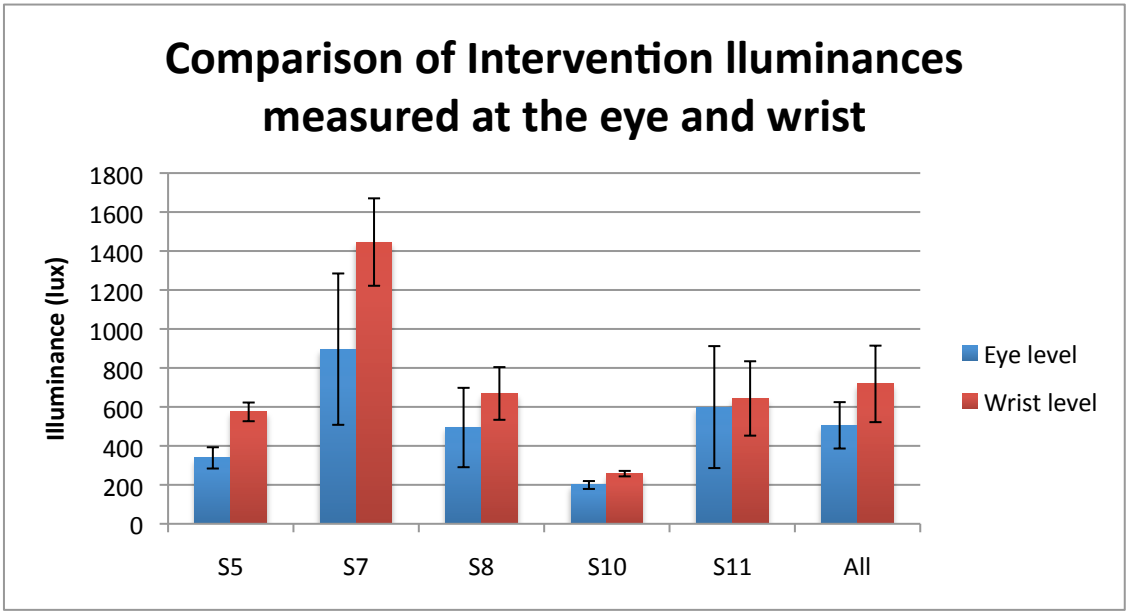


Figure 22: Comparison of average intervention illuminances (lux) at the eye and wrist. Average intervention period wrist illuminance was statistically higher than the intervention eye-level values (p=0.04)*.

6.1.2 Spot measured CL_A values

The baseline and intervention CL_A values of both eye and wrist spot measurements were derived using the human circadian phototransduction model by Rea et al. (Rea et al. 2005; Rea et al. 2011; Rea et al. 2010). This formula was inserted into the MATLAB program where illuminance (lux), pupil diameter, and the SPD of the light stimulus were used to derive CL_A. The parameters used to produce baseline CL_A results were the average of all baseline illuminances for all subjects, an assumed 2.3 mm pupil diameter, and the SPD of a standard 5000 K fluorescent lamp. A 2.3 mm pupil was assumed because it is the most conservative pupil size for older adults. Since the actual SPDs used in the lighting for each subject could not be physically measured, a 5000 K standard fluorescent SPD was used as a "catch-all" SPD to consider the mix of sources including incandescent, fluorescent, and diffuse sunlight. Note that the disadvantage of

having mixed sources considered in the baseline measurement is also applicable in the intervention CL_A and CS. Unlike baseline however, the SPD of the intervention fixture (9325 K GE45851 F55BX/AR/FS) was used instead of the SPD for the 5000 K standard.

For calculating intervention CL_A, the average intervention illuminance values for all subjects, a 2.3mm assumed pupil diameter, and the SPD of the 9325K GE 45851 F55BX/AR/FS intervention lamps were used in the human phototransduction equation to calculate CL_A values. Baseline eye-level CL_A values were 130.54 ± 199.37 and intervention eye-level CL_A values were 1078.28 ± 581.47; (note that again, outlier data from Subject 7 caused the SD to be higher than the average during baseline). Baseline wrist-level CL_A values were 179.11 ± 297.53, and intervention wrist-level CL_A values were 1554.28 ± 988.00. Both eye- and wrist-level CL_A results were consistent with the illuminance results: eye- and wrist-level intervention values were significantly higher than respective baseline values (p=0.01). Figure 23 illustrates the comparison between eye-level baseline and intervention CL_A results. Figure 24 illustrates the comparison between wrist-level baseline and intervention CL_A results.

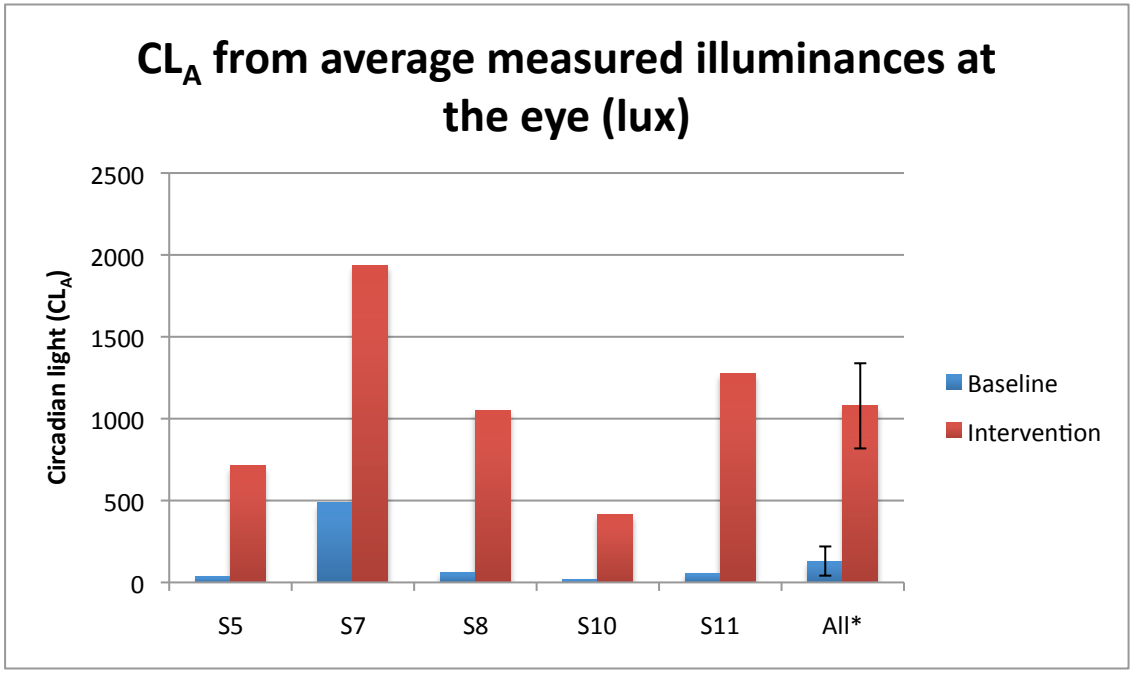


Figure 23: Comparison of CL_A values from average illuminance (lux) at the eye. The average intervention CL_A was statistically higher than the average baseline value (p=0.01)*.

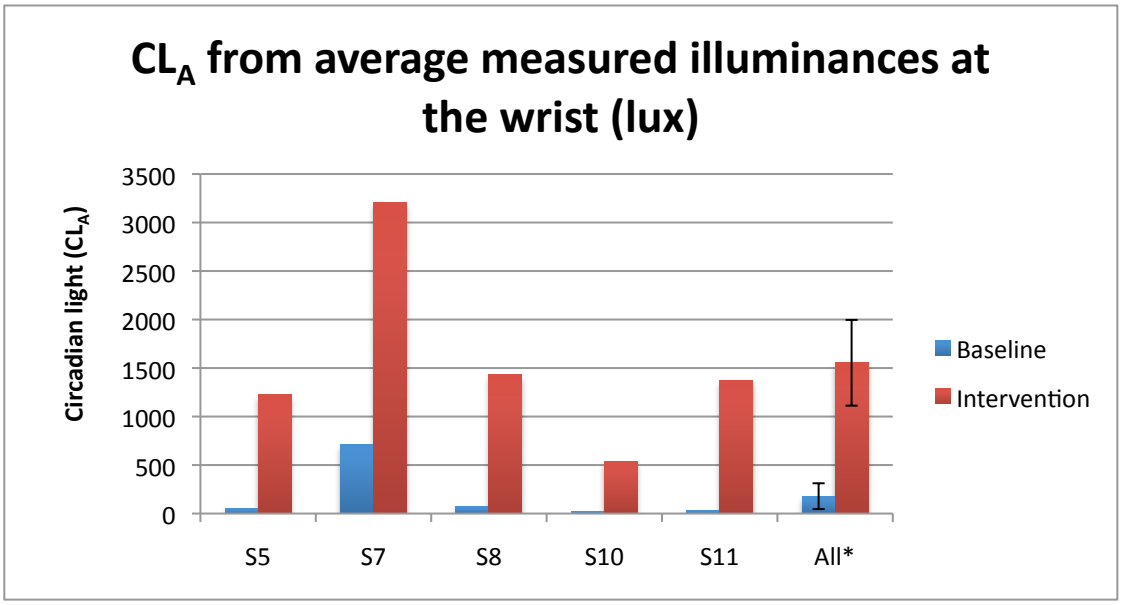


Figure 24: Comparison of CL_A values from average illuminance (lux) at the wrist. The average intervention illuminance was statistically higher than the average baseline value (p=0.01)*.

Subsequently, intervention eye- and wrist-level spot measured CL_A values were also compared. A ratio between the intervention eye-level CL_A "All (subjects)" value and the intervention wrist-level CL_A "All (subjects)" value was calculated to gauge the relationship between the two values. Wrist-level CL_A values were roughly 35% higher than eye-level CL_A values. Similar to EI vs. WI, intervention wrist-level CL_A was statistically higher than intervention eye-level CL_A values (p=0.04), indicating that Dimesimeter CL_A should overestimate the CL_A at eye-level (see Figure 25).

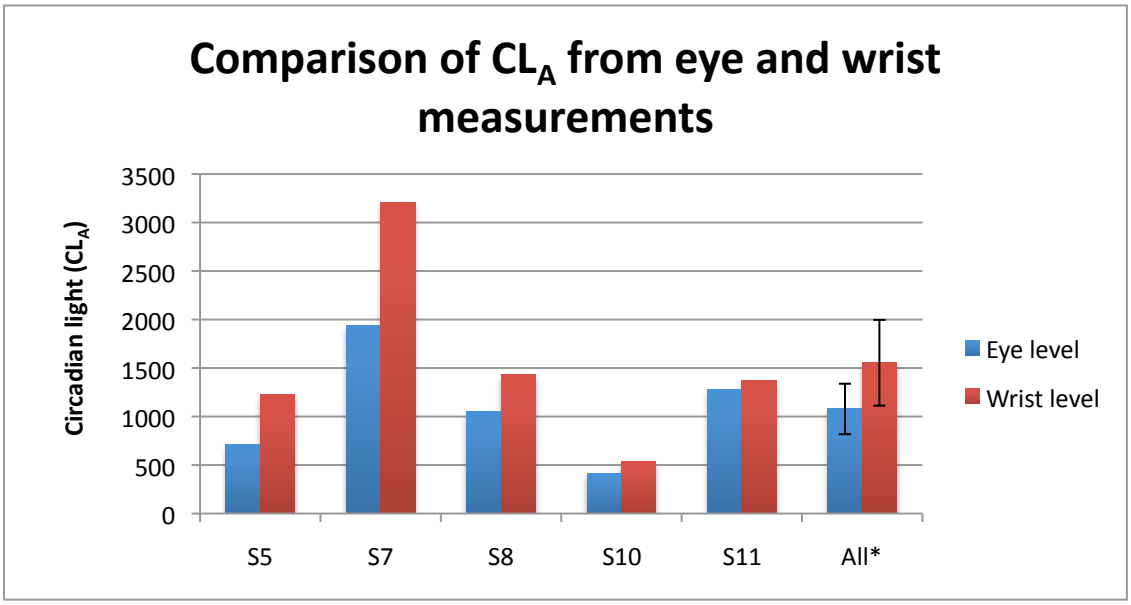


Figure 25: Comparison of the average intervention eye-level CL_A and the average intervention wrist-level CL_A. Average intervention period wrist-level CL_A was statistically higher than the intervention eye-level CL_A values (p=0.04)*.

6.1.3 Spot measured CS values

The CS values of eye- and wrist-level spot measurements were calculated using the CL_A conversion formula accompanying the human phototransduction model by Rea et al. (Rea et al. 2005; Rea et al. 2010; Rea et al. 2011). One-tailed Student's t-tests were used to evaluate whether or not intervention CS values of both eye- and wrist-level spot measurements were significantly higher than baseline values. Baseline eye-level CS values were 0.13 ± 0.16 where CS intervention values were statistically higher at 0.51 ± 0.09 (p=0.001). Wrist-level CS baseline values were 0.15 ± 0.19, and intervention values were also statistically higher at 0.56 ± 0.08 (p=0.02). Consistent with the illuminance and CL_A results, these results indicate that intervention CS values for both spot measurement types were higher than their respective baseline values. Figure 26 illustrates the comparison between baseline and intervention CS values derived from eye spot measurements. Figure 27 illustrates the comparison between baseline and intervention CS values derived wrist spot measurements.

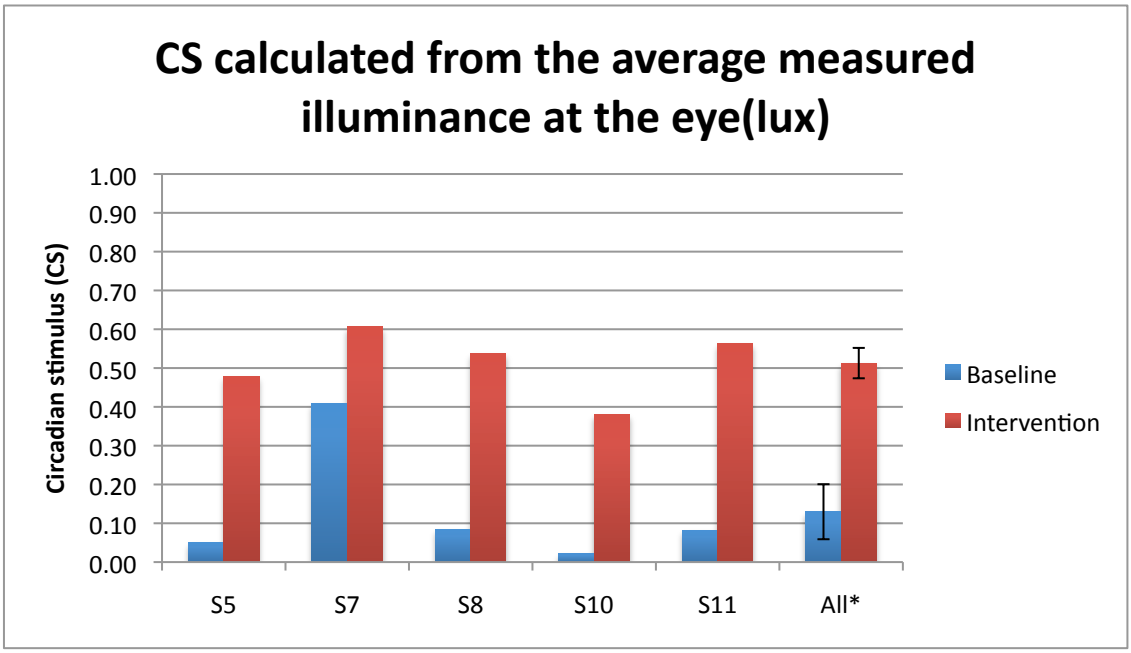


Figure 26: Comparison of CS values from average illuminances (lux) at the eye. Average intervention CS values were statistically higher than average baseline values (p=0.001)*.

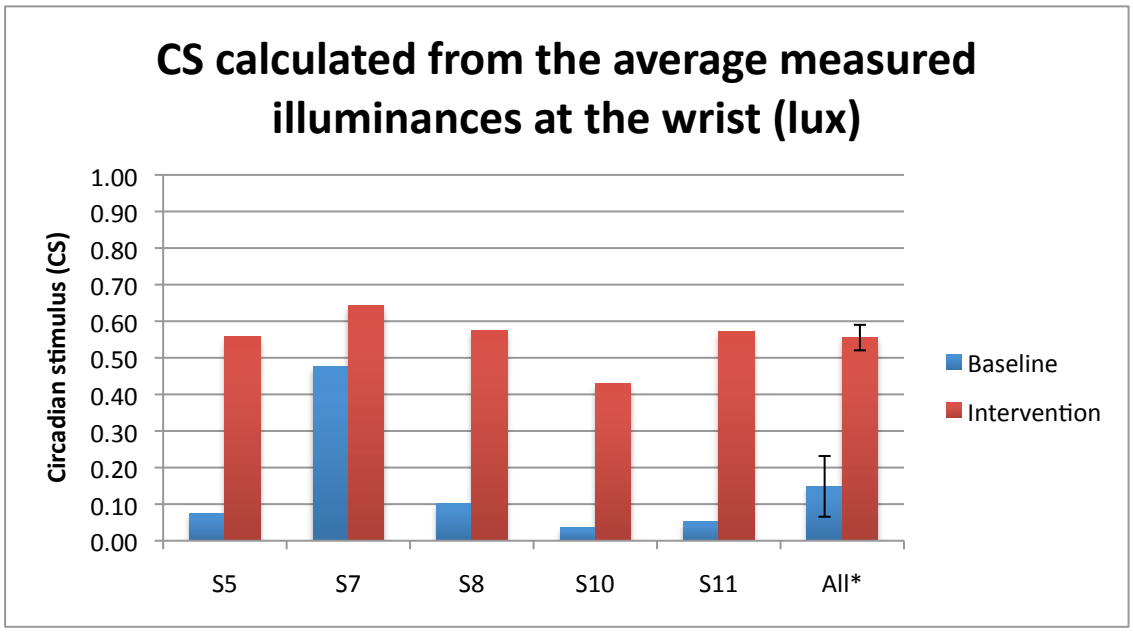


Figure 27: Comparison of CS values from average illuminances (lux) at the wrist. Average intervention CS values were statistically higher than average baseline values (p=0.02)*.

Intervention eye- and wrist-level CS values were also compared, and like previous eye and wrist measurement comparisons, wrist-level CS values were statistically higher

than eye-level CS (p=0.01). Additionally, a ratio between the intervention eye-level CS "All (subjects)" value and the intervention wrist-level CS "All (subjects)" value was calculated to gauge the relationship between the two values. Wrist-level CS was roughly 15% higher than eye-level CS. These calculations again indicate that while comparing Dimesimeter-measured CS with eye-level CS, Dimesimeter CS should presumably overestimate the amount of CS received at eye-level.

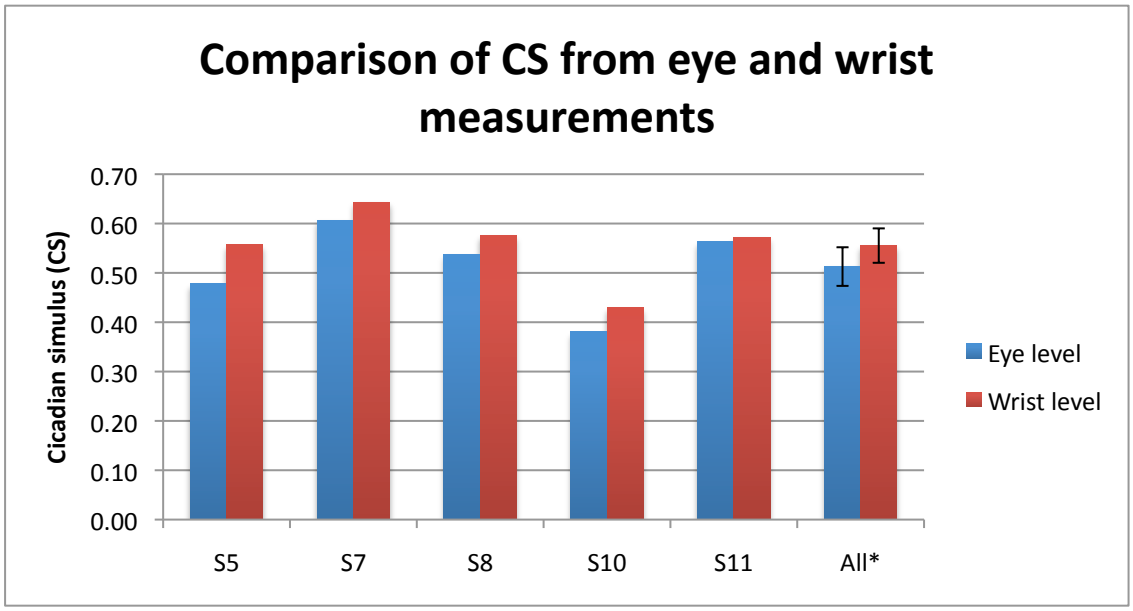


Figure 28: Comparison of the average intervention eye-level CS and wrist-level CS. The average intervention wrist-level CS was statistically higher than the average intervention eye-level CS (p=0.01)*.

6.1.4 Dimesimeter recorded light measurements

The following light measurement results are derived from Dimesimeter recordings spanning 1 week during the intervention period. Since only the light received during "time awake" is necessary to calculate light measurements from the Dimesimeter data, additional data processing was performed to exclude light data during "resting phase" and derive average and median photopic lux, CL_A, and CS results. From the data previously altered to eliminate times when the Dimesimeter was not worn, data from each Dimesimeter were individually examined to determine the "times awake" and "resting phase" per subject per experimental condition. Light and activity data during "resting phase" were excluded from the data analysis. For all subjects, "awake" and "resting" times were established using activity level and activity frequency. For all subjects,

"awake" was clearly implied with large clusters of densely packed activity spikes measuring ≥0.5 to 0.9, while rest was clearly marked by sparse clusters of low activity spikes <0.4 increments. Areas with a medium amount of activity spikes transitioning between <0.4 to ≥0.5 and ≥0.5 to <0.4 usually indicated the ending or beginning of the resting period respectively. However, Determining when subjects began or ended their resting period was challenging for several subjects. Some subjects, such as Subjects 5 and 7 showed sign of little sleep and/or extremely restless sleep. Given the observed patterns of the actigraph, however, it was determined that a prolonged drop in activity ≤0.4 increments for 10 or more minutes would be considered the beginning of the resting period, and 10 or more minutes of raised activity >0.4 afterwards marked the end of the resting period.

6.1.5 Dimesimeter recorded illuminance values

Average and median baseline and intervention illuminances were recorded continuously for each baseline and intervention 7-day period using a wrist-mounted Dimesimeter. The average baseline illuminance measurements of all subjects were 53.88 ± 64.77 lux, and intervention average values were 149.38 ± 113.07 lux. Using a one-tailed Student's t-test to compare baseline and intervention average illuminance, the average illuminance values during intervention were not statistically higher than the average baseline values ($p=0.06$). The median illuminance values during baseline were 4.76 ± 8.73 lux and 19.81 ± 11.53 lux during the intervention period. Evaluated using the Wilcoxon sign-rank test, the median intervention values were not significantly higher than baseline. These data suggest that both the most frequently occurring intervention illuminance values and the overall average intervention illuminance value were not significantly higher ($p=0.06$) than the baseline. Figure 29 represents the comparison of the average baseline and intervention illuminances recorded with a Dimesimeter. Figure 30 represents the comparison of the median baseline and intervention illuminances recorded with a Dimesimeter. It should be noted that while no significant difference was found between baseline and intervention average and median illuminances, both variables show a trend towards higher intervention levels.

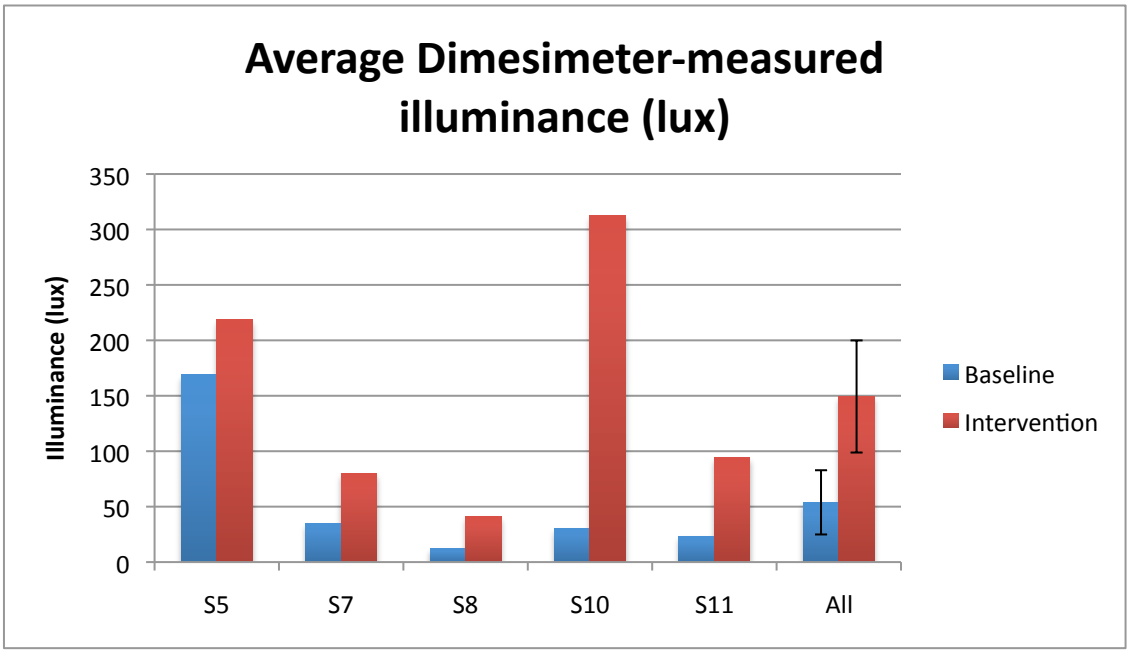


Figure 29: Comparison of the average baseline and intervention illuminances (lux) recorded with a Dimesimeter. No statistically significant difference was found (p=0.06).

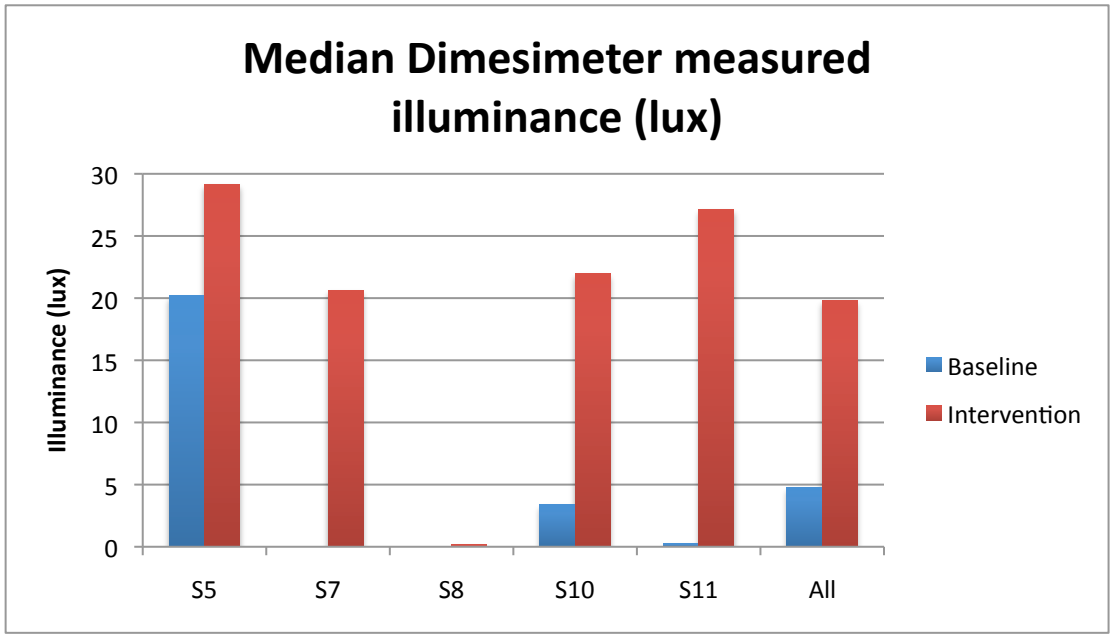


Figure 30: Comparison of the average baseline and intervention median illuminances (lux) recorded with a Dimesimeter. No statistically significant difference was found (p=0.06).

Dimesimeter-recorded intervention illuminances were also compared with EI and WI. The ratio between the intervention Dimesimeter "All (subjects)" illuminance and the

intervention “All (subjects)” EI was 77:200. The ratio between the intervention Dimesimeter “All (subjects)” illuminance and the intervention “All (subjects)” WI was 60:203. Whereas WI intervention values were significantly higher than EI intervention values ($p=0.04$), the Dimesimeter-recorded average intervention illuminances were significantly lower than both EI ($p=0.05$) and WI ($p=0.04$). These results indicate that the subjects may not have been receiving the intervention lighting since wrist-level measurements significantly overestimate the actual illuminances received at eye-level (See Figure 31). This indication is especially exaggerated since the intervention Dimesimeter average illuminances were not statically higher than baseline. While the novel luminaires had the ability to provide statistically higher light levels, as indicated by baseline and intervention comparisons with EI and WI, subjects were not receiving significantly higher light levels according to the Dimesimeter data.

Table 4: Table of average intervention illuminance values for eye- and wrist-level spot measurements and the Dimesimeter.

Average intervention illuminance (lux)			
	EI	WI	Dimesimeter
S5	338.33	574.50	218.53
S7	896.40	1446.00	80.00
S8	494.17	669.00	41.14
S10	199.20	257.50	313.04
S11	599.00	643.33	94.20
All	505.42	718.07	149.38

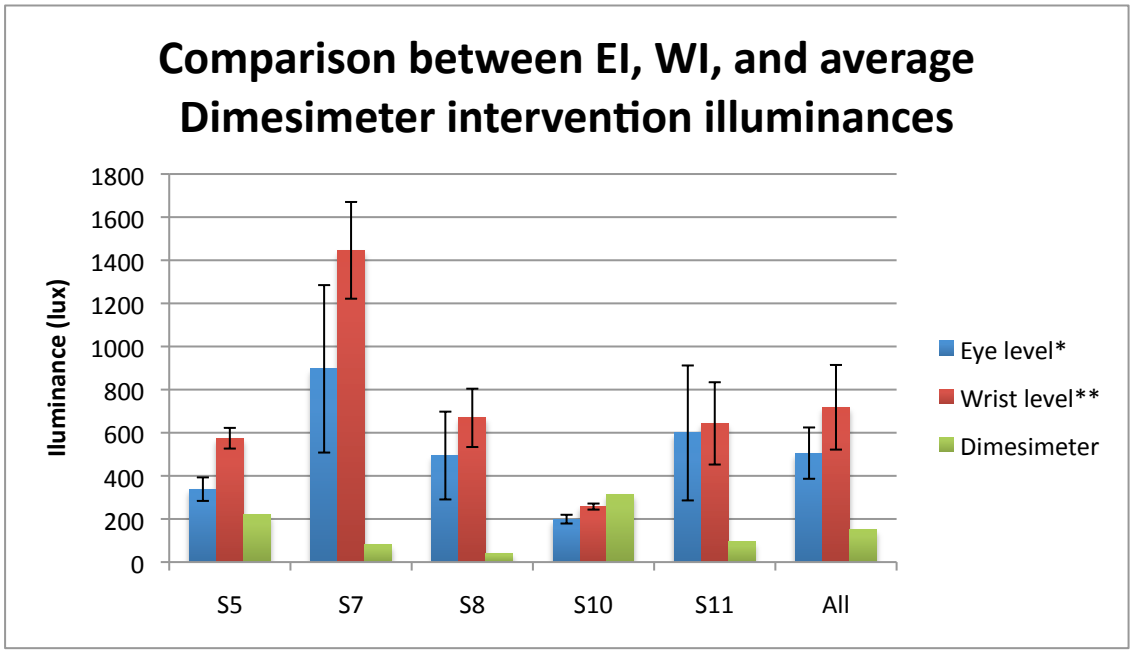


Figure 31: Comparison between the intervention EI, WI, and average Dimesimeter illuminances. WI was statistically higher than EI and Dimesimeter illuminance values (p=0.04). EI was significantly higher than Dimesimeter illuminance values (p=0.05)*.**

6.1.6 Dimesimeter recorded CL_A values

Average and median CL_A values were also calculated from the altered Dimesimeter data during the 7-day baseline and intervention data collection periods (see Table 2). Average baseline CL_A values for all subjects were 88.9 ± 110.19, and average intervention values were 405.74 ± 365.17. No statistically significance difference (p=0.07) was found between baseline and intervention average Dimesimeter CL_A values for times awake (activity >0.4 for 10 minutes or more) using a one-tailed Student's t-test (Figure 32); however the consistently increasing intervention values as compared to baseline indicated that the values were headed towards a greater significance. Median CL_A values for all subjects were 7.24 ± 5.61 for baseline and 27.89 ± 4.50 during the intervention. The Wilcoxon sign-rank revealed that the median intervention CL_A values also were not significantly (p=0.06) higher than baseline values (Figure 33). Consistent with average values, median CL_A values also trended towards statistically higher intervention values.

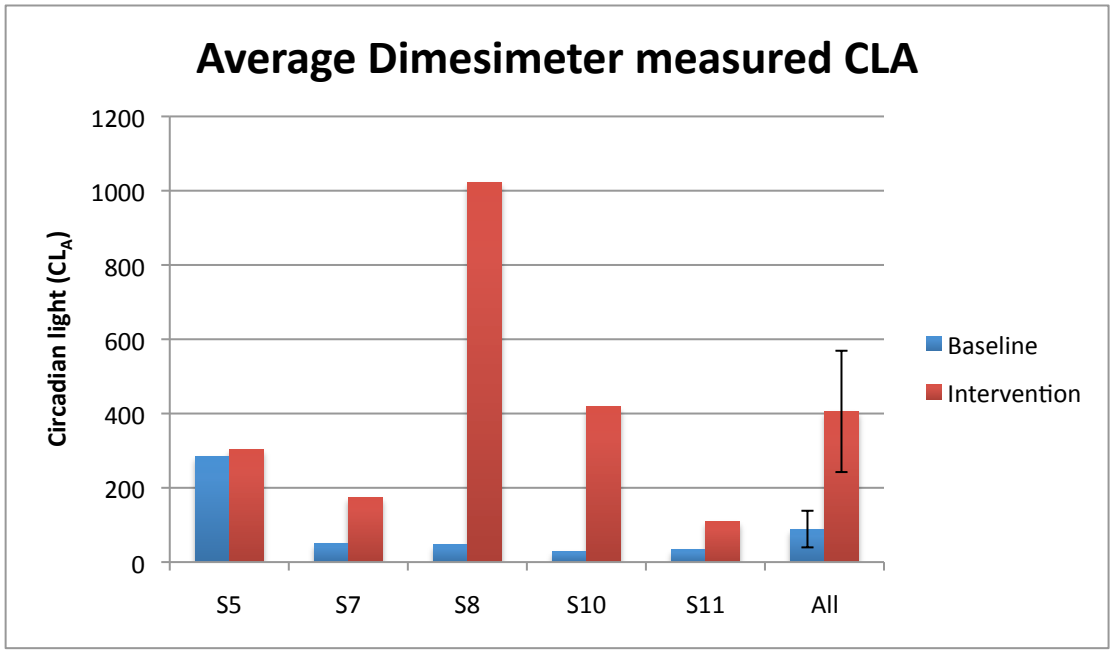


Figure 32: Comparison of the average CL_A recorded with a Dimesimeter. No statistically significant difference between baseline and intervention was found (p=0.07).

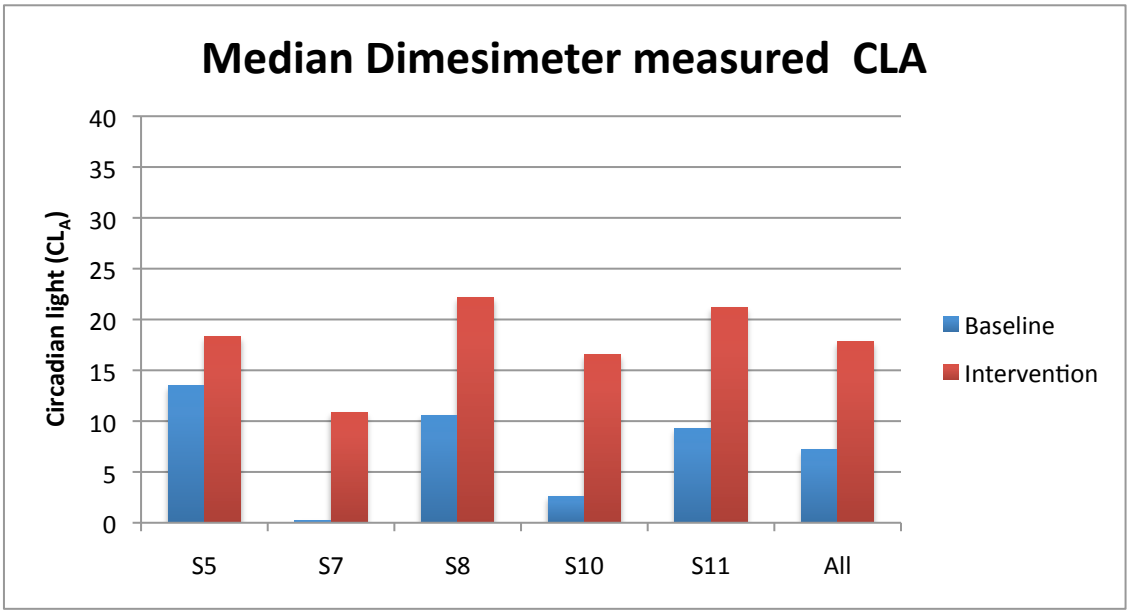


Figure 33: Comparison of the baseline and intervention median CL_A recorded with a Dimesimeter. No statistically significant difference was found (p=0.07).

When the Dimesimeter-recorded CL_A values were compared with spot measurement CL_A values, results again revealed that subjects may not be receiving the extra light provide by the novel luminaires. The ratio between the intervention Dimesimeter "All

(subjects)" CL_A and intervention eye-level "All (subjects)" CL_A was 79:116. The ratio between the intervention Dimesimeter "All (subjects)" CL_A and the intervention wrist-level "All (subjects)" CA was 73:94. Like average Dimesimeter illuminance, average intervention Dimesimeter CL_A was also statistically lower than both intervention eye- and wrist-level CL_A values ($p=0.05$ and $p=0.04$ respectively), with wrist-level CL_A being statistically higher than eye-level CL_A ($p=0.04$). Furthermore, intervention Dimesimeter CL_A values were not significantly higher than baseline (see Figure 32). Again, these results indicate that even though wrist spot measurements overcompensated for eye-level measurements, the Dimesimeter intervention CL_A values were still lower than both eye and wrist measured values (See Figure 34).

Table 5: Table of average CL_A intervention values for eye- and wrist-level spot measurements and the Dimesimeter.

Average intervention CL_A			
	Eye-level	Wrist-level	Dimesimeter
S5	711.94	1223.30	302.40
S7	1938.20	3202.90	175.00
S8	1048.10	1431.10	1023.40
S10	416.16	539.60	418.50
S11	1277.00	1374.50	109.40
All	1078.28	1554.28	405.74

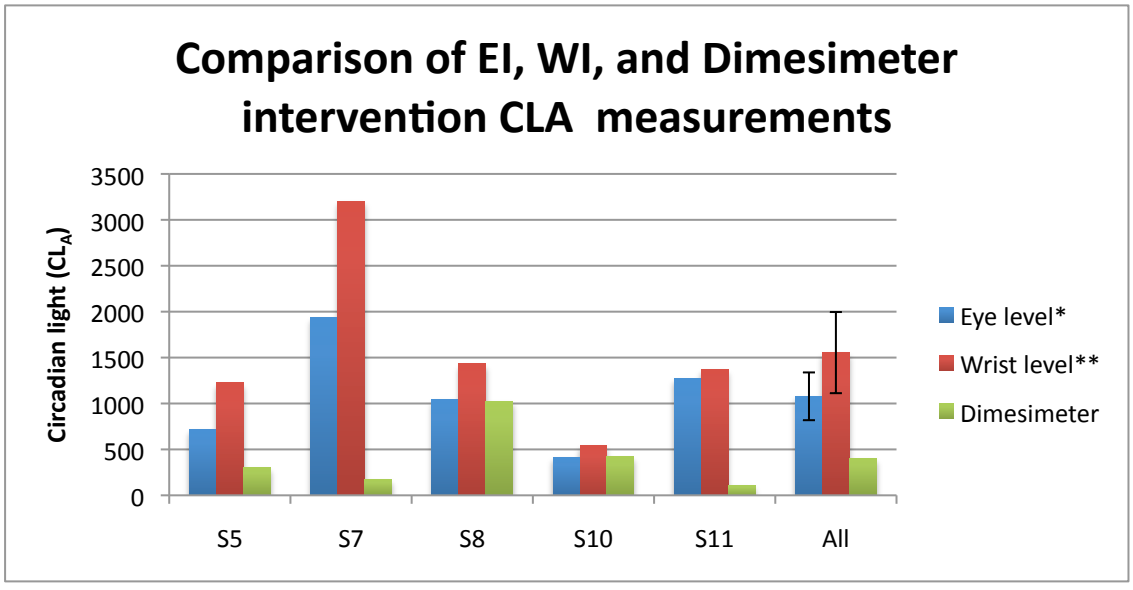


Figure 34: Comparison between the intervention spot measured eye- and wrist-level CL_A and the average intervention Dimesimeter CL_A. Wrist-level CL_A was

statistically higher (p=0.04) than eye-level CL_A, and Dimesimeter averaged CL_A. Wrist-level CL was statistically higher (p=0.05)* than Dimesimeter CL_A.**

6.1.7 Dimesimeter recorded CS values

CS values were calculated using the calculated CL_A values from the Dimesimeter data over the 7-day baseline and intervention periods. Average baseline CS values were.04 ± 0.02, and average intervention values were 0.10 ± 0.01. Using Student's one-tailed t-test, it was determined that for average CS values during times awake (see section 6), intervention values were significantly higher than baseline (p=0.0001). Median baseline values were 0.01 ± 0.02, and median intervention values were 0.01 ± 0.01. The Wilcoxon sign-rank test was not able to show any significant difference between intervention median values and baseline median values (p=0.06); however, intervention median values trended towards being higher than baseline values. These results imply that despite the non-significant statistical differences between illuminance and CL_A, intervention CS values can still be statistically higher than baseline values. Figure 35 illustrates the comparison between baseline and intervention average CS results. Figure 36 illustrates the comparison between baseline and intervention median CS results.

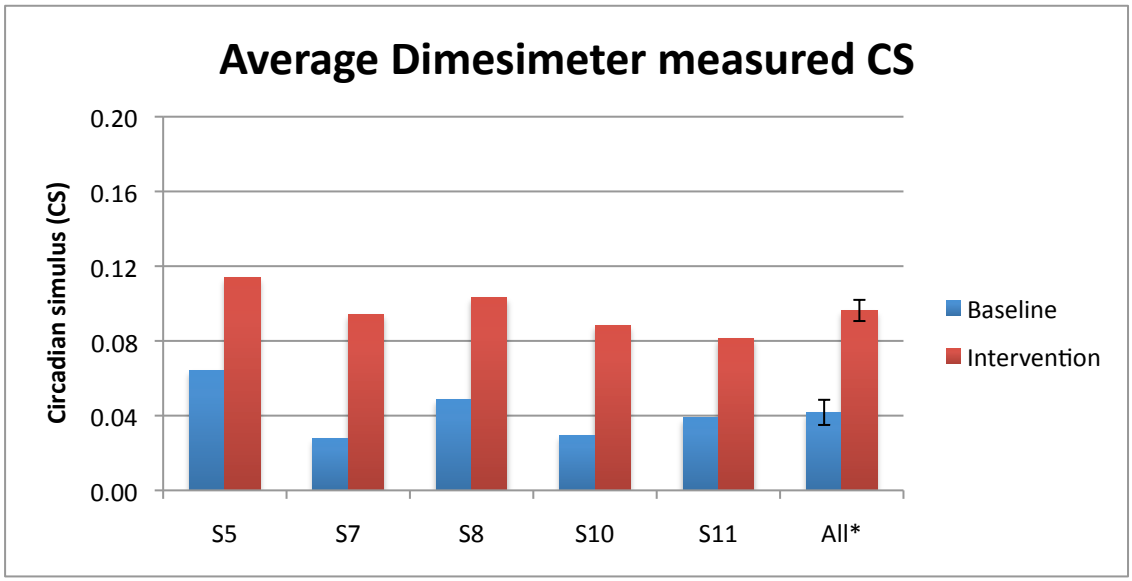


Figure 35: Comparison of the average CS recorded with a Dimesimeter. The average intervention value was statistically higher than baseline value (p≦0.0001)*.

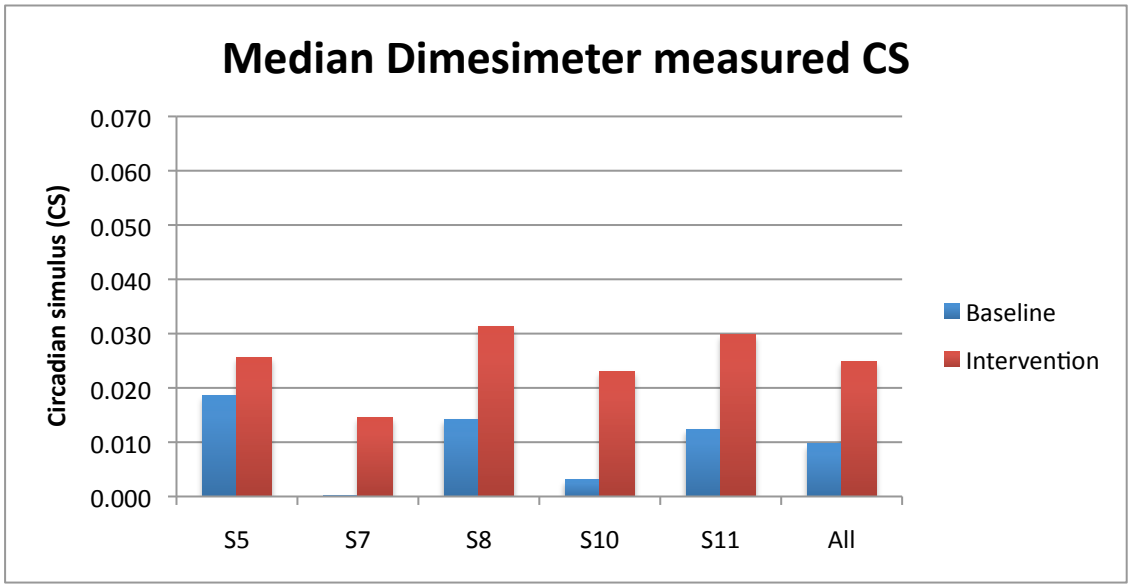


Figure 36: Comparison of baseline and intervention median CS recorded with a Dimesimeter. No statistically significant difference was found (p=0.06).

Compared to eye-level CS and wrist-level CS, average Dimesimeter values were again statistically lower than spot measurements (p=0.0002 and p=0.0001, respectively; Figure 37). Unlike previous comparisons, intervention Dimesimeter CS values were statistically higher than baseline Dimesimeter CS (p=0.0001), indicating that the non-significant upward trends from the intervention Dimesimeter illuminance and CL_A values led to a significant difference in intervention Dimesimeter CS (see Figure 36).

Table 6: Table of average CS Intervention values for eye- and wrist-level spot measurements and the Dimesimeter.

Average intervention CS			
	Eye-level	Wrist-level	Dimesimeter
S5	0.48	0.56	0.11
S7	0.61	0.64	0.09
S8	0.54	0.58	0.10
S10	0.38	0.43	0.09
S11	0.56	0.57	0.08
All	0.51	0.56	0.10

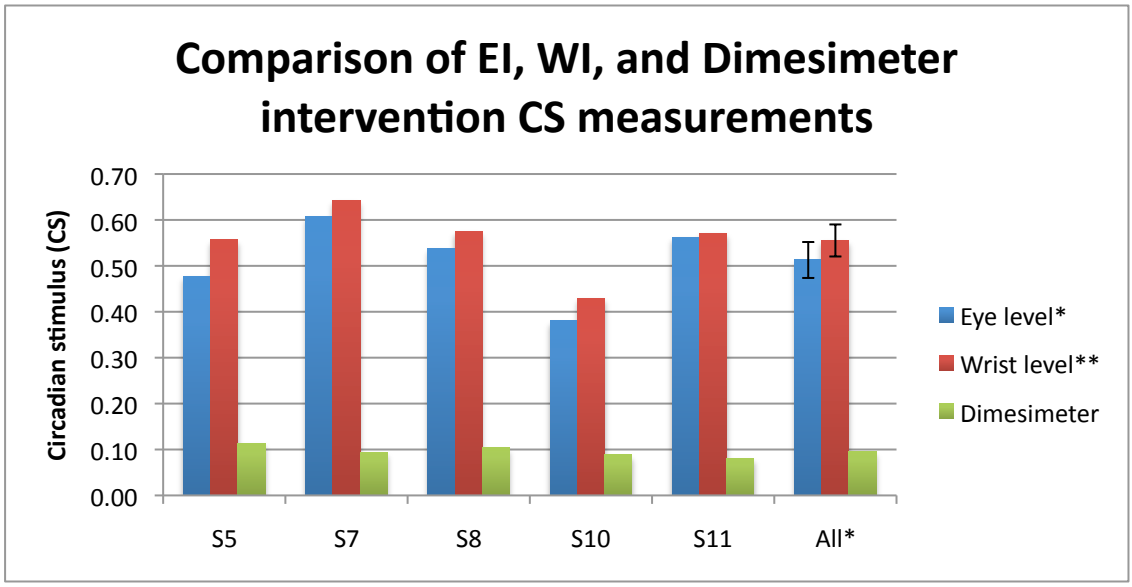


Figure 37: Comparison between the intervention spot measured eye- and wrist-level CS and average Dimesimeter CS. The intervention wrist-level CS was statistically higher than both the intervention eye-level CS and the intervention average Dimesimeter CS (p=0.0001). Eye-level CS was statistically higher than the average Dimesimeter CS (p=0.0002)*.**

6.2 Hypotheses results 1

The lighting intervention will significantly improve measures of rest/activity rhythm consolidation compared to baseline.

6.2.1 Hypothesis 1a: Inter-daily reliability (IR)

Inter-daily repeatability (IR), the resemblance of activity patterns during individual days, will be significantly higher during the intervention than during baseline.

IR is an approximation of the variance in 24-hour patterns of rest and activity in a data set. The closer a signal is to 1, the better the data "fits" to a 24-hour cosine curve. (Refer to section 6.2.2.4.3 for more detail). The baseline IR values for all subjects were 0.51 ± 0.23, and the intervention values for IR were 0.67 ± 0.30. A one-tailed Student's t-test showed that intervention period IR values were statistically (p=0.01) higher than baseline IR values (Figure 38). This result indicates that the lighting intervention was indeed able to increase the fit of the subjects' rest/activity cycle with the 24-hour cosine.

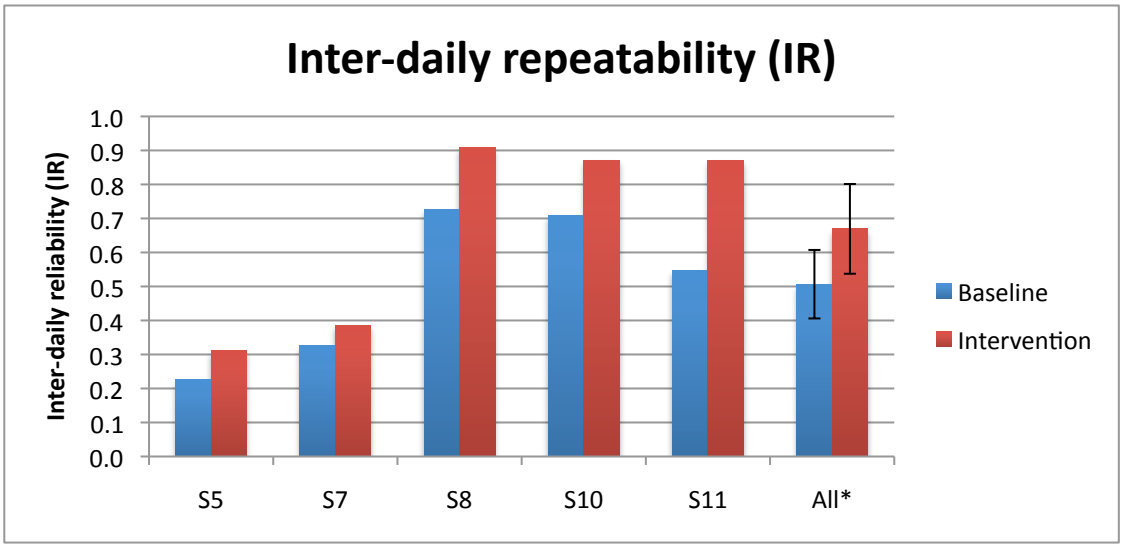


Figure 38: Comparison between the average baseline and intervention IR values. Intervention IR values were statistically higher than baseline values (p=0.01)*.

6.2.2 Hypothesis 1b: Phasor analysis

Phasor analysis was performed on the light and activity data from the Dimesimeters. For this analysis, at least three consecutive days of uninterrupted Dimesimeter data were needed to accurately represent the phasor magnitude of the subjects. The Dimesimeter data for all subjects was parsed to only contain consecutive days of full data sets for this analysis. Subject 7 did not have the minimum three consecutive days of data and was subsequently removed from these results.

6.2.2.1 Phasor magnitude

> The average phasor magnitude will be significantly higher during the intervention period than during baseline.

Phasor magnitude represents the correlation and phase relationship between the activity-rest data and the 24-hour light-dark cycle (Rea et al. 2008). Ideally, the higher the phasor magnitude, the better the relationship is between the phase and activity-rest data. Previous studies have shown that healthy older adults (≥60 years of age) have an average phasor magnitude of 0.40, whereas ADRD patients have an average phasor magnitude of 0.30 (Figueiro et al. 2012). Baseline phasor magnitude values were 0.21 ± 0.06 and intervention values were 0.26 ± 0.09. A one-tailed Student's t-test revealed a statistically significant difference between baseline and intervention phasor magnitude (p=0.03; see

Figure 39.) Light significantly increased the alignment of the rest/activity cycle with the 24-hour day in ADRD patient.

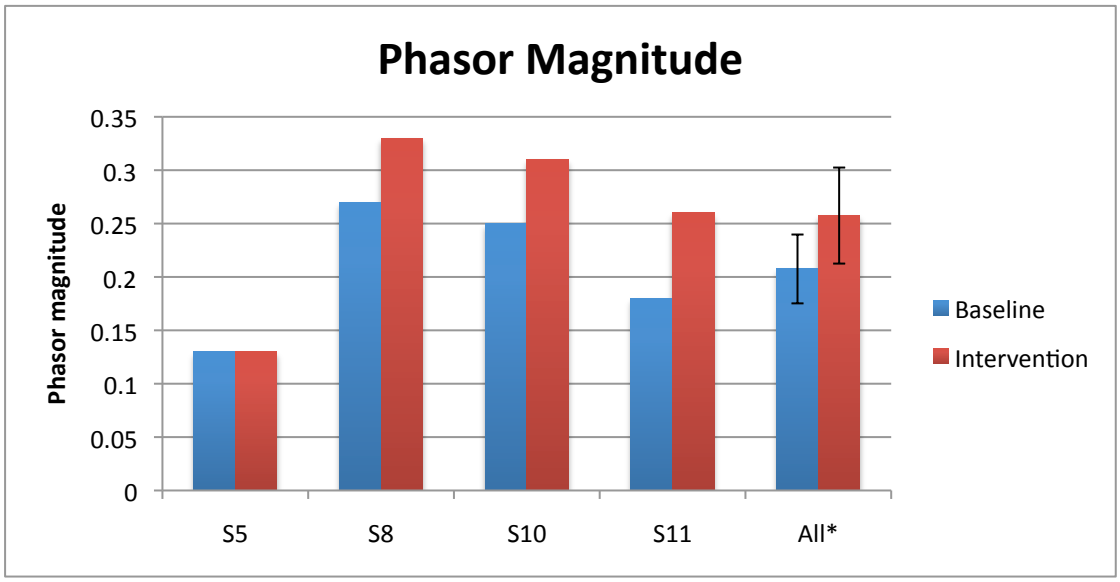


Figure 39: Comparison between the average baseline and intervention phasor magnitude values. The average intervention phasor magnitude was statistically higher than baseline (p=0.03)*.

6.2.3 Hypothesis 1c: M10

> The average activity of the 10 most active hours (M10) will be significantly higher during the intervention period than during baseline.

M10 was determined by averaging the 10 most-active hours in the 24-hour Dimesimeter subject profiles (Witting et al. 1990). Higher M10 scores indicate more activity whereas lower M10 scores indicate less activity during the 10 most-active hours of a day. Baseline values averaged 0.32 ± 0.07, and intervention values averaged 0.31 ± 0.06. A one-tailed Student's t-test was used to indicate whether or not intervention values were statistically higher than baseline values. Intervention levels of activity were not statistically higher or lower than baseline values (p=0.37), indicating that the activity of ADRD patients in the 10 most active hours in the 24-hour period did not increase during the intervention period (see Figure 40).

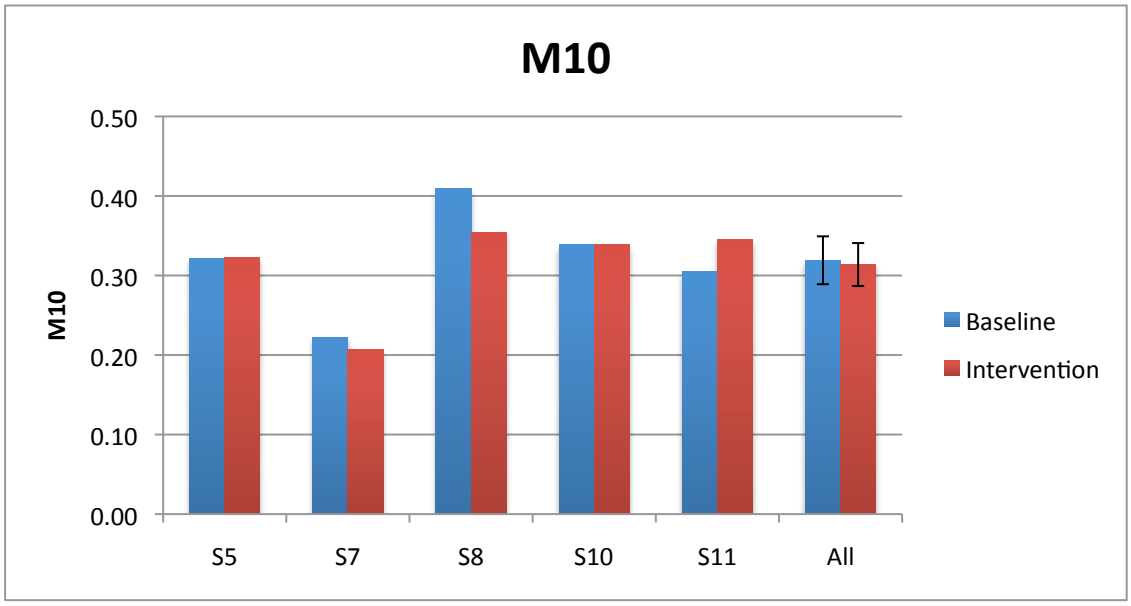


Figure 40: Comparison between the average baseline and intervention M10 values. No statistically significant (p=0.37) difference was found.

6.2.4 Hypothesis 1d: L5

> The average activity of the 5 least active hours (L5) will be significantly lower during the intervention period than during baseline.

L5 was determined by averaging the 5 least-active hours in the 24-hour activity Dimesimeter profile per subject (Witting et al. 1990). High L5 scores indicate higher activity, and low L5 scores indicate lower amounts of activity during the 5 least active hours of the day, which may indicate less activity during resting periods. Baseline L5 values averaged 0.12 ± 0.07, and intervention values averaged 0.10 ± 0.02. A one-tailed Student's t-test revealed no statistical difference between baseline and intervention values (p=0.09; Figure 41). The light intervention did not significantly increase rest during the least active hours of the day.

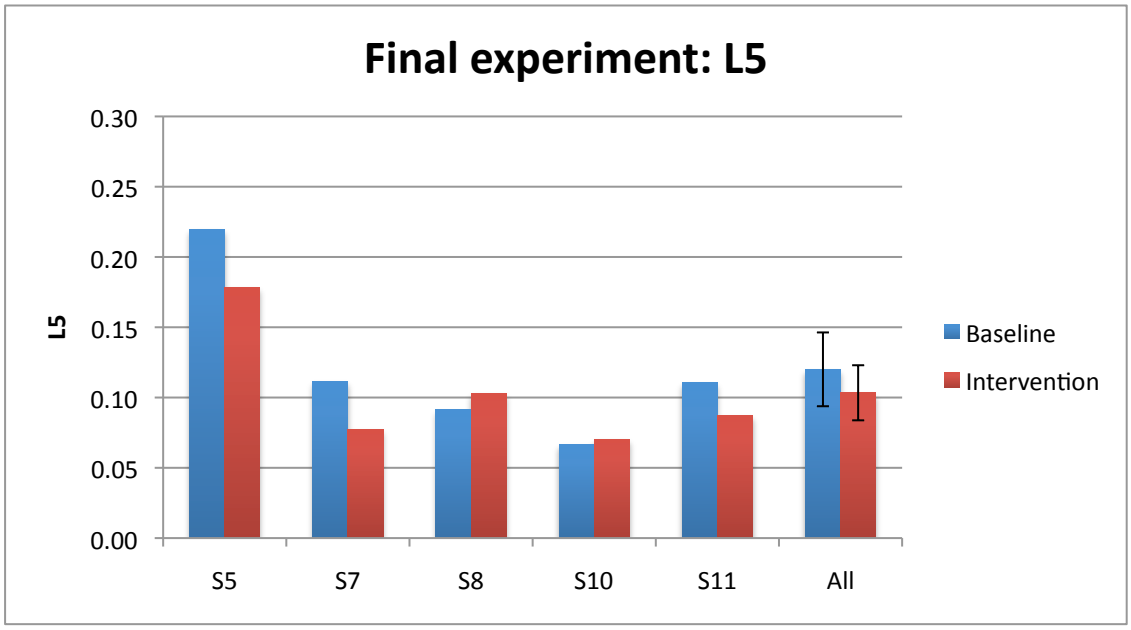


Figure 41: Comparison between the average baseline and intervention L5 values. No statistically significant (p=0.09) difference was found.

6.2.5 Hypothesis 1e: Relative Amplitude (RA)

> The relative amplitude of the circadian rhythm (RA) will be significantly higher during the intervention period than during baseline.

RA indicates the relative amplitude of the subjects' current level of rest/activity cycle. RA values were calculated as the difference between M10 and L5 divided by the sum of M10 and L5 (Van Someren et al. 1997; Witting et al. 1990). Baseline values averaged.50 ± 0.20, and intervention values averaged 0.51 ± 0.14. Using Student's one-tailed t-test, no significant difference was found between baseline and intervention RA values (p=0.15; see Figure 42). Light did not increase the amplitude of ADRD patients' rest/activity cycles.

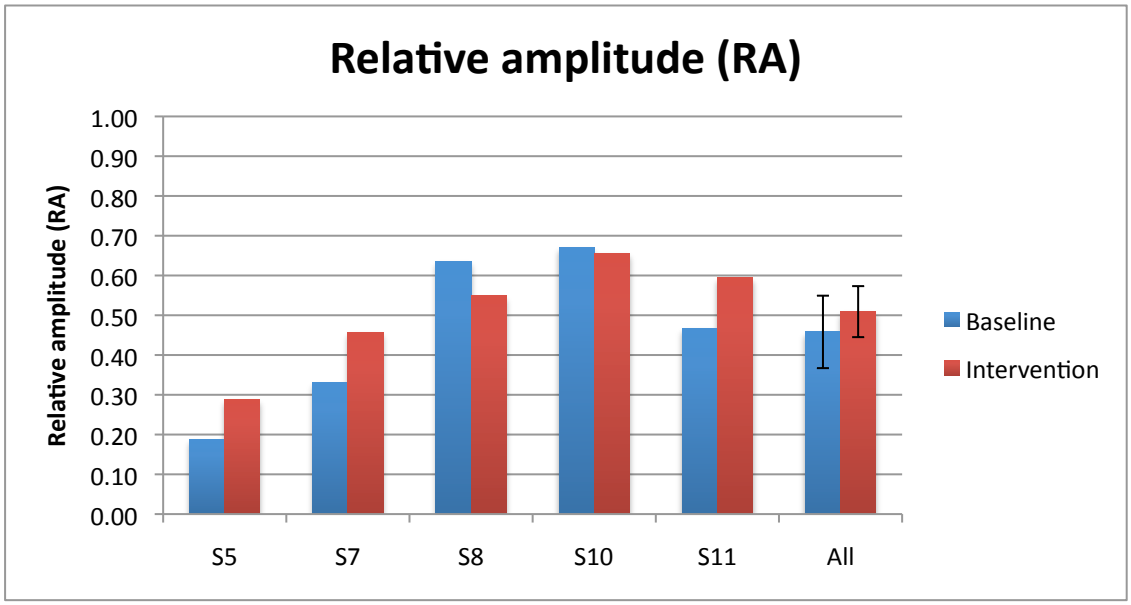


Figure 42: Comparison between the average baseline and intervention RA values. No statistically significant difference was found (p=0.15).

6.2.6 Hypothesis 1f: Activity

> Activity during the intervention period will be significantly higher during the intervention period than during baseline.

The Dimesimeter also recorded the activity of each subject during each 7-day intervention and baseline period. The activity data used for this parameter was determined by the longest period of activity during the subjective day for each participant. Since the ADRD patients did not have "regular" 24-hour subjective periods, the "subjective day" was determined as the beginning of a long period of activity to the end of a long resting period following (see section 6). These periods were determined separately per subject given the large differences among them. Once these "awake" periods were determined, the activity data were averaged, and one-tailed Student's t-test was used to evaluate whether or not intervention activity levels were significantly higher than baseline. All baseline average activity values per subject were 0.30 ± 0.06, and all intervention average values were 0.29 ± 0.06. No statistically significant difference was found between baseline and intervention average values (p=0.33); thus activity during the individualized "subjective days" did not significantly increase with intervention lighting. Figure 43 shows the average amount of baseline activity compared to the amount of intervention activity. Median activity values were also compared. Baseline median

values were 0.28 ± 0.12, and intervention median values were 0.28 ± 0.11. The Wilcoxon sign-rank test revealed that no statistical difference was found between the median baseline and intervention activity (p=0.43). Figure 44 shows the median baseline activity compared to the median intervention activity.

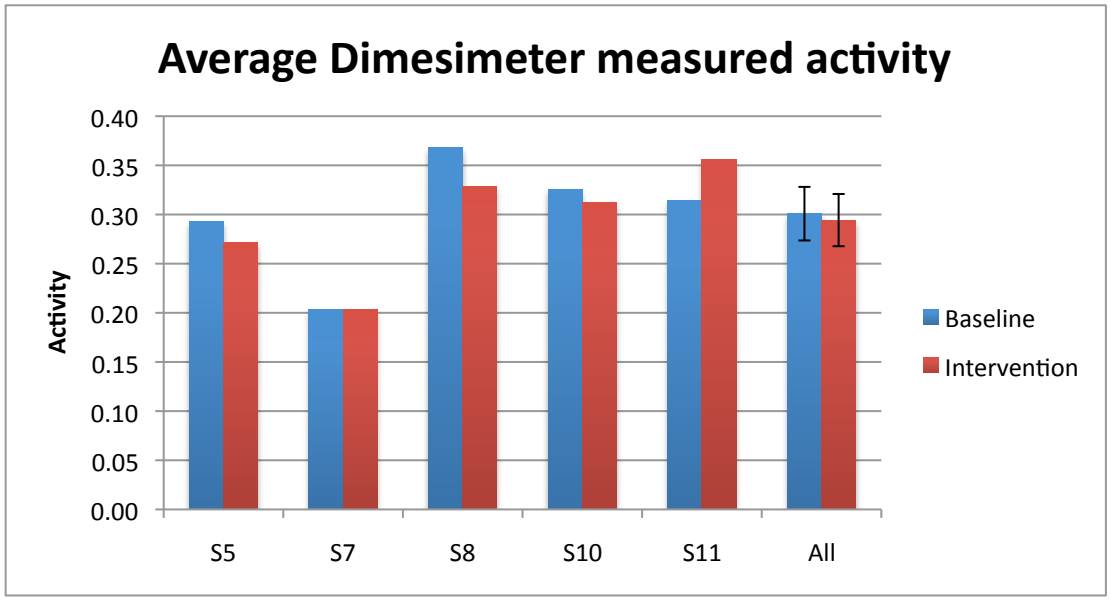


Figure 43: Comparison of the average baseline and intervention activity values recorded with a Dimesimeter. No statistically significant difference was found (p=0.33).

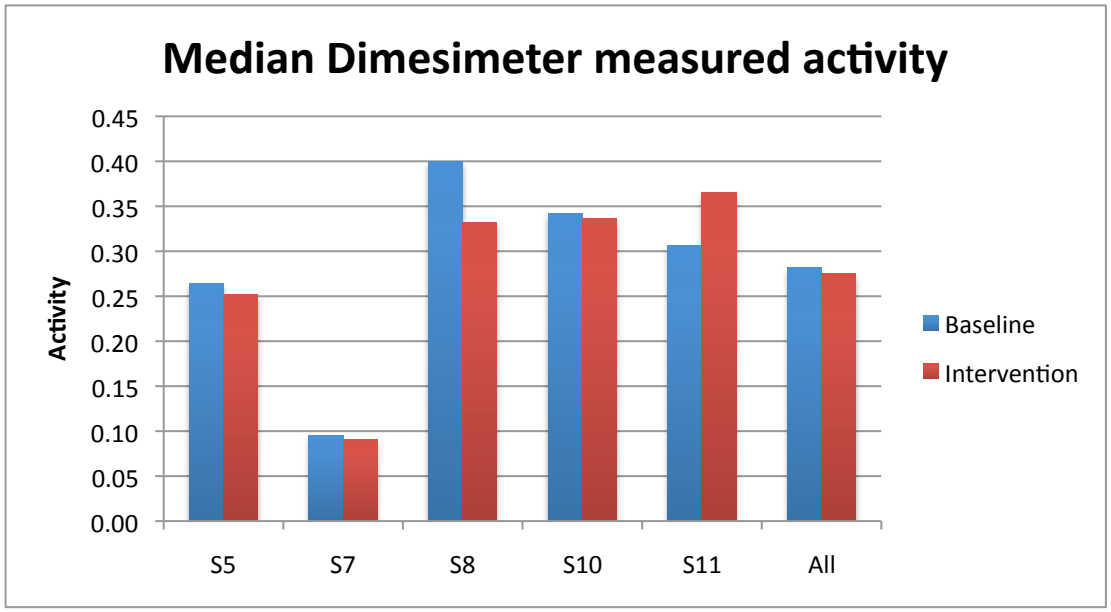


Figure 44: Comparison of the average baseline and intervention median Activity recorded with a Dimesimeter. No statistically significant (p=0.43) difference was found.

6.3 Hypothesis results 2

The lighting intervention will significantly improve sleep quality measures and behavior measures compared to baseline.

6.3.1 Hypothesis 2a: PSQI

Pittsburgh Sleep Quality Index scores will be significantly lower during the intervention period, indicating better subjective sleep quality.

The PSQI is a subjective survey indicating sleep quality (Buysse et al. 1988). A global score of ≥5 indicates significantly disrupted sleep. Baseline PSQI scores were 6 ± 1.38 and intervention scores were 6.4 ± 1.08. A one-tailed Student's t-test was used to determine if baseline scores were significantly higher than intervention scores. No statistical significance was found between baseline and intervention scores ($p=0.43$). (see Figure 45). It is important to note that some data were missing from the baseline questionnaires due to the inability of caregivers to answer certain questions. The missing answers to these questions caused some of the seven components of the global score to reduce to "0" for a conservative global score. Subject 5 missed 4/7 components, Subject 7 missed 3/7, Subject 10 missed 1/7 and Subject 11 missed 2/7. Likewise, due to missing data, the changes between baseline and intervention scores per question were not examined.

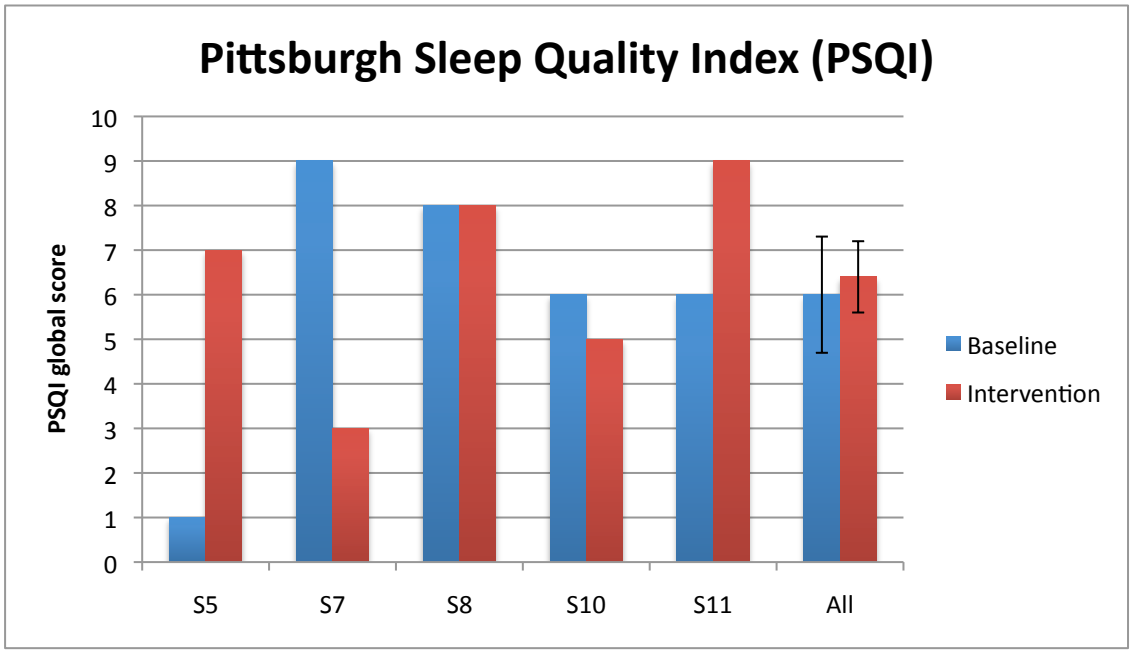


Figure 45: Comparison between the intervention and baseline PSQI scores. No statistically significant difference was found (p=0.43).

6.3.2 Hypothesis 2b: MDS-ADLs

> The Minimum Data Set-Activities of Daily Living Scale—Long Form (MDS-ADL) scores will be significantly lower during the intervention period than during baseline, indicating improved independence.

MDS-ADLs are subjective tests evaluating the ability of a subject to independently perform activities of daily living such eating or going to the bathroom (Morris, Fries, and Morris 1999). (See section 6.2.2.6.2 for more detail). Higher scores indicate more dependence whereas lower scores indicate independence. Additional studies also suggest that this test may indicate the severity of dementia where a score of 10 or more indicates severe dementia (van der Steen et al. 2006). Per baseline, subjects scored an average of 8.00 ± 7.21, and per intervention, subjects scored an average of 8.67 ± 6.42. This data indicates that the intervention lighting did not increase the independence of ADRD patients to perform ADLs. Using Student's one-tailed t-test, no significant difference was found between baseline and intervention scores (p=0.21). Note: Subject 8 was eliminated from these results because the subject suffered a fall during the intervention period, which greatly increased his/her dependence for activities of daily living. Subject 11's data were also eliminated due to an infection (Figure 46).

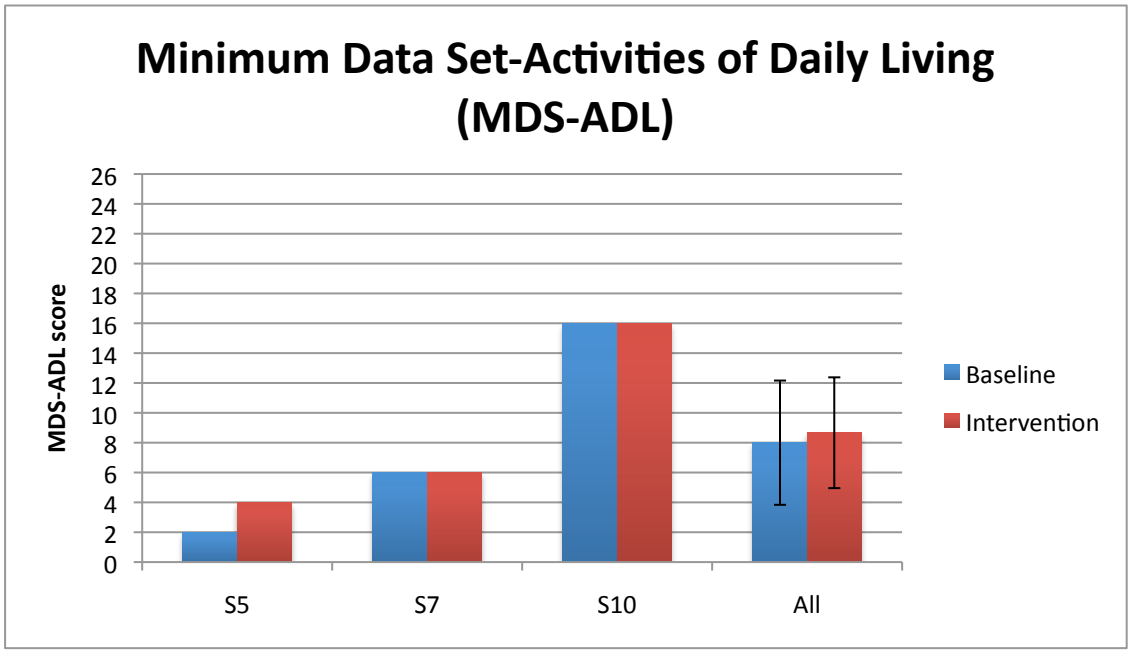


Figure 46: Comparison between the average baseline and intervention MDS-ADLs scores. No statistically significant difference was found (p=0.21).

6.3.3 Hypothesis 2c: CSDD

> Cornell Scale for Depression in Dementia (CSDD) scores will be significantly lower during the intervention period, indicating decreased depression

CSDD scores indicate the severity of depression that dementia patients' experience (Alexopoulos et al. 1988; Allan and Burns 1995). (See section 6.2.2.6.3 for more detail). The significant scoring cut-offs are as follows: ≤6 = an absence of significant depressive symptoms, >10 = probably major depression and >18 = definite major depression. Average subjective baseline scores were 10.67 ± 6.51 and average intervention scores were 3.48 ± 6.03. According to a one-tailed Student's t-test, CSDD scores were significantly lower during the intervention period compared to baseline scores (p=0.01), indicating the positive effects of light intervention on ADRD patients and depression. Note: Subject 8 was excluded again from a subjective test due to his/her fall incident during the intervention period. Primary caregivers reported that the fall increased the subject's anxiety and depression. Subject 11 was also excluded due to an infection, which also reportedly increased his/her anxiety and depression. (Figure 47).

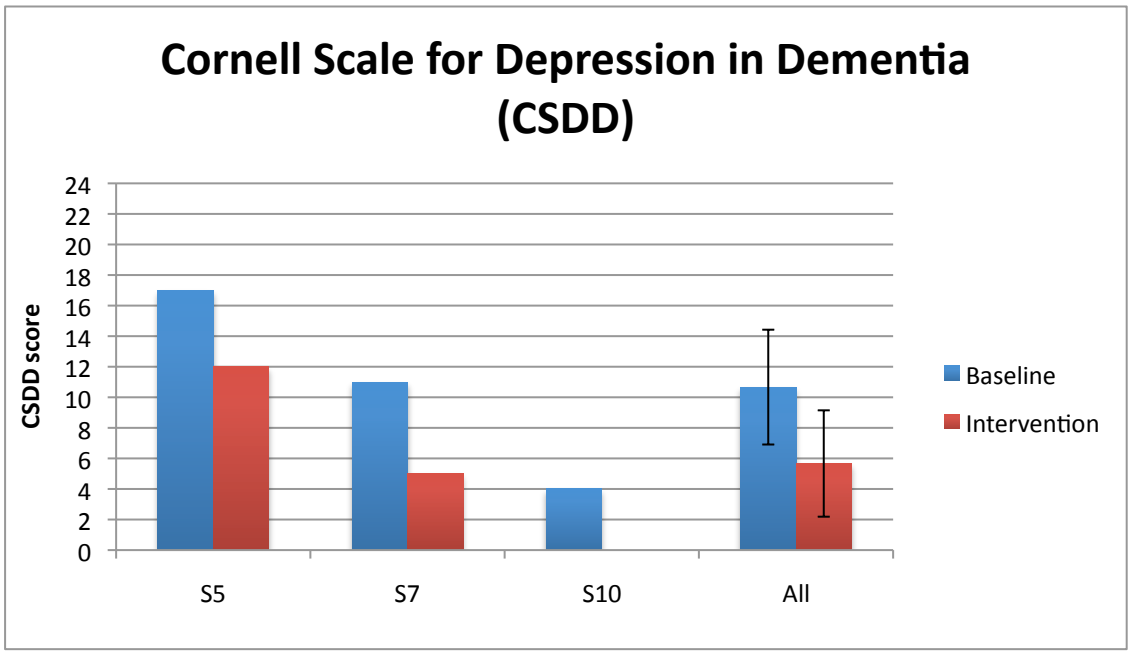


Figure 47: Comparison between the average baseline and intervention CSDD scores. Intervention scores were statistically lower than baseline values(p=0.01)*.

A breakdown of the scoring for the individual questions in the CSDD was also examined to reveal the specific behaviors reduced during the intervention period. However, one-tailed Student's t-tests performed on the individual CSDD questions revealed no statistical significance. A comparison of the differences between intervention and baseline scores was performed instead to examine trends. In the following chart, "Difference" values were derived from totaling all baseline scores of all subjects, all intervention scores of all subjects, and subtracting the baseline total from the intervention total per question; positive values represent reduced negative behaviors from baseline.

Table 7: Difference between baseline and intervention CSDD scores per query.

CSDD individual queries	Difference
Was anxious, or had an anxious expression or has been worrying constantly?	0
Had a sad expression, a sad voice or has been tearful?	1
Lacked reactivity to pleasant events?	-2
Was easily annoyed, short tempered or irritable?	1
Seems restless, or wrung his/her hands, or pulled his/her hair or otherwise agitated?	1
Had slow movements, or slow speech or slow reactions?	-1

Had many physical complaints?	2
Seems less interested in his/her usual activities than he/she did in the last month?	1
Was eating less than usual?	2
Lost weight?	2
Lacked energy or got tired more easily than he/she did in the last month?	2
Had lower mood or seemed sadder in the morning on most days?	1
Had difficulty falling asleep?	3
Woke up many times during the night?	2
Woke up earlier than usual?	0
Said that life is not worth living, or had suicidal wishes or had an attempt at suicide?	0
Blamed him/herself unnecessarily, or had feelings of failure or poor self-worth?	0
Expected the worst?	1
Expressed believes about his/her financial situation, or physical illness or losses that were untrue?	1

Besides the decrease in "Reactivity to pleasant events" and "slow movements/speech/reactions," subjects either displayed no change or demonstrated an improvement from baseline values in all other questions in the questionnaire. Notably, subjects experienced a decrease in difficulty falling asleep and night awakenings, which is consistent with light improving sleep.

6.3.4 Hypothesis 2d: CMAI

> Cohen-Mansfield Aggression Index (CMAI) scores will be significantly lower during the intervention period, indicating decreased agitation.

CMAI scores indicate the frequency of 29 agitated behaviors including verbally aggressive behaviors, physically aggressive behaviors, and non-aggressive, repeating behaviors (Cohen-Mansfield, Marx, and Rosenthal 1989; Carpenter et al. 2006; Chodosh et al. 2008; Cohen-Mansfield 1986). Higher scores indicate higher frequencies of agitated behaviors (see section 6.2.2.6.4 for more detail). As a group, CMAI scores ranged from 43.40 ± 14.40 during baseline and 32.6 ± 3.36 during the intervention period. Although intervention scores tended to trend lower than baseline, no statistical difference was found between baseline and intervention values ($p=0.08$). Light did not statistically reduce agitation, but the data suggests that light may have a mild effect

onagitation since all intervention scores for all subjects trend towards a lower value than baseline (Figure 48).

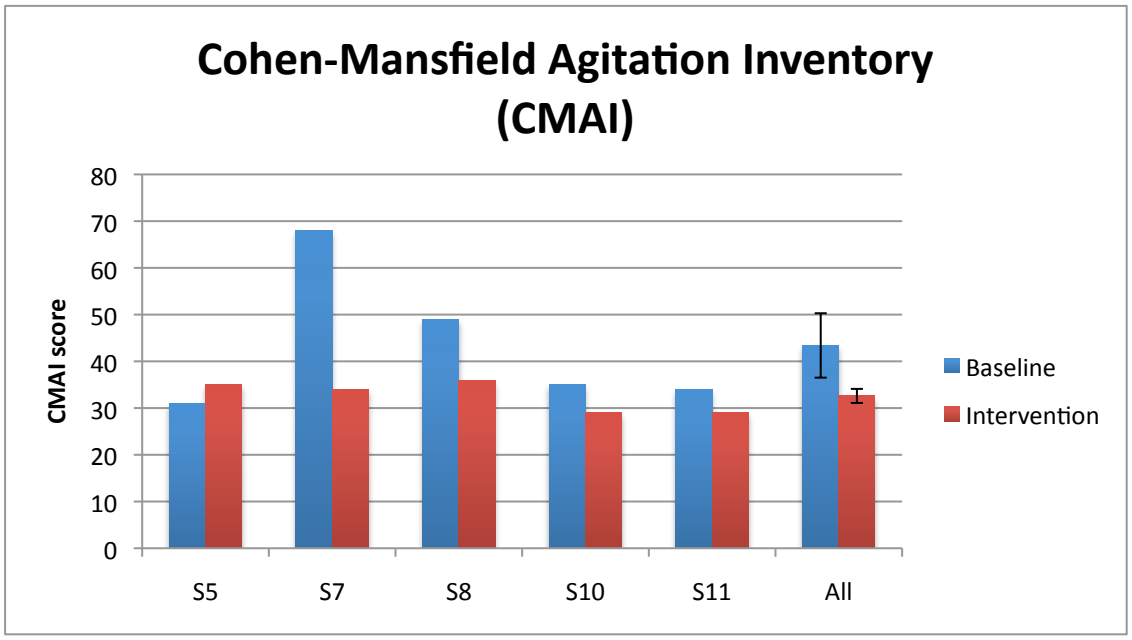


Figure 48: Comparison between the average baseline and intervention CMAI scores. No statistically significant difference was found (p=0.08).

Since this particular test gauged agitation based on the frequency of performed agitated behaviors, test scores were also examined by question to see which agitated behaviors decreased or increased from baseline to intervention scores since most behaviors displayed a downward trend during intervention. One-tailed Student's t-tests were used first to gauge the significance between individual baseline and intervention questions, but no statistical significance was found. A table was created instead to show the directional trend (difference) between baseline and intervention for individual agitated behaviors. In the following table, positive figures represent a reduction of the corresponding agitated behavior.

Table 8: CMAI scoring per question. 'Difference' was calculated as the difference between the baseline score and the intervention score.

CMAI Agitated Behaviors	Difference
Physically aggressive behaviors	
Hitting (including self)	0
Kicking	2
Grabbing onto people	4
Pushing	0
Throwing things	0
Biting	0
Scratching	0
Spitting (including food)	3
Hurt self or others	0
Tearing things or destroying property	0
Making physical sexual advances	0
Physically non-aggressive behaviors	
Paces, aimless wandering	8
Inappropriate dress or disrobing	6
Trying to get to a different place	5
Intentional falling	0
Eating/drinking inappropriate substances	0
Handling things inappropriately	0
Hiding things	3
Hoarding things	-1
Performing repetitious mannerisms	0
General restlessness	1
Verbally aggressive behaviors	
Screaming	4
Makin verbal sexual advances	0
Cursing or verbal aggression	-2
Repetitive sentences or questions	8
Verbally non-aggressive behaviors	
Strange noises	3
Complaining	2
Negativism	6
Constant warranted request for attention or help	2

These figures were derived from totaling baseline scores of all subjects, all intervention scores of all subjects, and subtracting the baseline total from the intervention total per question. Positive figures represent improvement from baseline agitation, and vice versa. According to the data three of eleven physically aggressive behaviors, five of ten

physically non-aggressive behaviors, two of four verbally aggressive behaviors, and four of four non-verbally aggressive behaviors were reduced during the intervention period. Otherwise, only one physically non-aggressive behavior and one verbally aggressive behavior increased during the intervention period, while the remaining behaviors showed no change. Again, while the data do not yield any statistically significant change between baseline and intervention values, there exists a trend towards decreasing aggression.

7. Discussion

7.1 Efficacy of the lighting intervention

This section discusses the efficacy of the novel luminaires on improving rest/activity rhythms, sleep quality, independence, depression, and agitation.

7.1.1 Rest/activity consolidation

According to IR and phasor magnitude, the tailored lighting system successfully increased rest/activity consolidation in the ADRD subjects. Despite the trend towards rest/activity consolidation however, M10, L5, and RA intervention values were not significantly different from baseline. Intervention M10 remained fairly consistent with baseline ($p=0.37$), indicating no change in the average 10 hours of highest activity; and intervention L5, the average 5 hours of lowest activity, displayed a slight dropping trend ($p=0.09$), suggesting only a slight decrease in nocturnal restlessness. Intervention RA also displayed a slight increase ($p=0.09$) over baseline values in response to the slightly decreased L5 intervention values. Since the changes between baseline and intervention M10, L5, and RA values were consistently small, it is possible that the addition of more subjects would also increase the significance of these parameters – especially for L5 and RA— indicating an overall reduction in nocturnal restlessness and an increase in rest/activity consolidation.

These results are somewhat consistent with Satlin et al. (1992), Riemersma-van der Lek et al. (2008), and van Someren et al. (1997), who studied similar rest/activity consolidation output variables. Compared to Satlin et al., this experiment was more able to demonstrate the increased rest/activity consolidation with the 24-hour cosine using IR. Satlin et al. were unable to find a significant increase in IS using a light-box intervention approach, but their consinor data analysis was significantly higher than baseline. (Like IS and IR, cosinor data analysis also compares the activity cosine with the 24 hour cosine). This thesis study also demonstrates more robust effects of light on rest/activity than Riemersma-van der Lek et al. 2008. In a 3-year, all-day indirect lighting intervention study, Riemersma-van der Lek et al. were unable to consolidate the circadian rhythms of ADRD patients with light alone. Statistically positive results on sleep and rest/activity rhythms were only observed in the combined therapy group of light and

melatonin. The combined treatment decreased nocturnal restlessness by 9% (p=0.01) and increase sleep efficiency by 3.5% (p=0.01). Light only increased total sleep duration (p=0.04). Overall, the results of this study were most similar to Van Someren et al. who demonstrated that an all-day lighting intervention could increase IS while not affecting amplitude (RA). Van Someren et al. suggested that the absence of significant changes in the amplitude indicated that improvements in IS resulted from a decrease in rest/activity rhythm variability rather than an increase in amplitude.

7.1.1.1 Subjective sleep quality

Subjective sleep quality was studied using the PSQI. Consistent with objective sleep quality findings, intervention PSQI was not statistically lower than baseline values (p=0.43). It should be noted however, that the PSQI scores for this experiment were incomplete. The caregivers for Subjects 5, 7, 10, and 11 did not complete the PSQI questionnaire during baseline, and in order to obtain a global score, a score of 0 was used as a conservative replacement per missing global component to prevent over-estimating the lowering of a subject's score from baseline to intervention (which would indicate increased sleep quality). The 0 substitution however, also over-estimates the increase of the PSQI score from baseline to intervention (indicated increased sleep disruption); therefore, only scores with either the complete data set and the conservatively improved PSQI score will be discussed. Subject 8 had a complete dataset, but showed no change whatsoever between baseline and intervention PSQI scores. This is inconsistent with his/her sleep quality, IR, and phasor magnitude, which increased from baseline; however, it is possible that the change was subjectively unnoticeable. Subject 10 demonstrated a conservative decrease from a 6 to 5, but a score of 5 was not necessarily an improvement. According to the PSQI, a score of 5 is still considered a statistically significant score indicating "sleep disruption." This parameter is consistent with sleep quality, but not in agreement with the IR and phasor magnitude results. Given the results it is possible that Subject 10 had improved his/her rest/activity consolidation, but still needs to improve actual sleep quality. Subject 7 displayed the most drastic improvement from baseline, decreasing from a 9 to 3, statistically improving subjective

sleep. Consistent with receiving the most eye-level CS, Subject 7 has the most improved PSQI score.

Most ADRD-related studies currently applying the PSQI use this questionnaire on caregivers only to assess caregiver sleep quality. Because the PSQI is a subjective questionnaire and would require a caregiver to complete it for the patient, it is possible that other studies deemed the questionnaire not objective enough for ADRD patients.

7.1.1.2 Independence

Independence was studied in this experiment using the MDS-ADLs questionnaire. Unlike the ambient light study by Riemersma-van der Lek et al. (2008) which found a statistical increase (p=.003) in nurse-informed ADLs independence in ADRD subjects (+1.8 points every year over a 3 years), this study did not find any statistical increase in ADRD independence (p=0.21). MDS-ADL scores of Subjects 7 and 10 remained unchanged from baseline, and Subject 5 had increased dependence during the intervention period. Subjects 8 and 11 were not included in the data because of physical illness during the intervention period. It is possible that more subjects were needed to show increased independence; however, it is also possible that independence can only be increased after a longer exposure period to a lighting intervention, such as 3 years as demonstrated by Riemersma-van der Lek et al. (2008).

7.1.1.3 Subjective depression

Similar to Riemersma-van der Lek et al., significance was found in the decrease of subjective depression measured by the CSDD. Rimermersma-van der Lek et al. found that 3 years of ambient all-day light statistically decreased subjective depression by 1.5 points (p=0.02). This study found that depression in ADRD also statistically decreased by an average of 5 points. Subject 7's CSDD in particular, fell from 11 to 5, indicating a within-subject statistical decrease in depression. It should be noted, that the caregivers for this subject also noted that the subject began to eat more during the intervention period, gaining 5 lb. In this subject's case, the weight gain was healthy and indicative of decreased depression according to the CSDD. This result is consistent with Subject 7 having received the most intervention CS according to eye-level measurements.

Additionally, statistical analyses were performed on all individual questions of the questionnaire to find any significant changes between individual depressive behaviors. No significance was found, but trends indicate that the subjects also felt a decrease in difficulty falling asleep after waking up at night, consistent with tailored circadian light improving sleep consolidation.

7.1.1.4 Subjective agitation

Compared to previous studies on agitation such as Satlin et al. and Mishima et al., this study found no statistical significance between baseline and intervention CMAI. Intervention CMAI scores however, had a strong trend towards reduced agitation as the caregivers for four out of five subjects reported a decrease in subjective aggression ($p=.08$). This finding may also be more consistent with Riemersma-van der Lek et al.'s study, demonstrating that CMAI scores only improved when the lighting intervention was paired with melatonin. It should be noted, however, that despite the non-statistical significance of intervention CMAI to baseline, caregivers for Subject 7 emphatically reported how the subject was no longer verbally aggressive during the intervention period. The lighting intervention was so popular among the staff, that the novel luminaires were left with the subject at the end of the experiment. Subject 7's case is consistent with having received the most intervention eye-level CS. It should also be noted that statistical analyses were run on all individual CMAI questions, but no significance was found between the baseline and intervention frequencies of any individual agitated behaviors.

7.2 Additional Studies

Since the conclusion of this portion of the experiment, the study has since continued, and a paper was submitted for publication with the addition of five more subjects for a total of ten subjects (seven females; mean age was 86.9 ± 4.7 years; Figueiro, Plitnick, and Lok 2013). Conducive to this study's predictions, the continued study conclusively demonstrated that more subjects increased the statistical significance of outcome parameters. Parameters that continued to demonstrate significance from baseline included phasor magnitude ($p=0.03$) and CSDD ($p=0.009$). Parameters that became

significant with the additional subjects included the CMAI (p=0.01) and the PSQI (p=0.02). It should be noted that the scoring for the PSQI in this continued experiment excluded any subjects that did not complete any portion of the PSQI questionnaires, whereas this study looked at all questionnaires conservatively. No analysis was performed on RA, M10, and L5. The following graphs illustrate the findings of Figueiro et al. 2013:

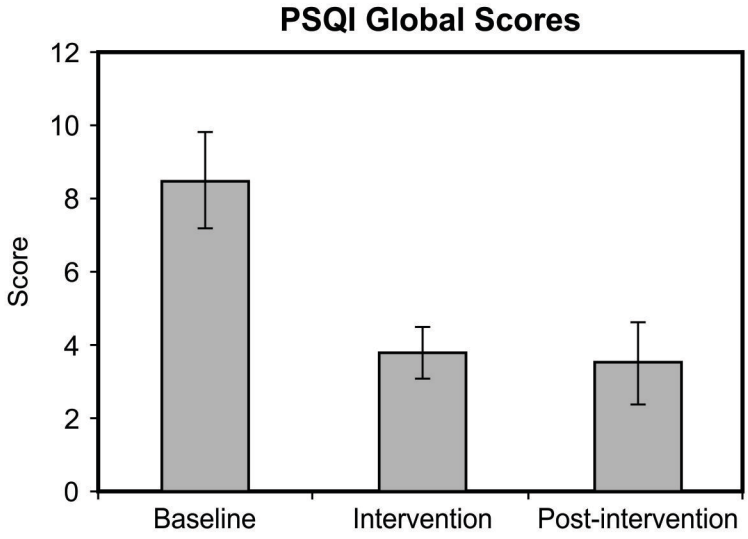


Figure 49: Mean ± standard error of the mean of the PSQI scores. Scores > 6 indicate sleep disturbances. A one-tailed, paired t-test showed significantly lower PSQI scores after intervention than after baseline (p=0.02). As shown above, sleep disturbances were reduced after the lighting intervention and remained low even after 4 weeks of the removal of the lighting intervention (Figueiro, Plitnick, and Lok 2013).

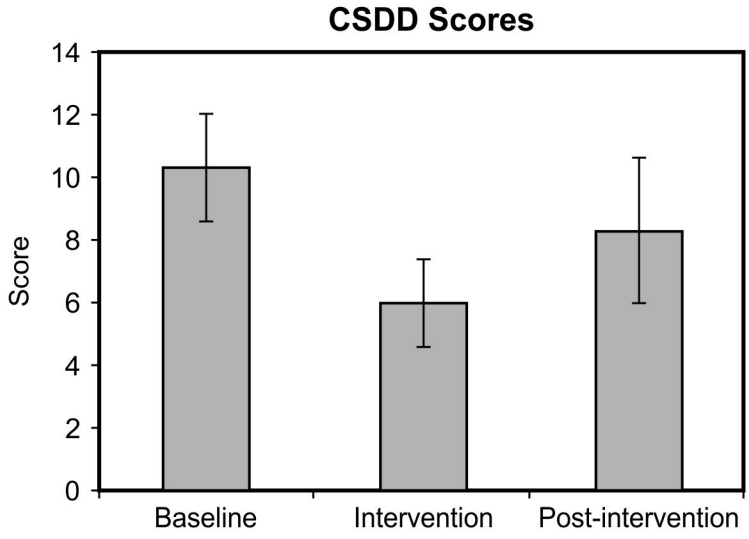


Figure 50: Mean ± standard error of the mean of the CSDD scores. A one-tailed, paired t-test showed significantly lower depression scores after intervention than after baseline (p=0.009). A higher score is associated with greater self-report of depression, with depression being associated with scores of 12 or higher (Figueiro, Plitnick, and Lok 2013).

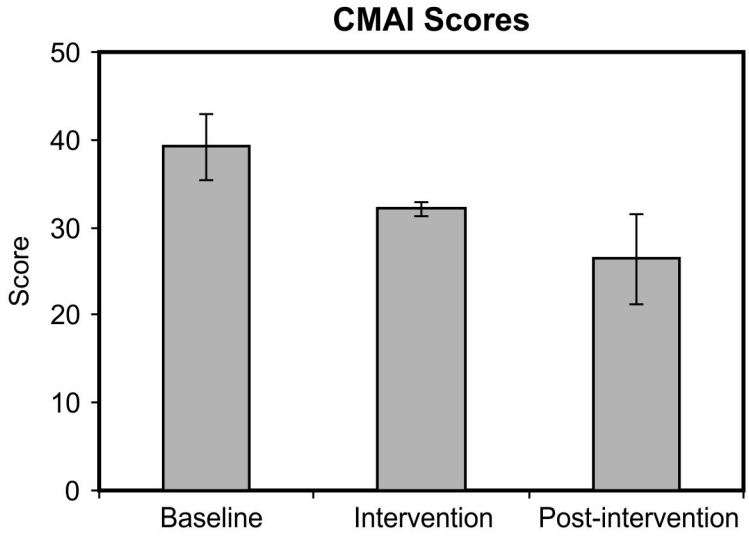


Figure 51: Mean ± standard error of the mean of the CMAI scores. A one-tailed, paired t-test revealed a significant difference baseline and intervention scores (p=0.037) and between baseline and post-intervention (p=0.01). A higher CMAI score is associated with greater depression (Figueiro, Plitnick, and Lok 2013).

7.3 Feasibility of the novel tailored lighting system

While this study focused on the outcomes of the tailored lighting system on ADRD patients, this study also explored the two basic principles of studying the feasibility of a

novel tailored lighting system: delivering and measuring the dose. The following section assesses the successes and challenges of the dose delivery (novel tailored lighting system) and comments on the quality of the current dose measuring system (the Dimesimeter).

7.3.1 Feasibility of the novel tailored lighting system

Performance is mainly used to gauge the feasibility of the novel lighting system; however, other parameters also discussed include stability, convenience, comfort, performance, and the user's response.

7.3.1.1 Performance

The goal of this experiment was to test the novel luminaire's ability to provide ≥320 lux at the eye as hypothesized to begin the process for specifying an ideal light dose for ADRD patients. The cut off was chosen because it was the average eye-level intervention illuminance of Subjects 2 and 4 from the pilot study who were exposed to four novel luminaires. Since additional luminaires would be an impediment to the subjects and caregivers, the original ≥400 lux exposure goal (recommended by Figueiro et al. 2008) was reduced to ≥320 lux. This experiment achieved an average illuminance of 505.42 ± 266.19 lux at the eye, which translates to a CL_A of 1078.28 ± 581.48, and a CS of 0.51 ± 0.09. Indeed the luminaires were able to provide ≥320 lux with an acceptable CL_A and CS. Additionally, this study also showed that the lighting intervention can successfully consolidate rest/activity rhythms, increase sleep quality (with the additional study), reduce depression, and reduce aggression.

It should be noted however that for one subject, this criterion was not met. The added illuminance from the fixtures during the intervention period for Subject 10 was 199.20 lux at eye-level. Despite having the least light exposure however, the available lighting intervention still had a positive effect on his/her outcome measures. Subject 10 contributed to the statistical significance of IR, phasor angle, and CSDD, and the near significance of phasor magnitude and CMAI. Overall, 320 lux of 9325 K CCT from 6 a.m. to 6 p.m. is a feasible "launch pad" to start tweaking the dose for more circadian efficacy.

7.3.1.2 Stability

Stability refers to the ability of the novel luminaire to withstand everyday use without breaking, failing, falling, or causing damage or injury. The stability issues during the experiment mainly dealt with malfunctioning NL1s, malfunctioning timers, and NL2 luminaire 'tipping.'

7.3.1.2.1 NL1

Although NL1s were built in the exact fashion of the pilot luminaires, the new batch of NL1s used in the final experiment did not always work properly. After the initial installation of the luminaires, we began receiving reports that some of the luminaires were displaying one of two problems: 1) one lamp turned off while the second was still lit in the luminaire, or 2) both lamps were turned off while the luminaire was still on. Because we visited the subjects once every week during the intervention period, problem luminaires were closely monitored. On-site luminaire maintenance included checking the timers to see if they were set correctly, inspecting if the lamps were in the sockets correctly and checking that ballast wires were securely attached to the sockets. If the luminaires were fixed on-site, the luminaires would be left alone; however, if the luminaires continued to malfunction, they would be replaced the same day with a new luminaire built in the lab to the same specifications. Unfortunately, the replacements soon suffered the same problems as the malfunctioning luminaires. To examine the problem, lamps, sockets, and ballasts were replaced and tested. Unfortunately, nothing was found and the problems remained. After further examination of the luminaires and additional consultation with lab technicians and investigators at the LRC, it was hypothesized that an over-sensitive end-of-life (EOL) mechanism that existed within the ballasts (GE F40/30BX/2G11) may have caused the malfunctioning. An EOL mechanism shuts down lamps, preventing abnormal EOL failure modes. The frequent switching on and off of the luminaires due to their connection to a timer and occupancy sensor may have caused the EOL mechanism to react negatively and turn off the lamps when the luminaire was turned on. Another hypothesis for the lamp failure was that because the NL1 fixtures were not originally UL rated, over-heating (despite the additional fans) might have caused the ballast to cycle the lamps; the lamp cycling from

overheating might have cause the EOL mechanism mentioned earlier react negatively. No official tests were conducted to confirm this hypothesis, since new fixtures (UL rated NL2s) were built to replace the NL1 models for future experiments. No problems were reported with the NL2s. Future luminaires may need to be UL rated for the biax lamps such as NL2 to increase the reliability of the fixtures.

7.3.1.2.2 Timers

Stability issues were also experienced with the luminaire timers. The performance of the luminaires was compromised because subjects sometimes tampered with the timers, usually cutting their light exposure. Instructions were left with the caregivers to reset the timers themselves if tampering occurred; however, this does not make up for the fact that the timers on the luminaire are not tamperproof. Further, when the caregivers were unable to resolve the timers, the timers were completely unplugged, thus turning off all the luminaires they were attached to in order to prevent unwanted light at night. Experimenters were required to revisit the subject and reset the timer. Timer tampering was reduced when the timers were placed behind hard-to-move objects; however, this is was not always the case. Moving timers behind large objects also resulted in the timers being pushed against the wall by the large objects and accidentally reconfigured. As an independent product in the market, timers may be an issue for these novel luminaires unless they are tamperproof.

7.3.1.2.3 NL2 "Tipping"

Caregivers and ADRD patients did not report any of the luminaires physically breaking or falling; however, experimenters did report a difficulty with the luminaire heads 'tipping' with NL2s (see Figure 17). Because the luminaire head can be either placed in an upright or horizontal position (see Figure 14A and 14B), instances have occurred where a fixture in the horizontal position fell back into the vertical position during installation, causing minor hand injuries. This problem was caused by the prototype fixture for the NL2 and henceforth noted for future productions of the NL2 fixture. Adding an extra screw to fasten the fixture head in the horizontal position solved the problem. NL1 fixtures did not need this extra screw since the physical properties (flat

back) of the original luminaire head allowed it to rest stably in the horizontal position. The new luminaire heads for the NL2 fixtures rested on a mounting arm bracket; thus, a screw was needed. Tipping problems ceased after the screw was added.

7.3.1.3 Convenience

Convenience refers to the ease of installation/usage, portability, and energy saving properties of the novel lighting system.

7.3.1.3.1 Installation and ease of use

The caregivers in the experiment were enabled to use the novel luminaire system because of its plug-and-play design. Since the pre-installation procedures already performed by the experimenters (setting the timers), installation only required placing the luminaire in an available space in the room and plugging the luminaire, with timer attached, into a standard 120-V wall outlet. The luminaires turned themselves on at 6:00 a.m. and off at 6:00 p.m. Caregivers appreciated that they only had to peek into the patient rooms after 6:00 a.m./p.m. to tell if the luminaires were working.

7.3.1.3.2 Portability

While the novel luminaire system is portable, the ease of moving the luminaires from one area to another requires more manpower than does a standard table lamp. Each luminaire weighs approximately 20 lbs each without the 10 lbs of sandbags around the base, and four luminaires were used per installation. Thus, approximately 120 lbs of equipment were moved in and out of each room per installation during the experiment. While the 10 lbs sandbags could be removed from the base of each luminaire and transported separately, moving two luminaires at the same time still equated to approximately 40 lbs per trip to or from the subject's room. It should be noted that the sandbags were necessary to balance the top-heavy luminaire. In the future, the novel luminaire could be designed to weigh less or to produce higher light output, decreasing the number of luminaires necessary for an installation.

7.3.1.3.3 Energy Saving

In addition to using energy-efficient fluorescent technology, the novel luminaire system was also wired with an occupancy sensor, which turned the luminaires off when the occupant left the room for an extended period of time (15 minutes). This feature added to the energy efficient intentions of the novel luminaire design without compromising its performance. Some subjects appreciated how the luminaires turned on when they arrived in the room without their having to physically turning on the lights. Some subjects disliked not being able to control the luminaires. The caregivers did not have a strong positive or negative opinion about the occupancy sensors, but appreciated the energy efficiency considerations.

7.3.1.4 Comfort

Comfort refers to whether or not lighting system caused any physical discomfort (not to be confused with User Response (section 7.2.5) which delves into personal opinion).

7.3.1.4.1 Glare

In most incidences, three of the four novel luminaires installed in the rooms did not cause glare because they were carefully placed to avoid direct viewing angles of the light source. Usually two of the four luminaires were tucked in a corner with their fixture heads in the horizontal position (Figure 19A), emitting only indirect ambient light. The remaining two were placed behind the ADRD patient's chair in an inward tilted position (Figure 19B). The inward tilt reduced the glare towards anyone directly approaching the chair from the front; however, glare was an issue from the side (Figure 19A). In the worst case scenario when no space was available for the novel luminaires, one of the horizontally positioned luminaires was positioned vertically in a corner (Figure 19A). The fixtures causing the most glare were the chair luminaires facing the entrance and vertically positioned corner luminaires. Interestingly, the caregivers complained only once about the glare from one vertically positioned luminaire (which was rectified). The only complaint from subjects about the light pertained to the overall brightness in the room (it was too bright). Overall, patients and caregivers did not find the luminaires

glary. It is possible that complaints were minimal however, because the caregivers/patients knew that the application was only temporary. Future models of the luminaire should continue to take glare into consideration during the product or application design phase.

7.3.1.4.2 Heat

The four additional luminaires in a small room running two biax lamps contributed to a slight temperature increase in the patient's rooms. Nursing staff commented on how these rooms became 'stuffy' when the additional heating from the building wide HVAC system was turned on; but when the HVAC was off, the heat from the lighting system was minor. Nursing staff also commented that the patients might actually enjoy the added heat because of their usually cooler body temperatures. Still, this issue needs to be resolved. In warm weather areas, this warming characteristic might cause overheating issues in both humans and the lighting system.

7.3.1.4.2.1 Dose barriers

It should be noted that while the dose successfully consolidated rest/activity rhythms, the pre-existing state of subjects' bedrooms might have prevented additional light from being received by the subject to strengthen the consolidation. While all five of the subjects utilized four novel luminaires in their rooms, all five rooms were also different which partially accounted for the varying illuminance at eye-level of all the subjects. These varying differences in these rooms that may have acted as barriers, which limited the light, include furniture, personal affects, and paint. For example, in Subject 10's room, furniture and personal affects obstructed the installation of luminaires in optimal areas during the intervention period. The installation areas for Subject 10 were limited to areas under low wall shelving against a wall, significantly blocking the amount of light from reflecting into the room. Other subjects had many photographs or pictures on the wall that they did not want obstructed by the luminaire. Some subjects were picky and requested that the luminaires be placed in less-than-optimal areas to reflect light back into the space due to cosmetic preferences. Paint darker than white was

also a barrier simply because it absorbed more light than white paint, preventing more light from reflecting back to the subject's eyes.

Another probable reason for low eye-level illuminances was the position of the main sitting/resting areas of the subject. Since the eye-level illuminances were only recorded at eye-level on the subject's available seating areas and bed, it is possible that the seating areas were exposed to the least light from the lighting intervention. Subject 10 also experienced this predicament. Thus, while the novel lighting intervention had the potential to provide ≥320 lux of light at the eye, environmental factors may have prevented the lighting from being effectively bright at key resting areas.

Possible solutions to alleviate these predicaments are to either increase the light output per novel luminaire or reduce the footprint of the luminaires to fit in smaller areas. Real estate is a limited in ADRD rooms, and these spaces are usually not designed to hold four novel luminaires for circadian tailored light. Still more effective is getting involved with the architect before a space for ADRD patients is designed. Working with the architect would likely solve equipment conflicts and possibly inspire more creative solutions to introduce circadian tailored light.

7.3.1.4.3 User Response

The user responses to the novel luminaires were varied. Of all nine subjects that were recruited for the experiment, three subjects did not like the novel luminaires, three subjects had favorable opinions about the novel luminaires, and three subjects did not express an overwhelmingly positive or negative opinion about the lighting intervention. Of the three subjects that did not like the novel luminaires, Subject 6 reportedly developed severe headaches from the lighting intervention, Subject 9 did not like how the luminaires blocked their wall pictures, and Subject 11 simply did not like the novel luminaires; the first two of these three subsequently withdrew from the experiment. Of the three subjects that did have favorable opinions about the lighting intervention, Subject 5 emphatically commented on how the lights brightened their room, Subject 7 reportedly gained 5 lb and became significantly less agitated, and Subject 10 enjoyed how the lights rendered their room "pinkish." The last three subjects that did not have overwhelmingly positive or negative opinions about the novel luminaires. One was too

sickly at the time of the lighting intervention and dropped from the study (Subject 13), one was hospitalized during the study and could not be interviewed (Subject 8), and the last subject dropped from the study because he/she could not keep the Dimesimeter on (Subject 12). Certainly, the subjects with the most unique responses were Subject 7, who gained weight, and Subject 6, who developed headaches. According to caregivers, Subject 7 began eating more because the lighting intervention reduced their depression (as discussed previously in Section 7.1.1.3); however, no explanation can be surmised thus far for Subject 6's headaches. Overall, whether positive, negative, or apathetic, subjects were always generally open to the idea of giving the lighting intervention a chance, but like most new products, the luminaires were generally a hit-or-miss.

7.3.1.5 Overall Acceptability

Overall, the novel circadian tailored luminaire system is on the right track in beginning to specify the dose and being an acceptable dose delivery apparatus for ADRD patients. Not only did the luminaires perform better than hypothesized–emitting 505.42 ± 266.19 lux amounting to a CL_A of 1078.28 ± 581.48, and a CS of 0.51 ± 0.09— the latest version of the novel luminaires (NL2s) were also fairly convenient and have no un-resolvable stability issues.

7.4 Measuring the dose: feasibility of using Dimesimeters

Dimesimeters are an advantage over the current actigraph technology for circadian research by recording calibrated circadian light exposure in addition to activity; however, throughout the course of this experiment, application problems with this product were realized. These notable issues are discussed in this section as possible areas of further research.

The most prevalent barrier lowering Dimesimeter compliance, is the demand that the device stays exposed on a subject's wrist for 24 hours a day (excluding showers). Except for Subject 5, who had an attentive spouse to constantly monitor his/her sleeves to stay folded up during most daylight hours, all other subjects were frequently found with their sleeves or throws covering their Dimesimeters. Evidence supporting that the subjects may have covered their Dimesimeters is the "Percent of Dimesimeter data

omitted […].” Table 2 indicates that while the Dimesimeters were able to record the majority of light input, large chunks of data were also missing. According to caregivers, the Dimesimeters were sometimes taken off or misplaced since the devices were noticeable and detachable. Although nurses were reminded through emails every other day during the intervention period to check the subjects' watches and keep the Dimesimeters exposed to light at all times, they cannot monitor subjects continuously. Thus, a large amount of illuminance data may have been lost in part due to sleeves, throws, or misplacement because the device was wrist detachable.

Since the technology may not be permanently or semi-permanently mounted to the subjects due to humanitarian concern for demented ADRD patients, research must further delve into solutions that increase the likelihood of ADRD subjects retaining their Dimesimeters. The most current proposed solution for measuring the dose of light using Dimesimeters is the application of two Dimesimeters: one mounted on the wrist, and another as a pendant (Figueiro et al. 2012). According to the study, wearing the Dimesimeter on the wrist compromises accurate light measurements relative to locating a calibrated photosensor at the plane of the cornea; however, using two Dimesimeters (wrist and pendant) should yield more accurate results.

7.5 Conclusion

In conclusion, the tailored lighting using the novel floor luminaires for dose delivery to ADRD patients was successful. Not only did the luminaires provide over 320 lux of light at eye-level, the application also garners statistically significant positive results on rest/activity consolidation, sleep quality, depression, and agitation (with the added study). As a prototype delivery apparatus, the novel luminaire is also fairly stable and convenient, able to stand on its own while providing a timed lighting regime that is energy efficient and needs no monitoring. More investigation however, is needed to verify the circadian effects of this specific product, but if its effects are confirmed, investment can be made into further investigating better approaches to improving the dosage for better entrainment and further developing the light apparatus to more successfully provide circadian tailored light.

8. Future Research

8.1 An ideal dose

Although this experiment has shown that light can successfully consolidate rest/activity cycles and decrease depression, more research can further the specification of the tailored circadian light dose. The next experiment for example, could focus on the acceptability of short-wavelength light. How much short-wavelength light will an ADRD patient accept for a permanent circadian tailored installation? Would the amount increase or decrease when an entire home/facility is lit with the light dose versus only one room? Questions such as these are important because although research is able to direct what light sources are the most efficacious for the circadian system, ultimately the user decides whether or not they choose to use the light.

8.2 Improving the dose delivery apparatus

More research can also focus on the development of the dose delivery apparatus. While the only stability issue was timer-related in this experiment, inconveniences with the luminaire's form factor could potentially harm its integration into mainstream use. To increase the flexibility of where the luminaire can be installed, research could focus on reducing the form factor or increasing the variability in installation options for the luminaire. Attractiveness may also be a factor to keep in mind while altering the form factor to increase positive user response. Another possible solution for increased acceptability is to increase the light output of the current luminaires. Potential users may more likely pick up the technology if less than four units are needed to bring the light levels to recommended levels. Likely the best solution however, is to simply get involved with the architect for well-planed, built-in solutions that only require the flip of a switch, but current institutional homes and private households usually cannot afford such retrofits. Other research directions include developing all new apparatuses. The following novel tailored lighting system concept and sketch were inspired by the experience gained from this experiment:

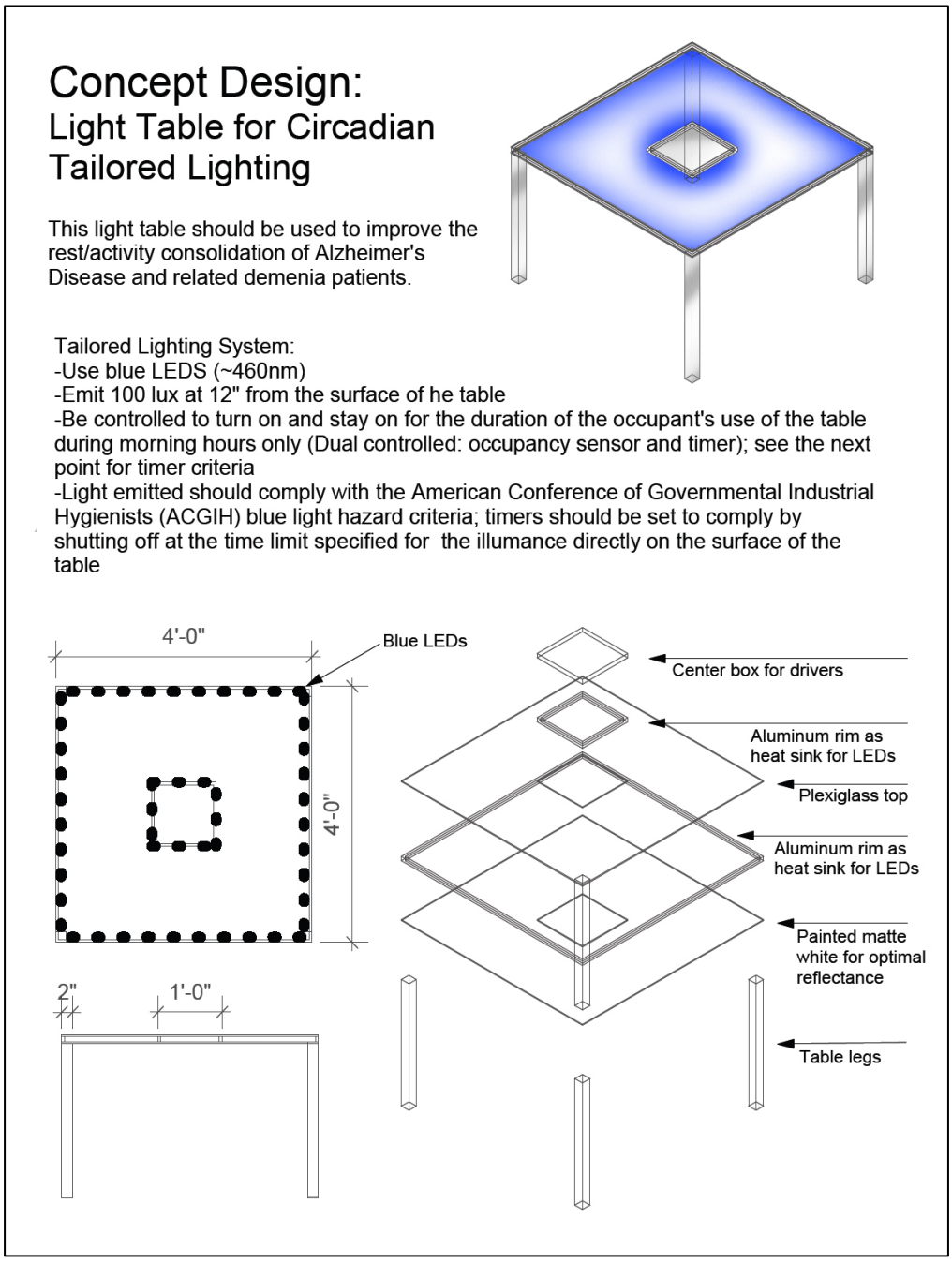


Figure 52: Table concept for novel tailored lighting system.

The novel tailored lighting table is an approach to circadian lighting more closely related to a light box than ambient lighting. Unlike a light box however, which could be perceived as an extraneous glowing box, this table is an integrated solution, allowing ADRD patients to eat and do other activities while they are situated to gaze at the

lighting intervention. Possible future studies could explore the construction, acceptability, and efficacy of this solution as compared to the NL1s and NL2s.

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